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AM Envelope

The potential of Additive Manufacturing for façade construction

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Contents (concise)

Abstract

The continuous development of the building envelope over the past hundred years can be exemplified by a few ground-breaking inventions. Firstly, the separation of primary and secondary structure during the beginning of the 20th century; by implementing a curtain wall façade to physically separate the façade from the building. This was followed by the development of double façades and a growing technologisation and use of the building envelope for building services and climate devices. Hereby the development of the 'Polyvalent Wall' by Mike Davies at the beginning of the 1980ies was a notable vision that formulated part of the building envelope as an active skin. The realisation of such a concept of a compact building envelope that encompasses all necessary supply units and building services in a very slender and integrated way has still not been accomplished.

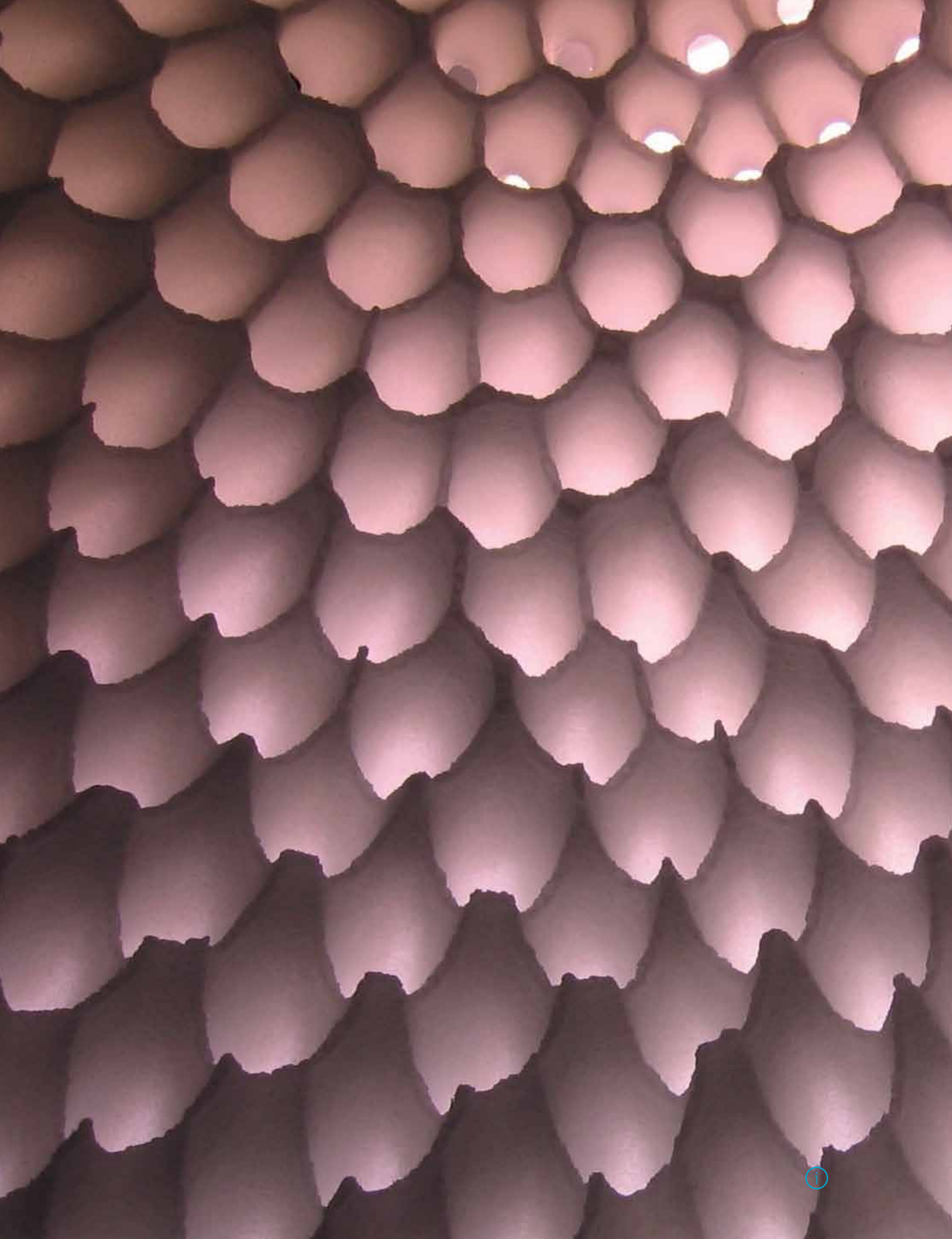
This vision has been followed by many technical developments; the latest being based on decentralised building services that are inseparably connected to the façade. But in spite of all these efforts, even forty years after Mike Davies' vision we are far from their realisation. Therefore, realising a 'dynamic building envelope' is a goal yet to be achieved.

One technology to materialise this desire is Additive Manufacturing (AM): Layered production of parts from a 3D file. Over the past twenty years this technology has evolved from a support tool for product development into an independent production method.

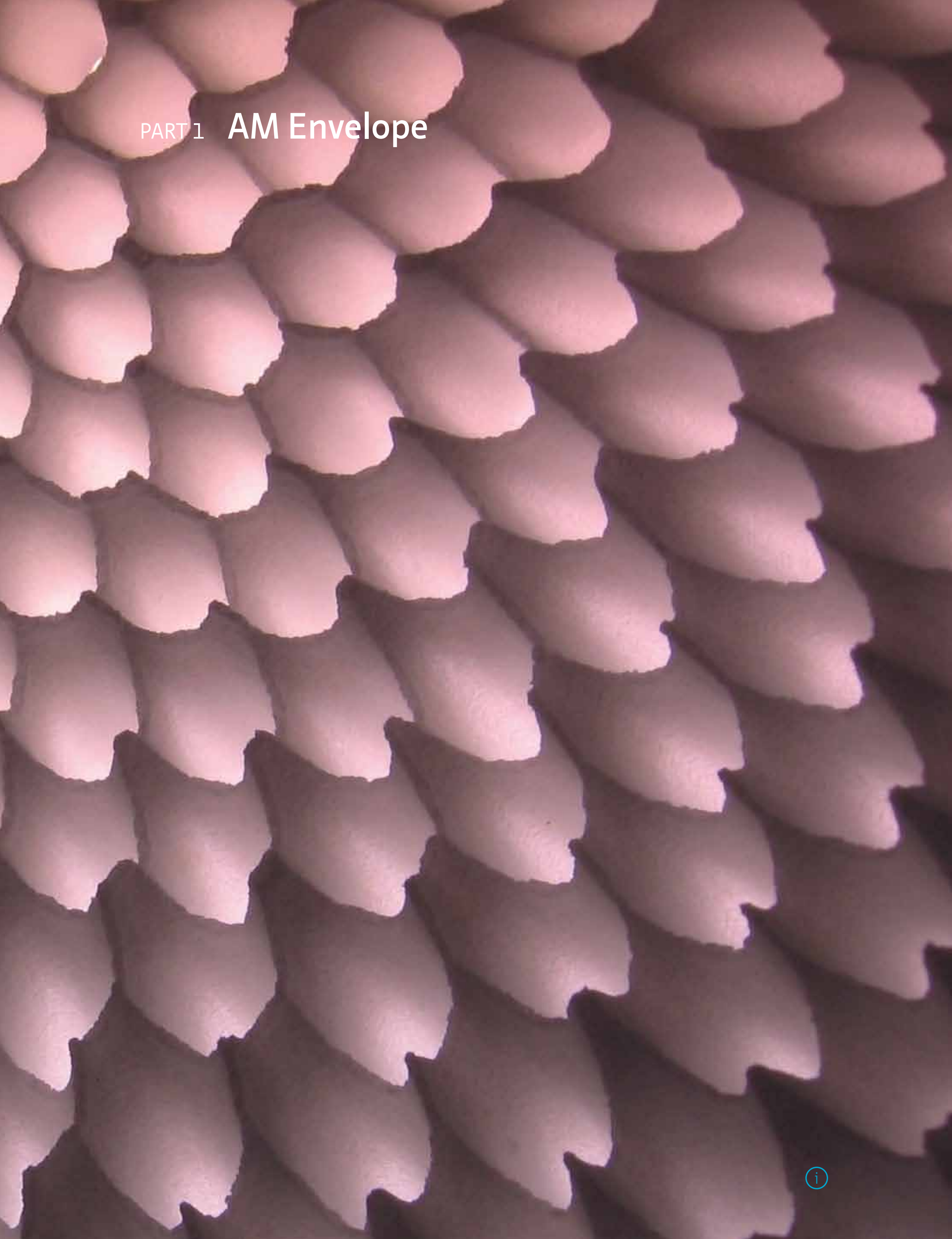
The term 'AM Envelope' (Additive Manufacturing Envelope) describes the transfer of this technology to the building envelope. Additive Fabrication is a building block that aids in developing the building envelope from a mere space enclosure to a dynamic building envelope. AM Envelope is an approach to this evolutionary step with the AM technology. This is exemplarily concretised and illustrated with building components for a post-beam façade, and then transferred to façade development over the next thirty years.

This dissertation shows the potential of the additive methods for the development of façade construction: Additive methods change the way we design, build and produce building envelopes.

Contents (extensive)



PART 1 AM Envelope



1 Introduction

This dissertation is motivated by the opportunities that Additive Manufacturing (AM) offers for producing components, structural designs and buildings. New technologies appear regularly - finding the one capable of having a big impact is difficult. In the case of the additive methods, the changes in our way of constructing and thinking of complex mechanisms or geometries are predictable. Therefore an early examination of the new methods is crucial to stay ahead or at least amongst the early adopters.

§ 1.1 Background

§ 1.1.1 The façade

To research the application potential of AM for the façade, we need to look at the developments in façade technology. In simple terms, the technological development of the building envelope as it applies to the buildings today can be narrowed down to the past hundred years. The introduction of the curtain wall and its subsequent development into the double façade is important because they are the basis of today's most commonly used façade types.[1]

However, in spite of these highly technological and very sophisticated façade systems, the demand for a true building skin has not yet been fulfilled. Mike Davies expressed this vision as early as in the Nineteen Eighties – and it still has not been reached. He envisioned a façade panel with an array of different functional layers. One for example would deal with sun shading, one would provide thermal insulation. All needed functions would perform automatically according to the given conditions, powered by self-generated energy from another layer within the wall. What was conceived as a slender, multi-layered and multifunctional envelope is still being realised as 15 to 30 centimetre thick walls with a myriad of individual components – far from Davies' vision. Even if the solutions sometimes are more adaptive than at the beginning of the technical sophistication, such as the development form centralised to decentralised building services, and the resulting immediate influence the user has on the indoor climate.[2]

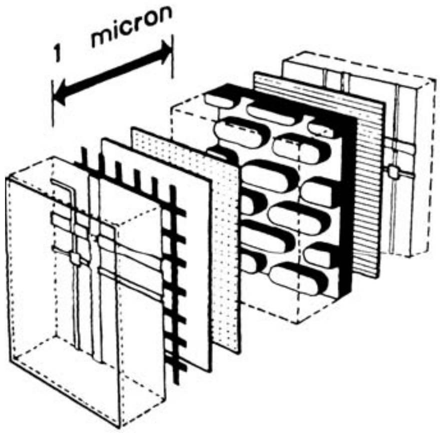


Figure 1
Concept sketch of the Polyvalent Wall by Mike Davies.

In this thesis the Polyvalent Wall is used as an envision of how future building envelopes should perform and how slender – aiming toward the human skin – they could be elaborated. It is therefore used as a symbolic ambition and a starting point to rethink our current façade technology and to stimulate technological development. Davies' idea is not meant as a realistic product example, but as one possible way to go.

§ 1.1.2 Additive Fabrication

'Additive Fabrication' summarises the family of additive methods as they are understood today – in the year 2012. This includes 'Rapid Prototyping (RP)' with its original intent to quickly generate illustrative models for product development. These models are used as a physical basis for discussion immediately following the design phase. But Additive Fabrication as a superordinate term also includes those fields of the same family for which specific areas of application have evolved from the basic concept: § 2.1.5 Rapid Tooling (RM), which, in industrial mass production has changed the manner of how production tools are made, as well as § 2.1.4 Rapid Manufacturing (RM) which is specifically designed for the production of end use products that are immediately usable without the need for subsequent production steps.

During the course of the development of the various methods and applications, a multitude of terms was used for the vast field of Additive Fabrication: Rapid Prototyping, Layered Fabrication, Rapid Manufacturing, Freeform Fabrication, Additive Fabrication, Layered Manufacturing, Direct Digital Manufacturing, Additive Manufacturing, etc. The term ‘Additive Manufacturing (AM)’[1] has evolved as a general term for these technologies [3]; thus, in this text Additive Manufacturing (AM) is used as a synonym for additive methods.

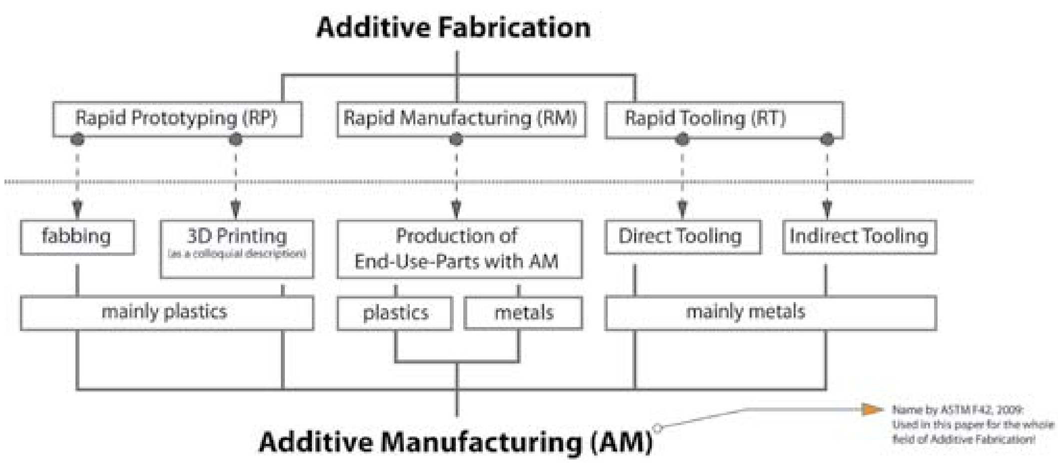


Figure 2
Overview ‘Additive Fabrication’; use and allocation of various terms for the different areas of the AM industry

Additive methods are characterised by adding layers of material to produce parts without the need of tools or preforms („tool less“ [4]). For all the different types of additive processes, 3D computer data is the basis for the manufacturing process. The parts are developed on the computer. For manufacturing, the data is then translated into a special computer language and generated with AM systems.

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1 ASTM International Committee F42 on Additive Manufacturing Technologies: “AM: ~ process of joining materials to make objects from 3D model data. Additive Manufacturing (AM) as opposed to subtractive manufacturing methodologies. Usually with AM parts which are processed layer upon layer. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.”

Reference [3]: ASTM, Typologies for layered fabrication processes, in ASTM F2792, A. USA, Editor. 2009, ASTM International Committee F42 on Additive Manufacturing Technologies: Annual Book of ASTM Standards, Volume 10.04

As a new part of the production chain, additive fabrication will change the way we design and produce as well as how we handle consumer goods and our built environment. In order to make these changes tangible for façade construction, case studies with realistic application concepts from the façade technology were conducted for this research. Initially it was difficult to identify such applications for Additive Manufacturing (AM) due to our habit to think subtractive rather than purely functional. However, it did lead to an intensive examination of the technologies and to approaches and results. Only a few initial steps into developing products with AM generate many new approaches for façade construction. Relevant aspects include material consumption, assembly as well as component performance in the façade system, amongst others.
Examining these approaches provides an indication of the manner and depth of the possible changes in the design process of façade constructions as well as possible changes in building construction and architecture in general. Examining these changes allows us to identify the potential of Additive Manufacturing.
The development of AM is still in the beginning stage; however, AM technologies offer the potential to lastingly change design and construction methods. The change in our way of thinking has long begun: file-to-factory, Building Integrated Modelling (BIM), digital materials are the key words in this ongoing discussion in the day and age of Grashopper[2]. Ideas that have been put on paper can no longer be stopped; their realisation is only a question of time. With the AM technologies the 'façade' as a mere enclosure could evolve into a 'dynamic building envelope' – analogous to the human being: a true skin. Further development of the new technologies is progressing rapidly; it is foreseeable that AM will be intuitively and naturally used in the future and, thus, find an application in many new areas – even in the somewhat conservative building sector.[6]

Results from research projects and student assignments will demonstrate how such changes can take effect when applied to façade construction. Different product development approaches for various components of a system façade are offered that were manifested in realised prototypes. Their potential in terms of being integrated into a real production chain in the field of façade systems will be discussed in this dissertation.

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2 About Grasshopper: For designers who are exploring new shapes using generative algorithms, Grasshopper® is a graphical algorithm editor tightly integrated with Rhino's 3-D modelling tools. Unlike RhinoScript, Grasshopper requires no knowledge of programming or scripting, but still allows designers to build form generators from the simple to the awe-inspiring.

Reference [5]: Davidson, S. Grasshopper - Generative Modelling for Rhino. 2012 [cited 2012; Available from: http://www.grasshopper3d.com/

§ 1.2 Motivation

§ 1.2.1 Engineering

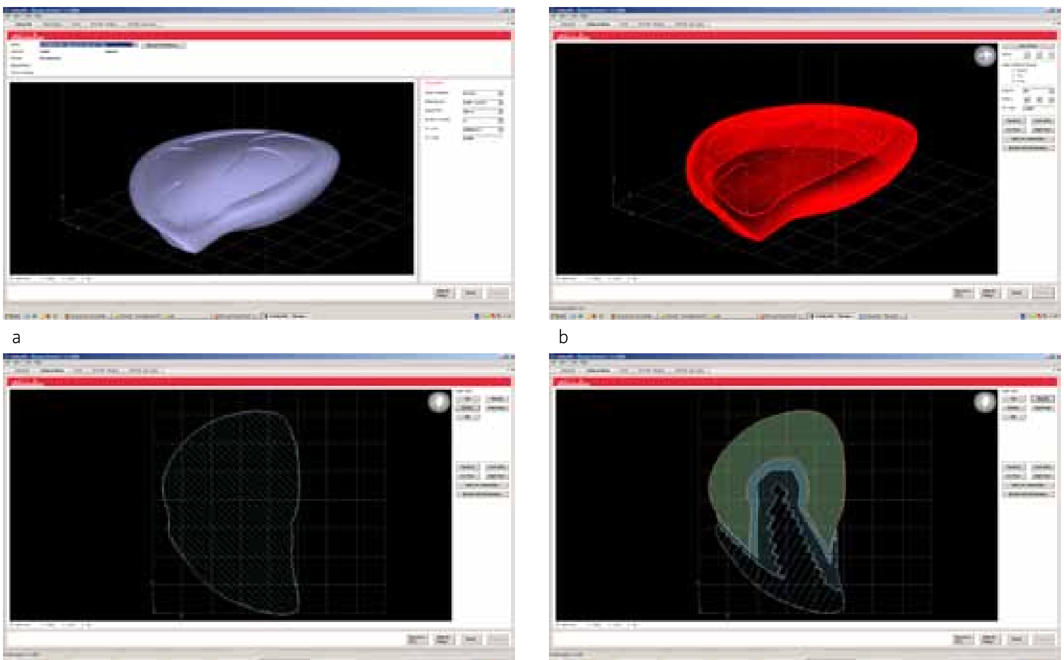
Since the end of the 19th century, the engineers who developed early architecture and structures were trained to solve challenges and problems within a given range of products and industrial standard parts. I-beams, rivets, bricks and other 'building' materials led to a predetermined range of sizes, measurements and, therefore, to repeating products. These circumstances led to the fact that the concept of 'design for production' is deeply embedded in our manner of thinking. This limits the possibilities of generating new constructions and new designs. We tend to fall back to the standards that still surround us today.

Most of the standard tools today are subtractive. In contrast, AM is the first attempt to think additive rather than subtractive. This leads to a whole new world of engineering because there is no need to assemble existing parts that will be later combined into the end product. We can start thinking about the performance we want to achieve with our product first, and then begin to engineer the needed materials around this performing feature. AM technology even allows us to engineer the parts integrally – for example the functionality of a hinge could be derived from the material properties rather than from fittings, bolts and joints added to the part. Additive methods allow for structures that are not realisable with the traditional manufacturing methods. AM can integrate complex functions into components without additional work expenditure. No longer taking place at the construction site, the assembly is done in the virtual model.

Against this background it became obvious that AM could take engineering to a new level. It was important to apply the technology in teachings and seminars to gain deeper insight into its usability. For this new design approach, the term 'Funktionales Konstruieren' (functional constructing) was introduced. We do not need to realise constructions with existing standard parts, but we can digitally materialise the part around its performance. This will gain in importance in façade technology, in building construction and ultimately in architecture.

An increasing number of recent architectural projects exemplifies that the realisation of visionary CAD designs (Computer Aided Drawing) is still coined by the limited possibilities of technical realisation that exist today. Free-form architecture requires expert knowledge. Thus, after creating a unified, homogenous overall design, the structure must be divided into transportable small components. During the planning process the requirements for individual building parts such as roof, wall and foundation are broken down into small components, only to be reassembled at the construction site. The result is one large unit that, upon closer inspection, can be broken down into its constructive parts.

Transition-free production, a true CAD-CAM workflow (Computer Aided Drawing – Computer Aided Manufacturing) from such open CAD designs into the built environment is not yet possible. AM technologies might be a solution to realise freeform designs. However, since the AM manufacturers' focus does not lie on architectural applications, the development in this area has not exceeded the research stage (see chapter 3 and chapter 4). In order to utilise AM technologies for building construction, they must be designed for large applications.



a b c d

Figure 3

*a) Screenshot of FDM job preparation on the computer; software used is Catalyst: the 3D *stl. file after the import.*
*b) The 3D *stl. file after the slicing was done by the software.*
c) In blue: the outline of the support structure; the first layer on top of the building platform.
d) In blue: outlines and filling of the support structure; in red: outline of the ABS part; in green: filling of the ABS part.

§ 1.2.2 Background AM

Since there is an unlimited array of possible applications in all fields of the industry, different AM technologies have appeared on the market since their invention in the mid-eighties of the previous century. Some have already ceased to exist; others are only starting to develop their full range of usage. What they all have in common is their great potential for specific applications, for example in aerospace, the automotive industry and medical application. AM is also becoming more and more popular in applications for end use products. However, a lot of companies still use the technology primarily for prototyping (fit and assembly, design studies) or pre-cast modelling rather than for actual end use parts. But end use parts are the area of application to which this technology is heading. It is important for architecture, building construction and façade engineering to find suitable applications for the technology to be able to exploit the potential as well.

Today, the most commonly used technologies in AM are Selective Laser Sintering (SLS § 2.2.1.2), Stereolithography (SLA § 2.2.1.1), 3D-Printing (3DP § 2.2.1.4) and Fused Deposition Modelling (FDM § 2.2.1.3). They are all used to generate physical models and parts from 3D-data without extra tooling, by adding building material layer by layer and solidifying it [3]. A great range of materials offers the possibility to conceive applications in many different product fields. Today, all of the technologies still only use one or two materials at a time, except for the 'Polyjet-Matrix' technology by Objet (§ 2.2.1.5) which started using 'digital materials' to produce gradient materials. [7][8] Interconnecting the processes and enhancing material properties seem to be the crux of the matter for an AM Envelope.

One major advantage of AM is the freedom of shape. Where the possibilities of 'conventional' tooling and manufacturing end (usually subtractive shaping methods), AM offers new possibilities and even enhancement of products and tools. The high standard that the processes have reached today also allows the metal-working industry to notice AM not only for prototyping (mainly in plastics), but to appreciate it as a new way to produce parts, even in metal. Direct Metal Fabrication (§ 2.2.3) - the name of this particular field of AM – can be used with a great range of metals, and is therefore suitable for façade applications.
The main focus of the research conducted as part of this dissertation was to identify possibilities to transfer AM technologies to existing and future façade construction. All aspects of its use as a production feature within the production line of the façade industry were investigated: Applicability for existing façade systems, status of intuitive usage, materials available for AM, potential for introducing AM as an alternative way to fulfil non-standard façades.[9]

With the increasing use of 3D applications, Additive Manufacturing also comes to the fore of architects. The applications in this field are still limited to the generation of printed 3D architectural models. But the advantages seen in modelling are the same as for AM of real architectural parts or even entire buildings. This means production without manual screwing, gluing, joining and fitting.

The new manufacturing technologies will change the way we design and manufacture as well as how we deal with consumer goods and the built environment.[10]
Today, printed end use parts are not yet applied in building technology or architecture. But printed end use parts are the field where an AM Envelope would push the limits.

§ 1.3 Hypothesis and sub-questions

The following hypothesis serves as a guideline for the scientific discourse of this dissertation:

Façade technology and façade construction will change with the application of Additive Manufacturing!

Since this hypothesis cannot be confirmed in one single statement, the dissertation will generate, prove and answer relevant sub-questions; to highlight the current state as well as to support the discussion about the target state.

Chapter 2:

- What technical possibilities for façade construction are available today with AM?
- Which changes do AM technologies have to undergo to be applicable to façade technology?
- Which external influences can cause such changes?
- Which technical requirements are posed on an AM Envelope?

Chapter 3:

- Which research approaches lead to first experiences with AM technologies in the building envelope?
- What are the effects of product-oriented project results on a general transfer of the AM technologies to façade technology?
- What means of assistance for planners and users of AM must be generated in order to guarantee AM oriented application in the façade?

Chapter 4:

- Which developments of the AM technologies for façades are conceivable?
- Which façade applications can result from these developments?
- What effect can an integration of high-tech technologies have on building technology?

Chapter 5:

- What is the potential of Additive Manufacturing for the building envelope?

The hypothesis focuses on façade construction. It is therefore clearly removed from the more general examination of the effect of AM on building construction in general and the influence that AM has on architecture in terms of design and appearance. These more expansive aspects are touched upon in chapter 4. However, due to the scope of the issue they are worth a separate dedicated discussion that is not part of this dissertation.

The hypothesis was examined using examples from the field of façade application. During the project phase, relevant data was acquired after immediate consultation with an industry partner. The analysis of this data therefore represents the view of future technology users (in this case façade manufacturers, façade builders) as well as of product users (architects, planners, customers).

Next to the hypothesis, the sub-questions aid in keeping the discussion focused and in illustrating the discourse. The sub-questions lead through the chapters and therefore allow for contextual allocation. They support a scientific discussion and make it easier for the reader to comprehend the content presented with regards to the main aspects of each chapter and against the background of the overall subject matter. Chapter 5 links the questions to a possible timeline covering the next few years. It provides concise answers and therewith rounds off the work.

§ 1.4 Approach and methodology

Because only few sources are available in the field of 'façade/building technology and AM', this work was conducted as a qualitative study based on the self-chosen hypothesis. The qualitative approach brings forth that the initial hypothesis evolves into a strong, independent theory. During the scope of the work this can lead to individual aspects gaining or loosing importance or to the inclusion or exclusion of individual aspects.

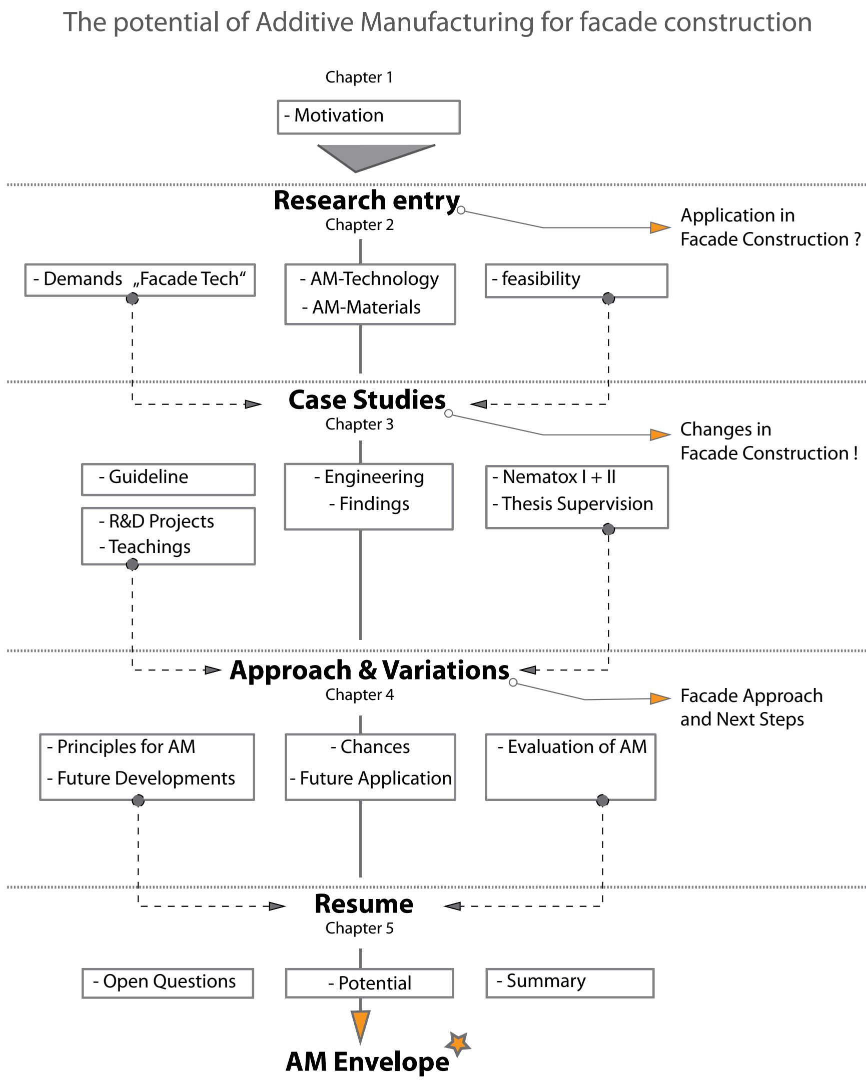


Figure 4

Structure of the dissertation (schematic representation of the work).

A ‘multi-method scenario’ was developed as a source to acquire data and information. With this scenario all contributing single parts flow into an overall collection of source material. A large number of sources were generated during the course of the project:

- case studies;
- workshops and seminars;
- discussions with experts (at tradeshows, conferences, project meetings, a. o.);
- personally collected data by the author;
- published data in various media.

The data from these sources combined with personal experience and reliable (published) knowledge form the basis for the results presented in this work.

Following an introductory chapter, chapter 2 describes the current state of the art of Additive Manufacturing. This serves as a basis to comprehend all relevant conceptual approaches and questions of this work. At this point, the work does not claim to be all encompassing because the development of the new technologies progresses so rapidly that a representation can only show the current ‘status 2012’. This is particularly true for § 2.5.1 which particularly highlights how fast the developments progress regarding the process chamber and system dimensions. All technical information was collected over a period of four years and was last updated mid 2012.

After the description of the technical aspects and topics as related to Additive Manufacturing, chapter 3 provides a product-oriented description of the research project. It forms the main part of the acquired data because the potential as well as the limitations of AM technologies as they apply to the façade can be determined by means of the projects and studies shown here. All data and findings related to § 3.3 through § 3.5 were generated in cooperation with the company Kawneer-Alcoa. The projects described are the result of a mission oriented research conducted by the author at Hochschule Ostwestfalen-Lippe (third party funded project “Influence of additive fabrication on the development of façade components”, Hochschule Ostwestfalen-Lippe, Fachbereich 1, Detmold, September 2008 through October 2010).

Summarising and evaluating the conducted case studies inevitably leads to transferring the results to façade technology in general. This is introduced in chapter 3 by means of the project results, and leads to a catalogue of requirements for future planning processes.

The described research approach should be continued; methods and ideas here fore are described in chapter 4. The evaluation of the potential is then looked at and discussed using realised and unrealised exceptional architecture. The current discussion about design and appearance of architecture and the translation into built realisation is put into context with AM.

The summary in chapter 5 rounds off the dissertation and, at the same time shows the steps necessary to continue this study and to apply Additive Fabrication to façade technology. The potential of future development and application of the AM technology in the building envelope is evaluated and put into context.

This work ends at a particular point in a dynamic process with the currently available results relevant to the posed hypothesis. It does not claim to be complete or to provide an ultimate evaluation of AM for façade technology. On the contrary, it challenges to use the findings to continue the integration of the AM technologies. The building sector in particularly needs a revolution to advance from the International Style with its gridlocked and sufficiently celebrated results toward a regionally anchored, thought out and manufactured architecture that fulfils today's demands, and places the needs and requirements of the user on centre stage.

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2 AM technologies for façade construction

This chapter answers the following questions:

- What technical possibilities for façade construction are available today with AM?
- Which changes do AM technologies have to undergo to be applicable to façade technology?
- Which external influences can cause such changes?
- Which technical requirements are posed on an AM Envelope?

This chapter explains the technical boundary conditions and the development of Additive Fabrication and puts them into context. Expected performances and developments related to an application in façade technology are formulated and assessed. Factors and technical developments are described which, from the author's point of view have an impact on further development of the AM technologies related to a transfer to building or façade technology.

Initial research into these technologies began as early as in the Sixties of the past century, when tests were conducted to cure fluid photopolymers. This research was then further developed by various institutes.[1] In 1987, the first system for stereolithographic fabrication of plastic prototypes was integrated into the development chain of injection moulded parts. The motivation behind this was the desire not to discuss mass production of plastic parts as a mere thought construct and on the basis of drawings only, but to be able to present a haptic representation of the design. This application hits the core of the original term 'Rapid Prototyping' (RP), and shows the immediate connection of this technology with a preliminary stage of mass production. 1:1 models of each developmental stage can be printed relatively quickly, meaning that improvements can be integrated at any given time. This option simply did not exist before due to the extremely high cost of the tools needed for the production process.

The materials as well as the technical equipment for AM technologies have been continuously developed since. A new market opened up that is still growing today, 20 years later, and that brings forth new developments at ever shorter intervals.[1]

It was only during this ongoing development that the potential of 'Rapid Prototyping' in terms of changing the fabrication method of parts was recognised, and its use as an independent production method was really considered. The step to use AM methods to produce ready-to-use parts directly meant that 'Rapid Prototyping' evolved into 'Rapid Manufacturing' (RM) and thus the creation of the superordinate term 'Additive Manufacturing' (AM).

One issue still hindering the step forward to consequently realising the possibilities that AM offers is the designers' habits. Developing new products is always coined by the existing boundaries of conventional manufacturing. Up until now, design ideas had to be altered such that they could be manufactured with the equipment commonly available ('Design for production'). For example, the rules for moulded parts clearly define the design process of such parts: technical restraints limit the freedom of design in terms of demouldability, homogenous wall thickness, and integration of slide feeds or split lines. With the application of AM this is no longer necessary since there is almost no constriction of form and shape. Developers need to fundamentally change their way of thinking in order to exploit AM to its full potential and to create true AM constructions ('Design for AM').

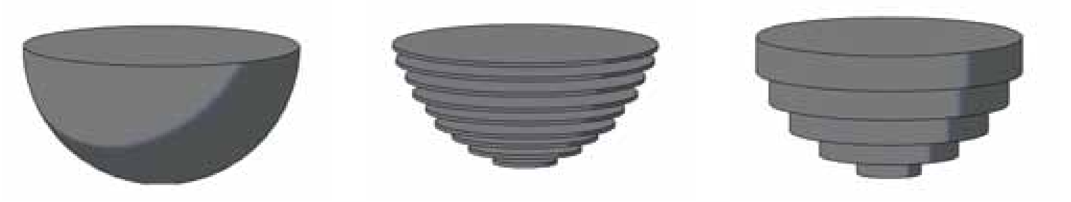
§ 2.1 State of the art

The term 'Additive Fabrication' encompasses more than twenty different technologies of layered production of prototypes, tools or series production parts.[2] The methods differ significantly from subtractive methods that involve removing material. Additive fabrication means fabrication without the use of tools or moulds – "tool-less"[3] - and therefore allows for great freedom of geometry: With layered fabrication it is possible to generate undercuts without having to remove material later which is not possible with methods based on counter moulds (for example injection moulding). Projections as well as cavities can be generated. It is no longer necessary to build massive, monolithic parts with enclosed surfaces. Instead, integrated joints, articulating bodies inside enclosed envelopes ('sphere in a sphere'), or contour-conform channels (to cool tools during mass production) can be realised. AM enhances the conventional methods with this constructive freedom. It goes beyond the hitherto feasible and is significantly different from the known methods (see [3] [4] [5] [6]).

The technology is used by designers and manufacturers in the areas of product design, consumer goods, industrial goods and medical and military applications. Products produced with layered construction include: protective covers for mobile phones, games consoles parts, designer lamps, machine parts, chassis and drive parts for airplanes and automobiles, tool elements, medical implants and many others (see [7] [8]).

§ 2.1.1 The principle of additive processes

The principle of Additive Manufacturing is the same for all of the different methods: special computer software breaks the Computer-Aided-Design (CAD) 3D model down into layers. These layers form horizontal layers/building plans/foot prints of the model. The breaking down process is called slicing. The AM output device (in the following also called 'printer') processes each layer of the model consecutively, whereby the contours and fillings of the part are cured. Depending on the method, this is done by either exposition, heating, or bonding in process chamber which typically is confined to certain dimensions. Different technical strategies are used to bond each new layer with the previous one. Thus, layer by layer, the physical representation of the virtual CAD model is generated. "With these methods [... AM methods, author's note] fabrication is not conducted subtractive from a massive body, such as with milling, but generatively (additive), i. e. the parts are created in layers by adding material or by the phase change of a material from a fluid or powdery state into a solid state. Fabrication is done without the use of moulding forms".[6] One single model can consist of several hundred layers, depending on its size. The layer thickness is defined by the resolution of the AM system used; it varies from several tenth of a millimetre down to a few microns. Once the building plan for the model has been fully processed, the completed model can be removed from the machine. The process can take from a few hours to several days. Depending on the technology applied, the actual 'printing' process is followed by various subsequent processes (post processing) such as removal of support fixings, surface cleaning, removal of uncured material, infiltration, and others.



a b c

Figure 5
a.) CAD model; b.) slicing process; c.) building process.

If AM is compared to conventional printing methods, each layer corresponds to one page of a document to be printed. The only difference being that you do not print on paper and not exclusively with ink. The finished product is a physical, three-dimensional rendition of the virtual computer model.

§ 2.1.2 Materializing a 3D modell

To generate a 3D model, a third, the vertical Z axis is needed in addition to the two horizontal axes (X and Y). Movable printheads or redirected light beams extend across the horizontal extension of the model. Hereby, we differentiate between vector-oriented and raster-oriented methods.[6] Building the model up in direction of the Z axis is done by incrementally lowering the work platform. "Depending on the individual methods used, different levels of accuracy and part properties occur along the three coordinates. This needs to be considered when aligning the part in the process chamber. Building time is another factor that depends on the positioning in the process chamber.
Some methods require supports when generating parts with protruding geometries [..., or in order to connect planes to the substrate plate when producing metal parts, author's note]. They need to be mounted before the manufacturing process begins and usually have to be manually removed once it is completed. The system user generates the supports by using options in the system software or separate software tools.
With some methods, using supports reduces the surface quality of the part, a fact that cannot be avoided entirely. It is therefore necessary to mark the areas where supports may not be placed."[6]

§ 2.1.3 Surface quality

The surface finish depends on the type of manufacturing process and the materials used. Thus, the user can influence the quality of the manufactured parts. With most systems, the user can select from different levels of resolution as well as change the parameter 'scanning speed' and 'laser intensity' for those systems using a laser for curing.
But as a general rule, most methods generate a stepped surface because the part is produced in layers.

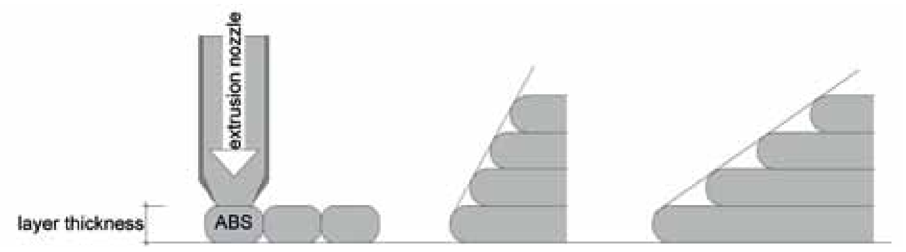


Figure 6
Schematic drawing of an FDM method and surface steps depending on the model contour.

Even in 2012, the addendum 'rapid' is a relative term in conjunction with AM methods because an actual production process may take up to several days. However, the equipment development has reached a stage where the combination of processing speed and material properties does achieve 'fast' effective manufacturing rates when compared to traditional methods. This comparison takes into consideration the time it takes to produce a conventional tool set (for example for injection moulding) for traditional methods. But speed is not the most important aspect when evaluating AM technologies. The main advantage lies in the great freedom of form compared to traditional methods. Thus, it is not cycle time alone that is important when evaluating processing methods but also process optimisation, process controllability as well as product and quality optimisation. As an example, optimised Rapid Tooling tools can not only optimise the manufactured product but the manufacturing process as well.[9]

Additional applications and markets have evolved from the original, generative method Rapid Prototyping (RP) resulting from an improvement of materials and equipment: Rapid Manufacturing (RM) and Rapid Tooling (RT). In the following, they will be described in more detail because the superordinate term Additive Manufacturing has evolved from these methods. Particularly in terms of transferring them to façade technology, aspects from all three original segments play a role.

§ 2.1.4 Rapid Manufacturing

Rapid Manufacturing (RM) means using Additive Manufacturing methods to produce ready-to-use products without the need to invest in tools. Critical factors are 'time to market', 'batch size 1', 'product and manufacturing cost / cost efficiency' and 'product testing before production'. RM is a unique service segment in the AM industry. Parts, design objects, small batch series amongst others are manufactured to order with a pool of AM equipment. RM with its significant design and production benefits can be seen as a new, separate market. Advantages gained through cost savings for tools (no customized tools, no casting moulds), new sales strategies, the impact on product development and design indicate the great potential this technology offers.
RM describes the professional use of AM technologies in an industrial production chain. Here, the technology is used to produce small series and combines continuous product optimisation with the additional benefits of manufacturing with AM.[10]

Figure 7
Jewellery part designed for AM by FOC, Amsterdam.

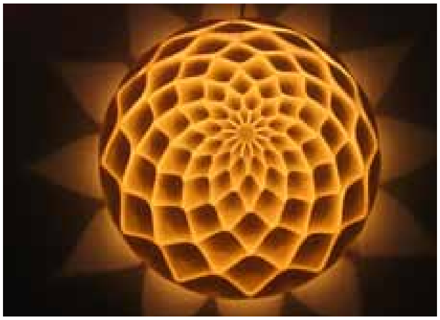


Figure 8
Lighting Design with AM by FOC, Amsterdam.

§ 2.1.5 Rapid Tooling

Rapid Tooling (RT) describes the application of additive methods for manufacturing production tools for mass products. The industry exploits the possibilities of CAD design combined with the unlimited freedom of form of AM. For injection mould nozzles to manufacture plastic parts, for example or for models of casting moulds or the casting moulds themselves. The advantage lies in eliminating the limitations of traditional subtractive methods for tool making. Free-forms, contour conform ducting, undercuts a. o. are no longer difficult to manufacture. The great range of materials available today allows us to directly create metal tools and use them for production. These tools equal their traditional counterparts in toughness, duration and utilisability. And not only that: material properties can be further improved by better cooling and the possibility of a targeted material mix.[7]

a b

Figure 9
a) Tool with integrated cooling channels; b) Illustration of contour conform cooling channels.

§ 2.2 Overview of the most common AM processes

Since 2009, all categories of the layering methods are summarised under the superordinate term 'Additive Manufacturing (AM)'. This regulation is the first universally valid agreement in the AM industry and was manifested by the regulation of the American Society for Testing and Materials (ASTM), committee F-4291, publication F2792, 09/2009. This standard defines AM as "AM: ~ process of joining materials to make objects from 3D model data. Additive Manufacturing (AM) as opposed to subtractive manufacturing methodologies. Usually with AM parts are processed layer upon layer. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication."[11]

For the German speaking areas, the 'Verein Deutscher Ingenieure' (VDI - Association of German Engineers) has published Norm 3404 to regulate the terms and applications of Additive Fabrication. The norm was introduced in 2009. The norm includes "field-proven tips and recommendations" in order to "improve the communication between customer and supplier and thus to support a binding services format and trouble free execution".[6] The efforts of VDI need to be viewed against the background of an increasing integration of the AM technologies into production processes and the according demands for standardisation and regulation.

During recent years, the term '3D printing' has become a widespread general term for additive methods, independent of specific technology, material and intended application (RP, RM, RT, or AM). When talking about these methods, it is therefore important to differentiate between the actual technology (3DP § 2.2.1.4) and the general term of '3D printing'. Typically, non professional media uses '3D printing' as the common term, which encompasses professional AM systems as well as 'fabbers' (appendix A I / Fabbing), systems usually used in a non-professional environment[3].

3 "A fabber (short for "digital fabricator") is a "factory in a box" that makes things automatically from digital data."

Reference [2]: Burns, M. fabbers.com. 1999-2003 [cited April 2012]; Available from: http://www.ennex.com/%7Efabbers/.

Considering the goal of transferring the layering principles to façade technology, it makes sense to make an initial differentiation between the individual methods depending on the building materials used. This also facilitates the introduction into the multitude of technologies. The material groups used are 'plastics', 'metals', and 'other materials'. In an AM family tree they are linked to the according available AM method.

The great number of available technologies can be traced back to the first additive method – SLA. All of the following technologies are based on the same manner of thought; building up the shape of the part layer by layer. Plastics as a material group with the according processing methods are at the centre of the development. Some can, again, be understood as a superordinate term for which different manufacturers have developed systems based on the same technology. In the field of plastics, the core technologies are Stereolithography (SLA § 2.2.1.1), Laser Sintering (LS § 2.2.1.2), Fused Deposition Modelling (FDM § 2.2.1.3), 3D Printing (3DP § 2.2.1.4), as well as the methods combined under the term (InkJet § 2.2.1.5).

In addition, methods to process metals were developed, mainly evolving from the application Rapid Tooling. This development is influenced by SLA as well as build-up welding which is a known and proven technology in machine and plant engineering. All technologies are evaluated in a matrix in terms of their relevance for façade technology, and are compared at the end of the chapter.

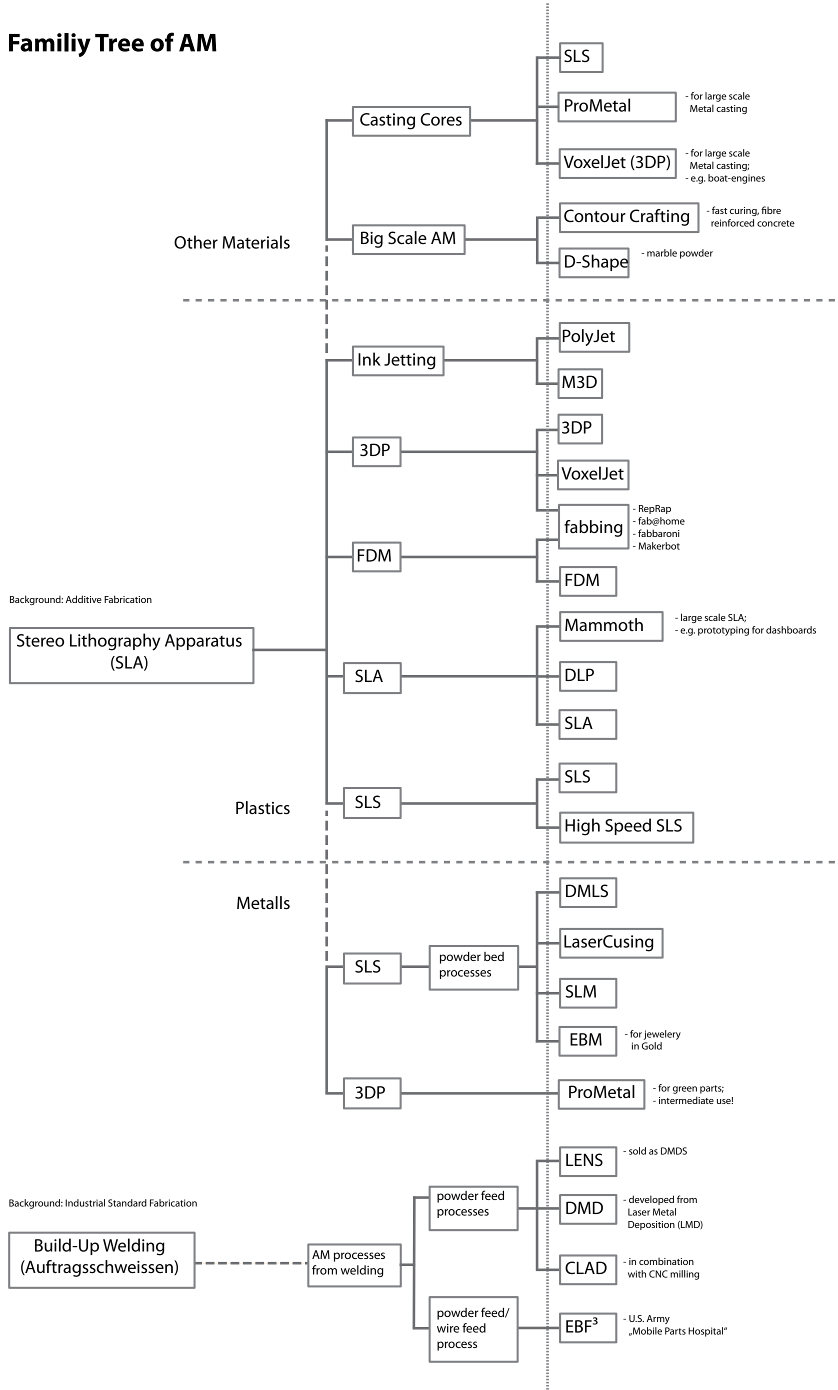


Figure 10

Family tree 'AM methods'.

§ 2.2.1 AM for plastics

The following describes only a few selected technologies to provide information about the basic principles of Additive Fabrication. After analysing and evaluating all methods, the performance aspects described here allow us to understand the relevant AM methods for façade technology.

Further information about the technologies (those briefly described here and others) can be found in the appendix A I / Characteristic tables of AM processes – plastics.
Note: The schematic sketches for the individual methods are based on Hopkinson et al. [3], but were redrawn and modified by the author.

The primary decisive criteria to estimate the potential of the technologies for their application in the façade technology are weight, rigidity, and load-bearing capability of the parts. Therefore, the focus of the technology descriptions will also lay on the methods to produce metal parts, even though, from a technical point of view they evolve from those used to produce plastic parts. For easier understanding, the descriptions are therefore based on the historic or content-technical development within Additive Fabrication.

§ 2.2.1.1 Stereolithography

Stereolithography (SLA) means curing thin layers of a light sensitive, fluid photopolymer with a light source. Laser or halogen lamps can serve as light source.

The part is generated in a bath of epoxy resin or acrylic resin. The light source traces the layers of the computer model; the resin is locally cured by the light source. To print overhangs, undercuts and filigree model parts, SLA requires an additional support structure. This is generated by the system software automatically analogous to the part.

When a layer is traced, the work platform is lowered by the selected layer thickness, and the surface is reflooded with resin. To improve wetting the model surface with new resin, the resin is heated to 30° to 40° Celsius, which decreases its viscosity. The temperature has no influence on the light exposure during the polymerisation process.

In a post curing process, the model runs through a light chamber to guarantee complete curing of the material. Thus, areas that are not fully exposed are also cured.

The supporting structure must be removed mechanically after curing.

The surfaces of the part can then be post-processed by polishing, blasting, or coating.

SLA methods allow for a high possible part accuracy. The layer resolution lies between 0.05 and 0.15 mm.

In order to be applied to an AM application, issues in terms of resistance to ultraviolet rays and humidity must be solved. Targeted further development of SLA materials shall achieve an even broader applicability of the SLA method in terms of direct serviceability.

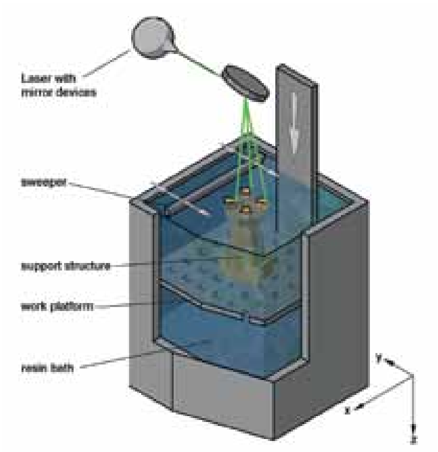


Figure 11
Schematic drawing: SLA method

Figure 12
Lighting Design produced with SLA

§ 2.2.1.2 Laser Sintering

In principle, with laser sintering (LS) the part is created similarly to SLA methods. However, a specified powder is used as building material rather than fluid resin.

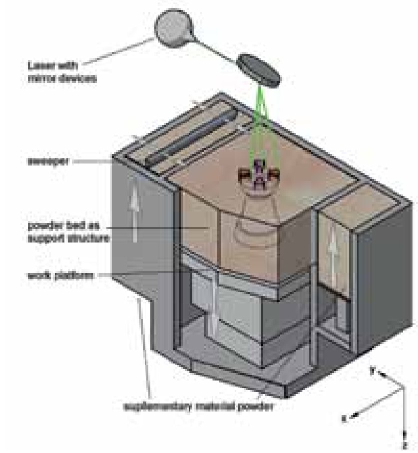


Figure 13
Schematic drawing: LS method

Figure 14
Sample piece produced with LS

Related to AM, the term sintering means: to melt powders below the actual melting temperature. The energy of the light source on a compact mass causes the material to melt (see [1] [35]).

After one powder layer is sintered, more powder is deposited onto the work platform, creating the next layer. Infrared light keeps the entire process chamber just below the temperature of the sintering process, within the so called crystallisation range of the material. This method keeps the energy demand of the actual process low; avoids warpage of the parts caused by abrupt heating, and improves the fusion with the previous layer.
The light source must only heat the material by a few degrees in order to melt it.
The non-sintered powder around the model remains as supporting material. Upon completion of the process it is returned to the storage container of the machine and can be reused when mixed with new powder.

LS allows for wall thicknesses of 0.8 mm. The layer thickness of the powder bed is usually around 0.1 mm.

In contrast to SLA, LS does not require an additional curing process. But the finished parts need to cool down before they can be 'unpacked' from the LS machine. As the surface finish is porous, these structures sometimes require an infiltration with other materials, depending on the application.

§ 2.2.1.3 Fused Deposition Modelling

Fused Deposition Modelling (FDM) is a 'true' additive method since the material is not cured or glued but actually deposited onto a work platform in layers.

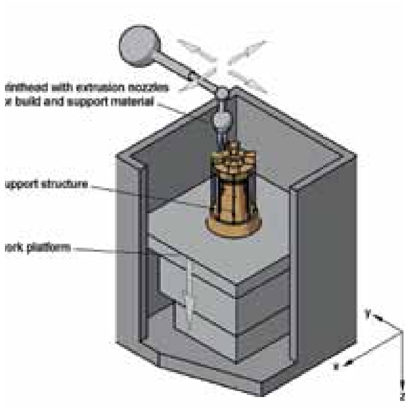


Figure 15
Schematic drawing: FDM method

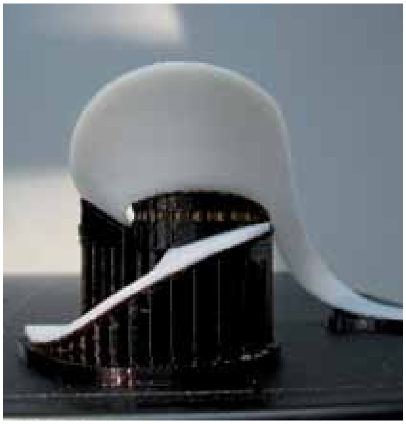


Figure 16
The visible structure of the different layers after completion of the FDM print job. In white: the ABS material; in brown: the soluble support structure

As with the SLA technology, the layers of the 3D data file are deposited consecutively on a work platform. The material is melted at approximately 280°C, applied with an extruder (a melting nozzle similar to the principle of a hot-glue gun) and cures directly onto the underlying layer. To ensure that the individual layers bond to one another, the entire process chamber is heated to and maintained at a certain temperature. Too early curing could prevent a new layer bonding with the previous one.

A supporting structure is necessary because the models are generated directly on the building platform. It supports overhangs, undercuts, filigree model parts and wall-like areas that are not self-supporting before cured. The support structure is generated automatically by the software and deposited through a secondary nozzle using a special support material. The support material is removed from the finished product either mechanically or in a solvent bath.

For each layer, the exact positioning of the string of material can be previewed and controlled with the software. The outer contours of the component are printed first, and then the remaining areas are filled in completely or following a grid pattern. The strings of material are positioned such that the shape is filled in precisely according to the contour. The cavities between the walls of the model are specified in order to control the processing speed, the material consumption and the density of the model. The geometry and the properties of the string of material result in model surfaces and edges with a stepped contour. This fact defines the limitations related to accuracy and surface finish of the method. The layer resolution lies between 0.127 and 0.330 mm.

Due to the very anisotropic structure of the material distribution, FDM technology also creates strongly anisotropic parts. The material properties are significantly better in X-Y, meaning in the 'full' material, than in Z where the fusion of the individual layers determine the properties of the part. Therefore, this technology is only partially suited to produce parts that are subjected to long-term stress.
FDM models can be finished by various methods.

§ 2.2.1.4 3D-Printing

3D printing (3DP) can be compared to inkjet printing on paper. The layers of the 3D data file of the model can be compared to the pages of a document. Equivalent to inkjet printing on paper, each layer from the data file is identified as one page and is printed onto a thin powder layer with colour pigments (colour printer cartridge) and a 'binder'.

The materials used are gypsum, starch, ceramic powder and sand. The binder is an adhesive that fuses the powder (and the ink) to a solid mass and glues it to the underlying layer. After one layer of the building plan has been printed, the work platform is lowered by the thickness of one layer, a roll or slider deposits a new layer of powder, and the next layer can be printed. The layer resolution lies between 0.09 and 0.1 mm. In this process, the unprinted powder serves as supporting material and is returned to the system. Overhangs, undercuts, filigree model parts and wall-like areas that are not self-supporting before cured are supported without having to print an additional structure. Upon completion of the process, powder residue is removed with a fine compressed air jet or a brush, and the surface of the model can be infiltrated with epoxy resin or instant adhesive, if necessary. 3DP models can be finished by sanding, filling, varnishing, polishing or galvanising.

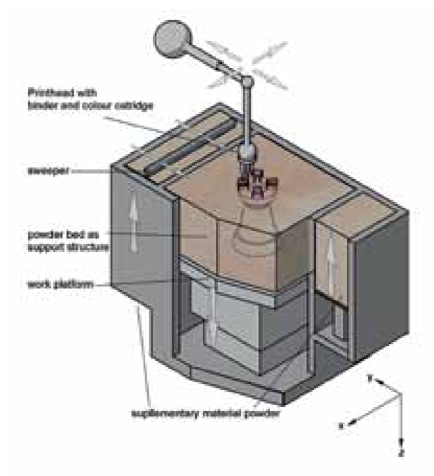


Figure 17
Schematic drawing: 3DP method

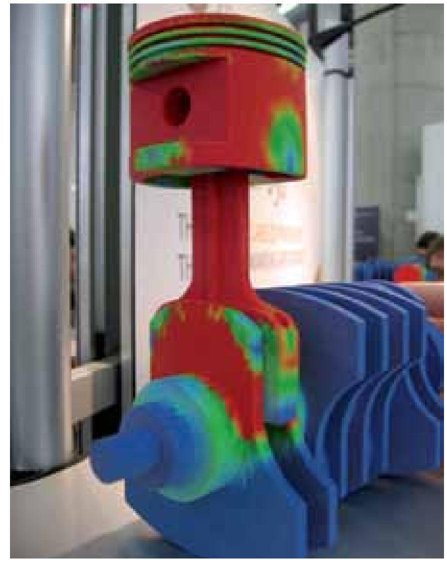


Figure 18
3DP part with representative colour coding of a FE-analysis

By using a colour cartridge, 3DP achieves true colour rendition; it is the only method that offers the possibility of multi-colour printing.
Therefore, this method is used for realistic renderings of surface finishes and colours, labelling, company logos, as well as simulated temperature, stress or deformation gradients from Finite Element Analysis (FEM).
Illustrating geological information (GIS) is another application of 3DP. Complex three-dimensional geological 'maps' can include more information than conventional repro products.
3DP models are also used as intermediate products for further use in printing block fabrication and moulding technology. The powder material for this process consists of silica sand bonded with an inorganic binder. The results are fragile casting cores that are used to fabricate metal casting moulds. Foundries have recognised the 3DP method as an opportunity to generate geometrically demanding parts directly from CAD data. All of the necessary supply and exhaust lines, lifting and fixing points are integrated directly in the CAD model.
Systems with process chambers as large as 4 x 2 x 1 metre have been built to produce casting cores for large ship's engines and body parts.

§ 2.2.1.5 PolyJet

The term 'Inkjet' combines those processes that use a series of printing nozzles instead of one printhead or a specific light source and mirror device. Highly viscous plastics are used as building material, as the coloured ink for desktop inkjet printers.

With the PolyJet™ method, the layers of the part are created with individual drops of material that are deposited onto the work platform. The printhead holds numerous nozzles that are arranged across the width of the platform. The light source for curing the material is mounted directly behind the print nozzles. The model area along the X axis is covered by the nozzles; the printhead runs along the Y axis, the so-called pass. Building up the height of the model is achieved by lowering the work platform. Immediately after one layer is complete, the deposited material is cured with ultraviolet light. In a secondary step, a roll smoothes the layer surfaces, onto which the next layer is deposited during the following pass. All of the material needed for one layer is pushed out of the nozzles simultaneously. The material used is an acrylic photopolymer. The necessary support structure is printed with a secondary row of nozzles. It consists of a gel-like material that, after completion, is removed by water jetting.

The layer thickness is about 0,016 – 0,030 mm and guarantees a very precise and smooth surface; eliminating the need to rework for most applications. Since the material is deposited in individual particles, the final resolution is very high.

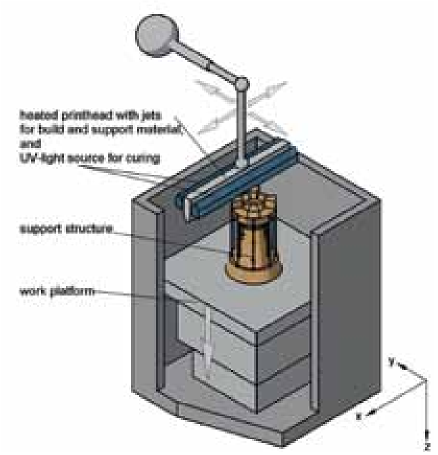


Figure 19
Schematic drawing: PolyJet™ method

Figure 20
PolyJet process during the UV-light curing of the plastic material on the building platform (below).

With the PolyJet technology it is possible to mix numerous gradients of the two original materials directly onto the process platform, using so-called 'digital materials'. Thus, different areas of the part can feature different material properties. We know this from handles with hard as well as soft parts, for example, or remote controls with a hard casing but soft buttons. This is of great advantage for realistic prototype production (for example for flexible joints, rubber soles, springs a. o.). Even though it is not yet possible to print the materials in a true gradient, meaning with seamless transition, current technical feasibility already points toward the next step: programming true seamless gradient materials (see § 2.4).

§ 2.2.2 Consumer applications

The increasing trend of consumers handling digital media and tools leads to a constantly growing demand to produce individualised products. AM allows us to 'print' individual avatars from virtual worlds and online games, data records for various everyday items are exchanged on online platforms. Thus, there is a growing desire to produce commodities from self-generated or purchased data – 'fabbing'. In this context fabbing is derived from 'fabricating' and describes generative manufacturing of finished products; Such as customised toys, mobile phone or games consoles enhancements, jewellery and design objects, sport equipment and spare parts for products of all sorts.

Again, RM is the originating technology behind this trend (for further information about the fabbing technologies see appendix A I / Fabbing).

Another branch of Additive Fabrication has developed as part of these home applications: There are a number of different kits and instructions available to make low-cost 3D printers for home use ('fabber' or 'personal fabricator') beyond those available from commercial suppliers (see [4] [13]).

The kits are based on freely available software and hardware. The user community also exchanges further developments on the internet, thus fine-tuning and technically optimising these systems from generation to generation. The principle technology of these systems is based on the above described AM technologies, mostly FDM, which are broken down to the feasible technical minimum. In terms of performance the fabbers sometimes equal professional systems: they achieve high resolutions and accommodate various materials.

Figure 21
Not yet assembled RepRap kit; Hochschule OWL 2012

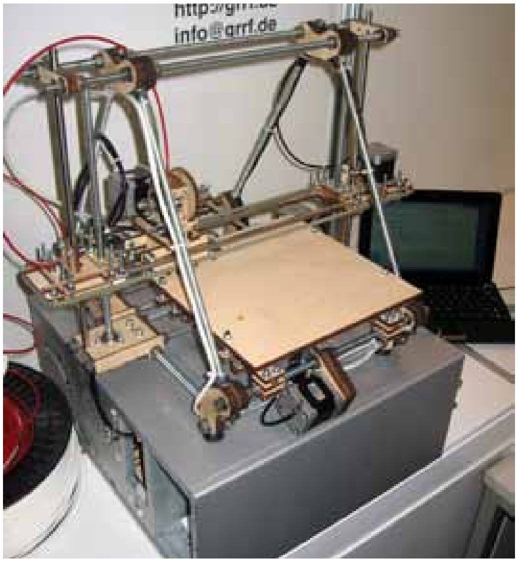


Figure 22
Self-assembled RepRap; FH Darmstadt 2010

Fabbers are mentioned here for the sake of completeness. In the context of this dissertation, they obviously do not lead to optimised or modified building technology with AM, but they do illustrate an increasing spread and usage of digital tools and AM methods, even for 'technological laymen'. For the future this means a growing acceptance of digital methods, which will play an ever greater role in our daily lives.

§ 2.2.3 AM for metals

Direct fabrication of metal parts is called Direct Metal Fabrication (DMF). The processes described in the following were initially intended for Rapid Tooling (RT); however, the trend goes toward using them to manufacture ready-to-use products. We can differentiate between two basic principles: 'powder feed process' and 'powder bed process'. Both use pure metal powder to manufacture parts whereby different material mixes and alloys are employed.

To generate metal parts, the materials are melted by applying heat. The energy sources are laser or electron beams. In order to achieve a controlled process, the resulting waste heat needs to be carefully directed. For almost all DMF methods, the models are manufactured on base plates (substrate plates) with a thickness of up to ten millimetres. The base plate is clamped inside the system and the model is then generated on this plate. In addition to the contour of the model serving as a heat conducting element, a support structure is needed to direct the waste heat. This

requires more intensive data preparation than creating plastic models. If the heat is not properly exhausted in one area of the part, the result is a melting bath accumulation and the model is caked with the surrounding material powder (material adhesion, defects). In addition to the issue of heat development within the part, tensions that can develop in a part are decisive criteria for success or failure with the DMF methods. Therefore support structures 'connect' the part to the substrate plate. This eliminates warpage, distortion and bending in Z direction. With powder bed processing, the worst case result of such distortion can cause abortion of the building process, because the wiper to smooth the subsequent material layer can get caught on the part. The part can get repositioned and detached from the substrate plate. The necessary support or connecting structures are challenging in terms of the surface quality of the directly manufactured parts. After removing the supports, unevenness and therefore reduced surface quality is unavoidable. That might prove problematic when working with enclosed bounding geometries. Currently, there are two strategies that can eliminate the limitation caused by the needed supports: Firstly, metallic materials are developed for AM methods other than the ones currently available, and secondly, the concept to manipulate the files prior to manufacturing in a way that they accommodate expected deformations and thus generate the actual targeted geometry.[16]
But as of now these limitations are still part of manufacturing metal components. [3] [14] [15]

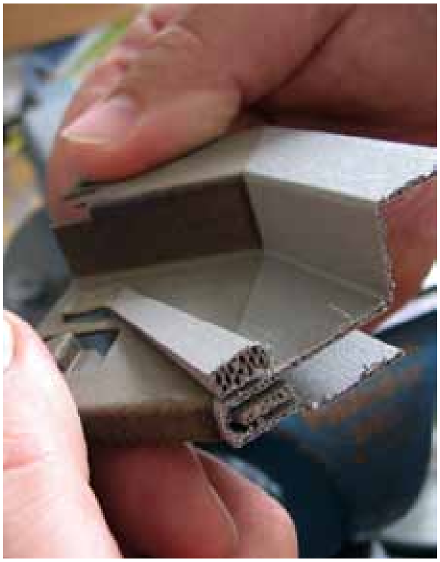


Figure 23
Support structure (light grey) of a DMF part (dark grey) after separation from substrate plate, @FKM Sintertechnik GmbH

Figure 24
Inside view of DMF part: connective points of the now removed support structure

Two strategies are conceivable to avoid reduced part quality:

1 The support structures are integrated into the part geometry at the very beginning of the design process, i.e. a specific part orientation and part geometry can avoid that defects of the outer contours are visible after the manufacturing process is complete. And support structures in the form of lightweight fillings can remain within the part; a method that can be used to further improve the performance properties of the part.

2 Very exact material parameters are used in order to avoid warpage or deformation, and therefore allow for 'Anchorless Selective Laser Melting (ASLM)'. To apply ASLM, it is necessary to define new material properties from specific metal alloys and mixtures. Eutectic metal alloys are used for ASLM that have a very precise melting point. With ASLM the material behaviour during and after melting is controllable, therefore no anchors are needed. This approach of 'support free DMF' is currently under research at Loughborough University in England. First results are available; however, it is too early to transfer them to general DMF methods.[16]

For DMF, the models are divided into different levels (shells). By using heat sources with different intensity levels, different material densities or structures can be generated for the individual shells. This is particularly important for lightweight design because lightweight structures can be created inside closed components when using lattice structures or 'hatches'.

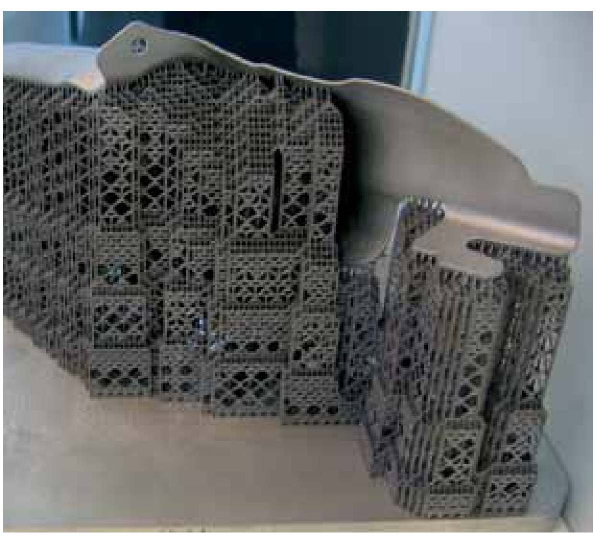


Figure 25
DMLS support structures still attached to the part and substrate plate.

Figure 26
DMF part of a turbine with internal honeycomb structures, by 'layerwise' @ RapidPro2012, Eindhoven

Once the process is completed, the finished DMF model must be separated from the base plate; with some methods by wire-cutting, with others the support structure can be removed manually by means of simple tools.

Powder feed process

For the powder feed process method (also Fused Metal Deposition method), an energy source (laser, electron beam) generates a melting bath on the surface of the model. Metal powder is then blown into the melding bath through one or more nozzles.
With this method, the axes for energy source and inserted material run unidirectional. The quality of the material joints within the model or on a carrier material (in case of repairs) can be compared to that of a welded seam.
Only powder feed process methods offer the possibility to use different materials in varying quantities in the same work step. To do this, different powders are transferred into the melting bath via different nozzles.
All powder feed processes evolved from the application of repairing defect or worn tools or parts (bearing shafts of large engines, turbine parts). The industry has known this method for quite some time under the term build-up welding. It allows rebuilding worn-out areas in layers, using the original building material. During post-processing, surfaces that are too inaccurate for mechanical engineering must be turned or finished; this is done with conventional methods such as CNC milling, sanding, polishing, and eroding. Since all components that need to be true to size must be reworked, the power feed process is a questionable method for complex parts. The advantage of tool-less manufacturing is therefore annihilated.
The method does not create a support structure.

§ 2.2.3.1 Laser Engineered Net Shaping

Laser Engineered Net Shaping (LENS) is one of the first technologies in the series of DMF methods; many other methods are based on this technology. The printhead consists of a central nozzle for the energy source and material nozzles that are arranged around it in a radial fashion. The head can be mounted onto different base systems as well as affixed to a robot arm. The part rotates in front of the nozzle whereby the material continuously builds up in the melting bath. The layer resolution lies at 0.500 mm.

The possibilities of using various materials in one component offers optimum exploitation of the material properties for tool making, particularly in terms of temperature behaviour and raw material cost. The method is used for repairs (machine turbine blades), to coat base bodies made of low-cost metals (the protective coating adds value), and to directly produce free geometries built in a base body.

§ 2.2.3.2 Direct Metal Deposition

Direct Metal Deposition (DMD™) is a direct successor of (laser) build-up welding; the method is also known as Laser Metal Deposition (LMD). It is a generative laser technology that deposits metal onto existing tools and components in layers. The layer resolution lies at 0.1 to 1.8 mm.

Pure metal powder as the source material is sprayed into the CO2 laser melting bath in particle form. Using pure metal offers a material density of 100%. The laser tip is mounted on a five-axial CNC robot, so that the metal layers can be deposited three-dimensionally. The material is stored in four chambers from which it can be mixed or used alternately. DMD™ was developed to repair industrial tools and to refine tool surface finishes. The combination with ceramic or non-metallic materials can lead to optimisation of the tool properties such as abrasion resistance and extended lifetime. In Rapid Tooling, this advantage is used to coat base tool forms made of copper with a protective layer of hard tool-steel. Thus, conductive copper can be used for tool making even though the material itself is too soft for a tool's usage. Rapid cooling of the tool after production enables fast reuse and thus faster production.

Since DMD™ is an additive method, worn tools can be rebuilt with the original material. After depositing additional material, the surfaces can be further processed with conventional methods. Today DMD™ is also applied in the field of RM. By processing different materials, DMD™ might be used to produce Functionally Graded Materials (FGM § 2.5.2.1 Functionally Graded Materials).[17]

§ 2.2.3.3 Electron Beam Free Form Fabrication

Electron Beam Free Form Fabrication (EBF3) combines various elements of the here described methods into one laser based deposition method which uses a firm metal wire for material supply. Systems for this method also feature an electron beam gun (see EBM method, Arcam). The method can therefore be differentiated from the other powder feed process methods, particularly due to lower energy consumption compared to the use of a laser. A vacuum is applied to the process chamber during processing. Components must be reworked with subtractive processes.

§ 2.2.3.4 Construction Laser Additive Directe

Construction Laser Additive Directe (CLAD) systems use a powder feed process to build up three-dimensional geometries. Combining this with specialised software and a three to five axial CNC system to move the printhead makes it possible to create components with a high degree of free-form shaping. Hereby, the “laser cladding” method correlates to build up welding; it evolved from applications for repairing machine parts. The layer thickness resolution lies between 0.10 and 1.20 mm.

Figure 27
Parts produced with the CLAD system; surfaces are still rough and need to be post-processed

Powder bed process

For the following methods the 3D model is generated from a powder bed of metal powder similar to the SLS method. But contrary to laser sintering of plastic powder, metal sintering includes transferring the process heat into a base substrate via the model contours and support structures. Even though a large number of different metal powders is available, currently only one powder type can be processed at a time.

The non-molten powder creates the support structure, and excess material is fed back into the production cycle after printing. In contrast to plastic materials, there is no tiring of the powder caused by heating. Therefore the powder can be reused without the need to add new material.

§ 2.2.3.5 Selective Laser Melting

The development of systems for Selective Laser Melting (SLM) went in a completely different direction as, from the beginning on it was focussed on processing metal powders. The systems can also process reactive metal powders such as aluminium and titanium because inert gas was used early on to create a protective atmosphere in the process chamber. Due to its technological edge, this type of system is still cutting-edge amongst the metal powder processes.

The resolution of the layer thickness lies between 0,20 and 0,10 mm.

Figure 28

System by SLM-Solutions, method: Selective Laser Melting (SLM) SLM 280 HL; Imagery courtesy of SLM-Solutions.

§ 2.2.3.6 LaserCusing

LaserCusing is an AM system that uses different metal powders, such as aluminium, titanium, stainless steel and other alloys to produce AM parts. The powder is laser-melted at a density of 100% and without adding any other substances. The entire amount of unused powder can be used for further processing without compromising quality.

Inside the LaserCusing system the substrate plate is fixed with an industrial standard fixation system. This allows the use of different CNC machines on the same part, as the mounting system always delivers defined reference points for the part. This for example allows a hybrid fabrication of CNC milled and AM printed parts.

The layer thickness resolution lies between 0,20 and 0,50 mm.

The term "Cusing" is derived from the first letter of the company name Concept Laser and part of the word fusing.

Figure 29
LaserCusing system with mounted substrate plate, @ FKM Sintertechnik GmbH

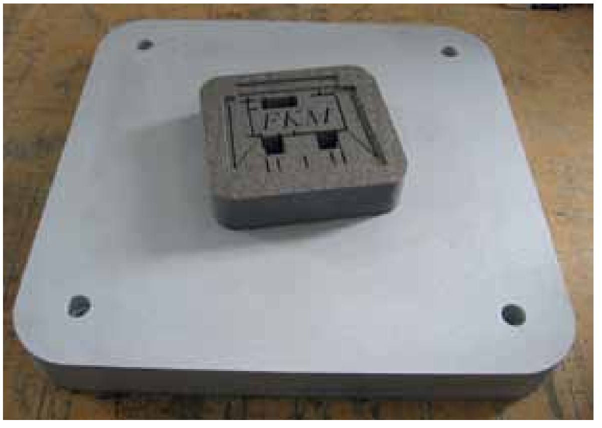


Figure 30
Substrate plate for LaserCusing process with built upon DMF part on it, @ FKM Sintertechnik GmbH

§ 2.2.3.7 Electronic Beam Melting

In principle, the Electronic Beam Melting (EBM) method resembles the LS method; the difference being that it employs an electron beam instead of a laser. An electron beam gun generates an electric arc to melt the metal powders. The energy generated melts the powder into the model at the powder bed surface. This is done under vacuum at an operating temperature of approximately 1000° Celsius. Metal parts produced with EBM show a higher level of melting-through than sintered parts. The cooling process is precisely controlled in order to achieve accurate cooling of the fabricated metal parts. The parts' density lies at 100%.
When using this method, the components need to be reworked since the surface finish quality is not high enough for all applications. Rework is done with conventional methods such as sanding, turning, milling, and blasting. The layer thickness resolution lies between 0,50 and 0,10 mm.

EBM can create durable yet very light-weight structures. In combination with biocompatible materials they are used for implants, and for manufacturing of components for the automotive and aerospace industries.

Figure 31
DMF hip implant made from titanium; fixations and a rough structure for the bone material to grow inside are provided directly from the CAD file. Customised part sizes are available.

Figure 32
DMF part in titanium; part height is ~ 20mm; the rough surface is clearly visible and shows the challenges for end use parts.

§ 2.2.3.8 Direct Metal Laser Sintering

The system technology for Direct Metal Laser Sintering (DMLS) has directly evolved from SLS. Instead of plastic powder, metal powder is sintered in the process chamber. Even though the DMLS method was initially developed for Rapid Tooling (RT), it remains an accepted method within AM. Because of different requirements in terms of surface quality, models might need to be reworked (milling, turning, sanding, blasting). The layer thickness resolution lies at 0,20 mm.

The DMLS method is used to produce components for tools or machines as well as end use products.

§ 2.2.4 AM for large scale structures

In addition to the known systems introduced here, there are additional approaches in research and development. The two methods described here are characterised by translating principles from the above described AM technologies; however, the difference lies in the scale compared to the commonly used methods. They are particularly interesting against the background of a possible transfer of these technologies to architecture.

§ 2.2.4.1 Contour Crafting

Contour Crafting (CC) generates large structures made of fibre reinforced high-performance concrete. The building material is printed in layers through a nozzle, while, at the same time, the lateral surfaces are smoothed with a trowel.

This is accomplished with a printhead that is mounted onto crane rails. Thus, the system dimensions can easily extend beyond 6000 x 6000 x 6000 mm. Resolution is several centimetres and depends on the nozzle used.

Figure 33
Size of a Contour Crafting wall in comparison to a human being, Imagery courtesy of B. Khoshnevis.

Figure 34
Contour Crafting 'nozzle' to generate concrete parts with internal light-weight structures, Imagery courtesy of B. Khoshnevis.

CC is an independent parallel development of the additive methods, since it is not immediately based on one of the above mentioned technologies, but was a separate development from the start. The principle of the generative build-up in layers is the same as for the already described AM methods. However, due to the vision and dimension involved it does assume a special position. System dimensions and the intended results are significantly different.

CC is certainly an important factor when examining the technological developments for architectural applications. The clearly formulated goal is the additive, automated fabrication of "homes", and is therefore a direct reference to architecture in general and the façade in particular. Further development needs to consider those parameters that are critical for the use on a construction site. This includes transferring the AM technology to an appropriate scale as well as considering the different tolerances that might occur. On-site, accuracy is measured in centimetres, not microns.[18]

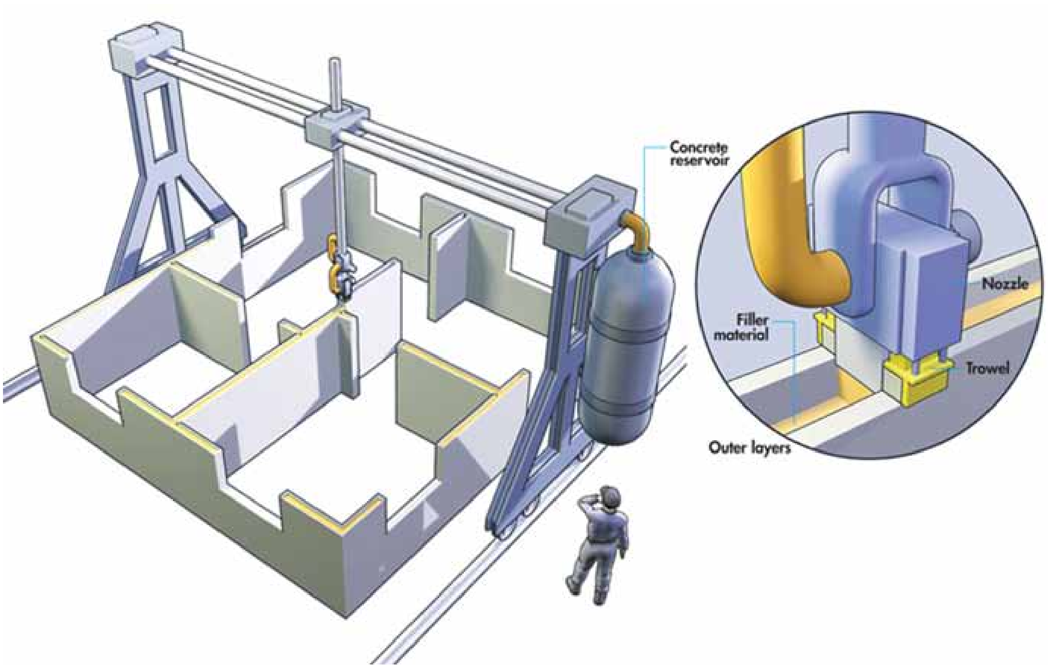


Figure 35
Visualisation of Contour Crafting set-up for the production of housing. Imagery courtesy of B. Khoshnevis.

§ 2.2.4.2 D-Shape

The production principle behind D-Shape is to scale 3DP and Inkjet methods to a new dimension. An inorganic binder is used to bond sand and stone powder of all sorts. Analogue to powder bed processes (SLS, DMLS), parts not joined to the building volume during the process serve as support structures.

Large scale process chambers are achieved by using light-weight scaffolding, which, in the future shall allow fabrication in the open. Geometric restrictions of the system depend on the limitations of the scaffolding geometry. The dimension of the process chamber can be as large as 6000 x 6000 x 6000 mm, but principally it can be extended to any conceivable size.

D-Shape is another method offering the dimensions and possibilities necessary for printed building technology. It was conceived to create life-size sculptures and buildings, and is called 'mega scale free-form printer of buildings'.

To date, only sculptures and sample building parts have been realised, rework is intensive, and no results in terms of actual material properties are available yet.[19]

§ 2.3 Summary AM technologies

The introduction of the different methods illustrates that the performance of AM façade components can be reduced to the material properties, and is not mainly influenced by the AM technologies themselves. All technologies have advantages and disadvantages, but their fundamental functionality is similar. Therefore, the initial decision to be made in terms of a possible application in the façade is to decide whether one wants to use only proven materials – in this case metals -, or if one is open to use yet to be developed plastics, specifically designed for a particular purpose.

The differences between the different AM materials groups are:

- the need to process metal powders in a protective atmosphere in order to avoid exothermally reactions and uncontrolled deflagration, when coming in contact with oxygen.
- the dependency on exclusively available materials from the system suppliers, in order to guarantee a certain component quality and secure warranty claim for the AM system. Only a few DMF systems allow the use of industry standard powder without loosing the warranty claim.
- the limitation of the building chamber for the AM technologies for plastics. 'Powder feed DMF processes' are the best choice when trying to extend the size of the process chamber because it allows for a combination with robot arms or large process platforms. For plastics, only 3DP methods offer the possibility of significantly larger process chambers. The AM technologies for 'Large scale structures' obviously offer the least limited building size.

In general, the following can be summarised:

- since the systems are very expensive they need to produce high quality parts in order to be economically efficient. The parts must feature obvious advantages over conventionally produced parts.
- to guarantee a successful use as manufacturing methods in real-life applications, production management, quality management and a reliable standardisation of norms and parameters must be established.
- in addition, testing methods need to be established that evaluate parts whose geometry changes constantly. For building products, for example, the slightest change in the product geometry makes it necessary to request a new approval. As such, this is not practical for AM methods since it is the uncomplicated handling

of changing geometries that make up the strength and justification of these methods. If tests and certificates were needed for each part (analogue to an "individual approval" for not yet introduced building products), this would result in an unlimited cost explosion and therefore most likely lead to an exclusion of these methods as 'standard' fabrication methods. It is more probable that the approval of specific methods rates the resulting products as approved. The products' properties can then be verified with according quality management.

[15] [14]

For a further differentiation of the various available AM systems, an overview of the most common technologies is followed by an evaluation matrix with regard to the possible application for façade construction.

List of relevant methods:

AM process (Abbreviation)	System description / Manufacturer	Build chamber in mm	Basic material
Direct Metal Laser Sintering (DMLS)	EOSINT M 270 / EOS	250x250x215	Metal
Laser Engineered Net Shaping (LENS)	LENS 850-R / Optomec	900x1500x900	Metal
Electron Beam Melting (EBM)	A1, A2 / Arcam	300x200x350	Metal
LaserCusing	M3 linear / Concept Laser	300x350x300	Metal
Selective Laser Melting (SLM)	SLM 280 HL / SLM Solutions	280x280x350	Metal
	AM 250 / Renishaw	250x250x300	Metal
	SLM 250 / Realizer	250x250x300	Metal
	DM250 / 3D Systems	250x250x300	Metal
Direct Metal Deposition (DMD)	66R / POM Group	3.2m x 3.665m x 360° (robot arm)	Metal
Electron Beam Free Form Fabrication (EBF^3) / Direct Manufacturing (DM)	VX4 / Sciaky	4978x2286x1778	Metal
Direct laser additive manufacturing (CLAD)	EasyClad Magic / Irepa Laser	1500x800x800	Metal
Aerosol Jet System (M3D)	Aerosol Jet Lab System / Optomec	370x470x mm	Plastics, Metal
Selective Laser Sintering (SLS)	EOSINT P 730 / EOS	700x380x580	Plastics
	sPro 230 / 3D Systems	550x550x750	Plastics
InkJet	Connex500 / Objet	500x400x200	Plastics
	ProJet5000 / 3D Systems	550x393x300	Plastics
	VX4000 / Voxeljet	4000 x 2000 x 1000	Plastics, Casting Sand
Stereolithography (SLA)	iPro 9000 SLA Center / 3D Systems	650x750x550	Plastics
	Mammoth / Materialise	2100x700x800	Plastics
Digital Light Processing (DLP)	Perfactory Xede / Envisi-ontec	457x304x508	Plastics
3D Printing (3DP)	Zprinter 650 / Z Corporation	254x381x203	Plastics
Fused Deposition Modeling (FDM)	Fortus 900mc / Stratasys	914x610x910	Plastics
D-Shape	D-Shape by Enrico Dini	6000x6000x6000	Mineral powder
Contour Crafting (CC)	Beta-System by Behrokh Khoshnevis	6000x6000x6000	Reinforced Concrete

Table 1

Overview of the described AM processes with abbreviation, system denomination, size of the building chamber and main material groups.

Evaluation matrix I: Technological comparison of methods

AM Process	Application for façade manufacturing			Potential for				Potential for AM Envelopes		
	suitable for integrated parts	fits into conventional façade manufacturing	materials suitable for façades	customisation	feasibility	use of free form	enhancement of façade technology	Summary	Ranking	processes for AM Envelopes
DMLS	+	+ +	+	+	+ +	+ + +	+	11	2	DMLS (Metals)
LENS	o	o	+	o	+	+	+	4		
EBM	o	o	+	o	–	+	–	2		
LaserCusing	+	+ +	+	+	+	+ + +	+	10	2	LaserCusing (Metals)
SLM	+	+ +	+	+	+ +	+ + +	+	11	1	SLM (Metals)
DMD	–	+	+	o	+	+	+	5		
EBF³	–	o	+	o	+	+	+	4		
CLAD	–	+	+	o	+	+	+	5		
M3D	o	–	–	o	–	+	–	1		
SLS	+	+	o	+	+	+ + +	+	8	3	SLS (with PEEK, specialized materials)
PolyJet	+ +	o	+	+ +	o	+ +	o	7	3	PolyJet (Material issues)
MultiJet	+	–	–	+	o	+ +	o	4		
Voxeljet	o	o	o	+	o	+ + +	o	4		
SLA	o	– –	–	+	o	+	o	2		
DLP	+	– – –	–	+	o	+	o	3		
3DP	o	– – –	–	+	o	+ + +	o	4		
FDM	+	o	o	+	o	o	o	2		
D-Shape	–	– – –	o	–	–	– – –	–	3		
CC	–	– – –	+	–	–	–	+	2		

Table 2

Matrix I: potential of AM processes regarding different aspects of manufacturing with AM, and the AM processes themselves.

Upon consideration and evaluation of the entire spectrum of technologies in the matrix shown above, the selection for the façade can be narrowed down to five AM technologies:

- **PolyJet** the most visionary technology in terms of freedom of design but also in terms of an extensive combination of existing materials all the way to composite parts. However, it must be noted that the PolyJet technology is only of limited suitability for a direct application in the façade. According to matrix 1, the PolyJet technology is ranked third.

- **Selective Laser Sintering** (SLS), because the technological developments that the company EOS conducted has made it into the market leader in the field of laser sintering. And considering that the materials for this method are developed in direct collaboration with the supply industry. It can therefore be assumed that application specific materials, for example for the façade, can easily be developed. Currently, PEEK, a high performance plastic, is the material of choice; it features a number of positive material properties, but costs a multiple of conventional polyamide. According to matrix 1, SLS is also ranked third.
- **Direct Metal Laser Sintering** (DMLS) is a further development of SLS for the material group 'metal'. Technologically, it equals the system technology for plastics, and is therefore principally suited for an application in the façade technology. The processes for metal are slightly more complicated because the materials are harder to handle. However, the components already stand up to the currently known industrial metal parts and thus benefit from the fact that their performance is estimable for the façade application. Therefore, DMLS is ranked second.
- **LaserCusing** offers the material and process related advantages mentioned under DMLS, but exhibits additional 'features' that make it easier to integrate the technology into a production chain. The parts are placed in the system directly with standard clamping systems. Therefore, the parts can be accurately reworked with other CNC systems that use the same clamping mechanism. Like DMLS, LaserCusing is ranked second.
- **Selective Laser Melting** (SLM) is currently the most suitable technology to generate metal façade components as indicated in the matrix. The system offers the possibility to use industry standard powders and therefore economic production, independent from specific material suppliers. The technology was not developed from existing system technologies for plastics, but rather directly oriented toward metal parts fabrication. In the AM industry, the developers of SLM systems have the most experience with the material aluminium. They introduced an aluminium-ready system to the market when merely producing aluminium parts was still questioned by most experts. Standardised quality control within the system yields tested parts; the first step toward true AM production. In addition, the developments over the last years suggest that SLM can be quickly adapted to new fields of application. Selective Laser Melting is ranked first in the matrix of AM technologies.

By assessing those five AM technologies again with adjusted criteria toward AM Envelopes, a final selection of three relevant technologies can be made. DMLS was ranked third place, LaserCusing second, and SLM first. The result of this second assessment shows a clear dedication of this research toward AM technologies for metals. Even though a high potential can be seen for the PolyJet technologie, still the aspects that are more relevant for the building envelope rule over those possible developments.

Evaluation matrix II:
Estimate of the potential of suitable methods related to an AM Envelope

AM processes from Matrix I	evolution in		façade systems	Architectural design		Recom-mendation	Ranking Matrix II		AM processes for AM Envelope
	size of building chamber	new materials	potential for system integration	Change of shape / form	change of engineering	Application makes sense!	Summary	Ranking	
DMLS	+	+	+	+	+ +	+	11	3	DMLS
LaserCusing	+ +	+	+ + +	+	+ +	+ +	14	2	LaserCusing
SLM	+ + +	+	+ + +	+	+ +	+ +	16	1	SLM
SLS	+	o	o	+	+ +	o	6		
PolyJet	-	+ + +	-	+ + +	+ + +	-	9		

Table 3
Matrix II: further assessment of the potential of AM on the background of Matrix I

Quantifier	Intention
_	negative
+	positive
o	neutral

Table 4
Explanation for the used quantification in Matrix I and Matrix II

During the research it became clear that size of the building chamber and building speed are other issues with AM, even if this fact is denied by most of the system providers.

Meetings at FKM Sintertechnik GmbH, the largest service provider in Selective Laser Sintering in Europe provided in-depth knowledge. Over the last years, the company opened up their portfolio to include DMF processes, although their core business lies in AM in plastics. This fact shows that the market has an increasing demand for DMF processes, and that the 'big players' are starting to adjust to it.

The meetings with FKM Sintertechnik provided deep insight into the development process of AM systems. It can be stated that - over the last three years alone - all three mentioned selection criteria for AM technologies (in this case DMF) were drastically enhanced:

- material choices evolved from "provider-only-materials" to a selection of industrial standard powders;
- until the end of 2012, the envelope size will assumingly increase by a factor of eight from 250x250x250mm to 500x500x500mm;
- processing speed will be increased using different strategies: enlarging the energy source (laser power), using multiple lasers and scanning devices ('multi beam').

The investigated DMF-systems all offer a different range of possible products. Some are specifically enhanced for medical applications, others aim at Rapid Tooling. It is always the demand for a particular application that pushes the technologies onward. Therefore, there is hope that façade applications will drive the AM systems toward fulfilling their specific requirements. But ultimately it is the user who needs to push the limits according to his/her demands. It is therefore necessary to provide a thorough description of the technologies and the possibilities and limitations involved to give the individual user the opportunity to give it a try.[14]

In general, the following can be summarised:

- Since the systems are very expensive they need to produce high quality parts in order to be economically efficient. The parts must feature obvious advantages over conventionally produced parts.
- To guarantee a successful use as manufacturing methods in real-life applications, production management, quality management and a reliable standardisation of norms and parameters must be established.
- In addition, testing methods need to be established that evaluate parts whose geometry changes constantly. For building products, for example, the slightest change in the product geometry makes it necessary to request a new approval. As such, this is not practical for AM methods since it is the uncomplicated handling of changing geometries that make up the strength and justification of these methods. If tests and certificates were needed for each part (analogue to an "individual approval" for not yet introduced building products), this would result in an unlimited cost explosion and therefore most likely lead to an exclusion of these methods as 'standard' fabrication methods. It is more probable that the approval of specific methods rates the resulting products as approved. The products' properties can then be verified with according quality management.
- At the moment, none of the described AM technologies offers an appropriate building speed that would be needed to fulfil the demands of a bigger parts production.

[15] [14]

The intended integration into existing production technology must be considered in order to make a final decision for or against a particular method, and the parameters to create the component must be determined. It is not possible to make a generalised statement that is valid for all applications alike.

The prototypes for this research were made with plastics as well as DMF methods. Followed by a detailed examination and continued application conducted with the DMF methods using aluminium.

§ 2.4 AM materials

A wide choice of materials is available for the AM technologies.
All manufacturers continuously develop new materials for specific applications, because with AM, the material is the key factor for new applications. In principle we can differentiate between 'plastics' (§ 2.4.1), 'metals' (§ 2.4.2) and 'other materials' (§ 2.4.3).

When developing materials for AM processes, the process requirements (melting temperature, grain size, flowability) and the type of desired components play an important role. 3DP models, for example, are used for design studies related to colouring, shape and ergonomics. With these applications, there are no initial requirements for certain functionalities or durability, but colour depth and surface texture are critical. This means that there are different demands posed on the material for prototypes and design samples than for those of end use parts. Since, originally, the methods and materials were developed for Rapid Prototyping and not for end use parts, it is necessary to focus the development of additive methods and materials on this demand (see [3] [7]).

If used to produce consumables, all of the materials currently in use must still prove their durability for the entire lifetime of the finished product. Aspects related to lifetime durability are UV resistance and humidity resistance. When manufacturing prototypes for sampling or development, the material properties might not play a key role, but when transferring the development to the AM process they become the deciding factors for or against the use of the technology. The big challenge for process developers is to match the material properties necessary for a trouble free manufacturing process with the desired properties of the final product. However, during the past few years several methods have been 'reconfigured' for use with industry standards, and process-safe materials were developed that feature the desired properties. The use of industry standards leads to drastically reduced AM manufacturing cost, because there is no need for expensive specialty materials. One example is the SLM method (DMF), which can be operated as an open system with the possibility to use industry standard metal powder. The price for a system specific mix and an industry standard powder can vary by a factor of ten. However, if industry powders are used with systems that have not been approved for these materials by the manufacturers - as is the case with SLS systems by EOS, for example - the supplier cannot guarantee any material properties and the user looses the right to warranty claims.

The primary goal of all material developments for AM systems is to closely match the material properties and characteristics of conventional end use parts manufacturing processes (see [7] [3]). However, additional possibilities for AM products also come from printed textures, material gradients, programmed porosity and others. Changing the performance properties can therefore create new unique features from the raw material, independent of the factually achieved material characteristics. Enhanced product properties can be developed from a combination of functional construction and the materials available. Such new properties can create a clear distinction between new AM products and conventionally manufactured mass products; a direct comparison with accepted mass products is not possible.

The methods for direct fabrication of metal parts (DMF) have undergone a somewhat simpler development, regarding the materials used. Related to the functional construction of building parts for the façade, a large number of established alloys and material powders is available that stand up to a comparison with conventionally processed metal. The modifications necessary to use these powders in AM systems are similar to those for traditional methods. Therefore, the material properties of DMF products can be relatively easily compared to those of metals from conventional fabrication.

§ 2.4.1 Plastics

Because additive methods were initially used for prototype manufacturing, plastics is the largest group of materials used. Many of the products on the market are based on proprietary recipes and compositions. Currently, all classifications and descriptions of AM materials derive from long established materials used with conventional production methods. The properties are developed by balancing AM manufacturability and the properties desired by the user. All descriptions draw comparisons to industry standards; for example for ABS the AM material is described as 'ABS-like', which implicates that similar properties to those of the industry product in question are achieved. But it is still difficult to draw a direct comparison with pure plastics. To achieve broad acceptance of the technology as a production method, AM materials must be comparable to conventional materials.

At this time, plastics used in conventional production cannot be replaced by AM materials. Instead the user needs to choose a material that comes closest to his/her requirements. Thus, some properties can be achieved, others cannot. Permanent resistance against humidity, ultraviolet light, heat and isotropic material properties are problematic issues, independent of the orientation of the part in the process chamber. And it is difficult to match the strength of die cast parts. Due to their technical characteristics, AM processes inevitably lead to different results as conventional methods, and therefore to different material and product properties.

Currently, plastics such as ABS, acrylate, photopolymer, polyamide (nylon), epoxy, polycarbonate and PMMA (acryl glass) are used for these processes. Material mixes are modified for defined applications, for example for aeronautical engineering, in order to impart specific properties on the materials, which are later introduced to the general AM market. Polyamide, for example, was modified in a way that it was classified as 'incombustible' and could therefore be used for aeroplanes. In certain cases, high performance plastics from conventional fabrication are made available for AM methods. PEEK, for example, a material which was produced for special applications in the automotive industry for the SLS method. The benefits of such a high performance plastic materials also open up new possibilities for applications in façade and building technology in terms of material use, component optimisation and component properties. PEEK in particular is characterised by a number of specific benefits; amongst others, the manufacturer points out the following properties for 'EOS PEEK HP3':

- high-temperature behaviour;
- high wear resistance;
- chemical resistance;
- optimum reaction to fire, smoke and toxicity;
- good hydrolysis resistance;
- potential biocompatibility;
- sterilisability.

"Due to this extraordinary combination of properties, EOS PEEK HP3 is optimally suited for the highest requirements, for example in the medical industry and aeronautics as well as motor sports.
For medical applications, these properties turn the material into an ideal alternative for stainless steel and titanium. And in aeronautics and motor sports, where light weight and fire resistance are critical, EOS PEEK HP3 has evolved to a suitable replacement material."[20]

It is thus conceivable to employ products made of such high performance plastics in suitable areas of the façade if improved performance justifies the application, and if fabrication with any other than AM is not feasible.

Basic Material	AM process	Manufacturer	Note
Plastics			
ABS	FDM	Stratasys	also: ABS composites
	DLP	Envisiontec	
	SLS	EOS, 3D Systems	ABS-like materials
	InkJet	Objet	ABS-like materials
Acrylate	SLA	3D Systems	thermoplastic materials
	DLP	Envisiontec	Hearing aids
	InkJet	Objet	specific acrylic mixtures
Photopolymer	SLA	3D Systems	thermoplastic materials
	InkJet	Objet	jetted photopolymer
	InkJet	3D Systems	thermoplastic materials
Polyamide	SLS	EOS	pure plastics
	SLS	EOS	also: Alumide (Polyamide -aluminium composite)
Epoxy resins	SLA	3D Systems	
	DLP	Envisiontec	also: epoxy composite
PVC-Foil	LOM	Solidimension	
Polypropylene	SLA	3D Systems	thermoplastic materials
	DLP	Envisiontec	
Polystyrene	SLS	EOS	
Polycarbonate	FDM	Stratasys	also: PC-ABS composites
	SLS	EOS, 3D Systems	only for casting cores
PMMA	InkJet	Voxeljet	PMMA ~ acrylic-glass; only applied as binder for the sintering process!
	SLS	3D Systems	PMMA ~ acrylic-glass; only applied as binder for the sintering process!

Table 5

The basic materials in plastics for AM, and the suitable AM process to use them.

§ 2.4.2 Metals

Similarly to processes using plastics, special material mixes are offered to manufacture metal parts with Direct Metal Fabrication (DMF). Only a few methods use pure metals; in most cases specific alloys are used. Currently available materials for DMF are titanium, aluminium, cobalt chromate, tool steel, stainless steel and various alloys of these materials.

Flow characteristic, granulation, filling density are the determining factors when choosing a powder for a certain method. These parameters can also have a significant influence on the material properties of the manufactured part.

Depending on the method used, parts fabricated with DMF might need to be reworked. Analogue to conventional metal processing methods, different material properties can be achieved with hardening and annealing. Currently, various research facilities examine the microstructure of the "printed" metals to enable early intervention, possibly already during the building process. Such specialised metallurgic research is necessary, in particular if the methods are used to fabricate components for aeronautics but also for future façade and building technology applications.

Material mixes of plastic granulate with metal are offered for some processes that use materials in powder form, for example 'Alumide' for LS by EOS. However, the materials made with these processes are considered plastics, since plastic is the major component. They do not exhibit the properties of a metal material.

Basic Material	AM process	Manufacturer	Note
Metals			
Titanium	DMLS	EOS	
	LENS	Optomec	
	EBM	Arcam	
Titanium alloys	SLS	EOS	
	LaserCusing	Concept Laser	
	LENS	Optomec	
	EBM	Arcam	
Aluminium	SLS	EOS	Alumide: Polyamide-Aluminum composite
	LaserCusing	Concept Laser	
	DMLS	EOS	
Steel	EBM	Arcam	
	SLS		
	LaserCusing	Concept Laser	
Stainless steel	SLS		
	LaserCusing	Concept Laser	
	LENS	Optomec	
	DMD	POM / Trumpf	
Tool steel	LENS	Optomec	
	DMD	POM / Trumpf	
	SLS	3D Systems	for infiltration of green parts
Nickel alloys	DMLS	EOS	
	LaserCusing	Concept Laser	
Bronze alloys	SLS	3D Systems	for infiltration of green parts
	LaserCusing	Concept Laser	
	SLS	EOS	within plastic compound
Cobalt-Chrome alloys	SLS	EOS	
	LaserCusing	Concept Laser	
	EBM	Arcam	
Copper	LENS	Optomec	
	M3D	Optomec	Aerosol Jet System
Iron-Copper alloys	LaserCusing	Concept Laser	

Table 6
The basic materials in metals for AM, and the suitable AM process to use them.

§ 2.4.3 Other materials

In addition to plastics, other materials such as starch, ceramic, silicium, wax, gypsum, moulding sand or electronic conducts are used for certain applications. They are often used as an intermediate step of conventional production, for example for the very first models for castings.

In the future, we might expect the use of other materials for Additive Fabrication such as glass (see § 4.2.2 Direct Glass Fabrication) or wood. In order to employ the method in the building technology the material spectrum must be broadened, and properties such as transparency, formability and durability must be examined.

Basic Material	AM process	Manufacturer	Note
Other materials			
Starch	3DP	Z-Corporation	
Ceramics	SLS	Phenix Systems	France
	DLP	Envisiontec	
	3DP	Z-Corporation	
	InkJet	TNO	Beta system; paste materials
Silica	M3D	Optomec	Aerosol Jet System
Wax	InkJet	Solidscape	
	DLP	Envisiontec	casting cores for jewellery
Gypsum	3DP	Z-Corporation	
Casting sand	SLS	EOS	Resin coated sand
	3DP	Z-Corporation	
	InkJet	Voxeljet	
Conductive tracks	M3D	Optomec	Aerosol Jet System
	InkJet	TNO	Beta system; paste materials

Table 7

The basic other materials for AM, and the suitable AM process to use them.

§ 2.5 AM evolution from new impulses

Impulses from independent fields or strong economic demands are needed to further develop the AM technologies for new areas of application. Since there are only a few industry segments that currently provide a market for Additive Fabrication, we cannot expect self-motivated development for the building industry. But we can still formulate the specifications for system technologies or materials by preconceiving the requirements that a building technology with generatively fabricated components would pose. These requirements can focus on specific areas of Additive Fabrication. The most important areas are:

- AM system technology (§ 2.5.1)
  - Process chamber
  - Process speed

- AM materials (§ 2.5.2)
  - New materials
  - Functional gradient materials
  - Transferring AM materials to architecture

- Automated building technology (§ 2.5.3)
  - Building robots
  - Digital fabrication

A new approach to the modified materials as well as joints and constructions for AM gives a new meaning to the development of functional components. If the new techniques are used intelligently, generative fabricated products can even gain added value. For example: available lightweight building structures allow for flexible components with improved or adapted properties and reduced material consumption. Conversely, system suppliers must react to the findings and demands from such new areas of application to further spread the use of AM technologies. Often, developers lack the specific knowledge or particular way of thinking without which the requirements cannot be detected. The following sections describe the requirements of such technology changes in AM, and provide insight into possible applications in building technology.

§ 2.5.1 AM system technology

§ 2.5.1.1 Size of the building chamber

At first glance, the obvious discrepancy between building technology and AM is the relatively small size of the process chambers offered by the systems currently available. At the time this research work was started in 2007, an average AM system could produce a building volume of 0.0225 m^3. This relates to a process chamber with a footprint of 30cm x 30cm and a height in Z direction of 25cm. During a period of only four years, these boundaries were extended by a factor of 356; with current building volumes of 8m^3!

This development is used to exemplarily illustrate the dependency between technology development and market demand: The 8m^3 system is manufactured by Voxeljet in Friedberg, Germany; the target market is the automotive industry, with its demand for metal casting cores. The reason for this rapid development in size is the demand for larger casting cores to be fabricated according to the '3D Printing' principle. AM makes it possible to digitally develop improved components without the need to pre-consider whether or how they can be realised. The performance that these components exhibit exceeds that of conventional casting cores. And since the number of items sold (in this case large scale engines) is comparatively small, individual fabrication not only makes sense but almost seams the only practical solution. It was always a customer demand that caused the company to change their system. The example of the Voxeljet system shows that contrary to the opinion of other '3D Printing' companies it is not technically impossible to increase the size of the system, even if it is true that some material and technology parameters cannot simply be scaled up.[14] But the example also shows that process development in other directions, for example for other target groups, does not lie in the interest of the firms. In practical terms, the company is opposed to transferring the Voxeljet principle to other areas than that of manufacturing casting cores[4].

4 One-on-one interview between the author and a company representative of Voxeljet on 01. Dec. 2011 on the occasion of EuroMold 2011.

Systems with larger than average process chambers existed even before the development of the Voxeljet machine. All of these developments were driven by customer requests as well. The Belgium company Materialise built its first "Mammoth" SLA system as early as in the year 2000. For a long time, this system with a process chamber of 2.1x0.7x 0.8m, was the one able to produce the largest possible components.[21] The development was motivated by the dimensions of dashboards in the automotive industry. The requirement was to produce the prototypes for these dashboards without joints.

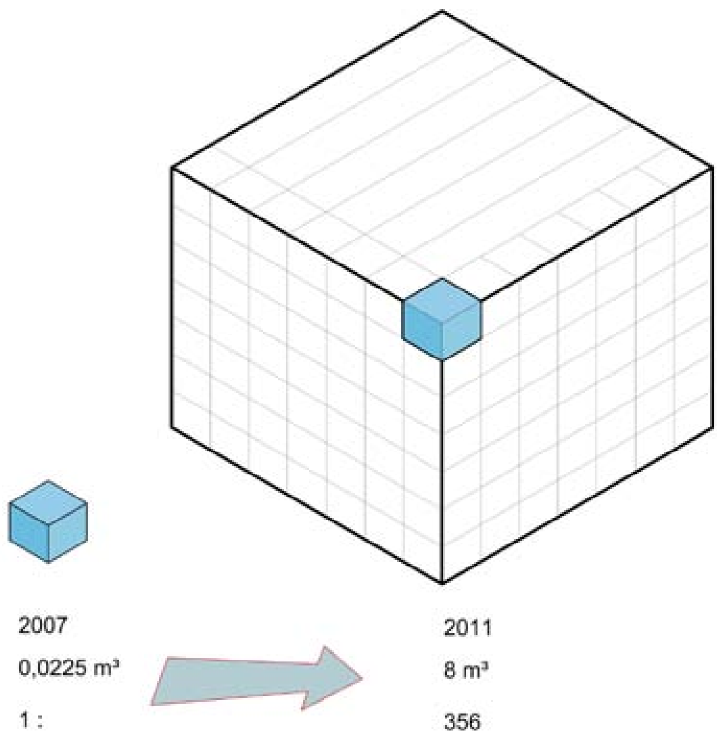


Figure 36
Schematic presentation of the increased process chamber dimensions since 2008.

§ 2.5.1.2 Process speed

Similarly to future process chamber dimensions, it is difficult to foresee future developments in the area of increasing the process speed. It is obvious however; that we need specified, realistic process speeds in order to integrate AM methods into industrial manufacturing. Even today, the addendum 'rapid' is a relative term because the methods cannot yet achieve fast processing times.

At the beginning of the development, the focus lay on comparing conventional prototyping with Rapid Prototyping. The fact that AM technologies do not require tools led to an advantage, particularly in terms of the time needed to turn the initial idea into the finished prototype. Another benefit of Additive Fabrication is the fact, that the product can be developed quickly in collaboration with the customer or user, and that initial improvements can be integrated during the developmental stage. Since making new tools is extremely expensive, this option simply does not exist with conventional methods. Another advantage is that product series with a batch size of 1 are entirely possible. This means that with AM the production of small series or even single pieces is economical. This is exactly the strong point of Additive Fabrication: With this production method it is irrelevant whether 100 equal or 100 unique parts need to be manufactured. AM allows for customised products fulfilling customer demands – meaning one of a kind products without added cost, one of a kind products at the price of mass products (see [3]), whereby the actual time to produce these items plays only a minor role.

But if we draw a direct comparison between AM methods and conventional fabrication methods, this advantage is lost and the processing time turns into a disadvantage. High speed milling and CNC controlled processing centres feature disparately higher yields because the products are generated from semi-finished parts. With Additive Fabrication, the manufacturing cycle for each part is the same. Depending on the method, the production time needed can usually be calculated from the building volume. Currently, only the production of large quantities of small parts yields satisfactory results.
For building technology that means that in order to realise large building volumes, a large number of building parts must be available in a relatively short period of time. Hereby, an integration of AM might interrupt conventional processes. A curved façade, for example, designed to be produced with AM nodes, would require several hundred nodes. It might take 24 hours to produce one component; at a high risk of defects. This means that in order to apply AM to building technology, these processes must be included in planning, i.e. the methods must be very dependable to ensure reliable planning. On the other hand, the example given also shows that in façade technology AM will not be applied to create large surfaces and volumes but rather to provide better solutions for neuralgic interfaces and joints – areas where a different technology can improve the whole.

In terms of system technologies, there is a noticeable competition between different system suppliers to offer the fastest feasible processing speeds, and therefore an attempt to assimilate the different systems. The methods using a laser as the light source, for example, are optimised for greater speeds by changing the energy performance of the laser, by adding more lasers in one system, by improvements in mirror and scanning technologies, or by changing the process chamber temperatures and material properties. The systems also feature different resolutions which can influence processing times. If parts are produced at higher speeds, the surfaces of the part will exhibit lower resolution. Another options is to differentiate between contour and filling geometry, and thus to apply different densities to different areas of a part; which in turn will lead to time savings. To do this, two different lasers with different light performance are used.

Another approach is the invention of systems without a laser as the energy source. By not using a laser, the above described combination of process speed and resolution is decoupled. One strategy is to use a masking system to expose the building material with light. In this case the whole building chamber surface is exposed in one step; all areas not to be solidified are masked by individual masks for each layer of the build job. One system being investigated in is called 'Selective Mask Sintering', another is the 'High Speed Sintering'. Both are aiming at new solutions to enhance building speed.

§ 2.5.2 AM materials

§ 2.5.2.1 Functionally Graded Materials

Functionally Graded Materials (FGM) are materials consisting of different material types that interpenetrate one another in a controlled gradient. The advantage of FGM's is the combination of different material properties in a single part. Gradients from hard to soft or rigid to flexible can be printed; thus potentially replacing parts that consist of two types of material (for example a rubber seal around a window).

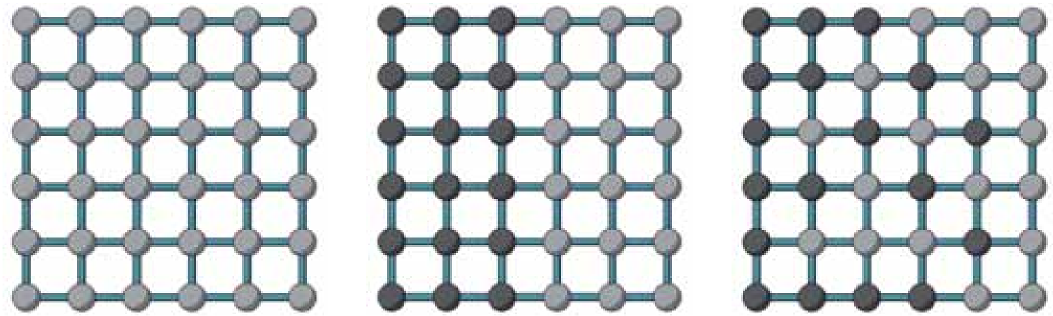
A notable development in this field was conducted by the group 'Additive Manufacturing' of the department 'High Tech Systems and Materials' at the Dutch research institute TNO: 'High Viscous Material Ink Jetting'.

Hereby, a software application breaks down the shape of the three-dimensional model into layers made up of individual droplets. The number and arrangement of the necessary droplets for each geometrical shape is recalculated and saved as a GIFF file (Graphics Interchange File Format). In addition, the group succeeded in allocating material properties to the required GIFF files so that one volume can consist of areas of different materials. And these areas can feature different resolutions of the material particles used. The system then reads the information contained in the file and processes it accurately. The principle is based on that of Inkjetting, which sprays viscous plastic droplets onto a building platform at high speed. With the TNO system, the individual material droplets are directed by means of electrical power. Thus, different materials can be melted together to form a true gradient. The material used for this technology is a powder-filled polymer paste. The paste can contain any type of powder.

The prototype system makes it possible to print a small spiral of material with a density of 100 per cent on one end and zero per cent at the other.[22]

Figure 37
Prototyp of FGM part produced with the High Viscous Inkjetting system of TNO

Figure 38
Beta system for High Viscous Inkjetting of TNO



a b c

Figure 39
a.) Homogenous material;, b.) joined material; c.) Functionally Graded Material (FGM)

In addition to creating gradients, the system can also print vertical 'walls' only a few droplets wide – without support material and without the inherent viscosity of the material causing the 'wall' to be instable. TNO sees the future of this technology in micro printing; but it certainly offers potential for future application in AM.

Thus, AM not only allows for freedom of form but freedom of material as well. If a system allows us to generate different materials and material compounds and to arrange them freely, anything can be printed. However, this path breaking technology has not yet reached marketability.

Issues to be solved relate to the software, to extending the hardware and to a controlled placement of different materials for the different application principles of the AM methods (see [3] [23]).

One of the problems is that none of the CAD software programs currently on the market can handle graded materials. In order to use FGM, new CAD software must be developed!

In order to fully define 3D parts, a new method is needed to describe all points in a three-dimensional space. This could be done with 'Volumetric Pixels' (so called 'voxels', see appendix A II / Glossary / Voxel). Dissolving the three-dimensional shape into image points which can then be described with material properties.

The main reason for reducing geometric shapes to basic information such as edges and corners is the extremely large storage capacity required. 3D models with complex geometries would generate infinitely large datasets when described with voxels. It is not yet possible to handle such datasets because of the limitations of the computer processors currently available as well as the file format used to describe 3D models, the '*.stl' format. Current discussion about a new, encompassing data format shows that further development of the AM methods is closely linked to established formats and standards (see appendix A II / Software).

But as a general material principle, FGMs open new ways of designing structures and parts. The opportunities are connected to future visions of building construction, as existing solutions can be thought in a absolutely new way. So far, graded materials have been successfully produced with the LENS method.[3] Two types of titanium alloys are printed into one another in a smooth transition. But it has to be admitted, that the properties of those two metal alloys are fairly close to each other and do not push the limits of the FGM capacities.

§ 2.5.2.2 Digital materials

The PolyJet Matrix technology by Objet (§ 2.2.1.5) introduced the so-called 'digital materials' for AM methods: from two source materials, new, digitally specified material mixes can be generated directly on the building platform in a multitude of gradations. The viscous polymer droplets used for this method are deposited from two cartridges, and mixed on the building platform according to the percentage ratio that was predetermined in the digital model. Depositing the different materials droplet by droplet ensures that, when hitting the building platform, the base materials mix at the predefined ratio. The 'digital materials' do not yet represent 'voxels'; but gradations between two different materials can be approximately displayed. Such gradations are known from handles with hard as well as soft parts, for example, or remote controls

with a hard casing but soft buttons. This is of great advantage for realistic prototype production (for example for flexible joints, rubber soles, springs a. o.).
Until 2012, the systems supported up to six pre-programmed material mixes made up of two base materials each. Further development depends on improving the software, not the system technology.
Manufacturability of 'digital materials' marks a significant step in material and system development, and opens up a development of true seamless graded materials (FGM's) on the basis of an available AM process.

The possibility to apply freely programmable materials would be of great advantage for various building structural details: if 'digital materials' were available in certified quality for building applications, technical principles should and must be completely revaluated and rethought in terms of design and performance. This means that combined with known biomimicry principles, component walls could be produced analogue to the human bone structure. Foreseeable benefits relate to resource-conserving material use as well as to building in earthquake-prone areas by 'programming' flexibility into certain components. True gradations of material properties in an integrated component shed new light on articulated joints and fittings of all sorts. Changes in manufacturing, assembly and maintenance expenditure shift the range of cost and application for all hitherto known areas of use – in furniture construction as well as in building technology.

§ 2.5.2.3 Programmed lightweight building structures

Software developers and research institutes work on developing programmed lightweight building structures. These are controlled by algorithms and, using a simple 'Drag and Drop' user interface, allow translating three-dimensional bodies into structures with predefined properties. One product available in the market is 'Selective Space Structures' (by Fruth Innovative Technologien GmbH). With this product, grid structures can be easily created following predetermined patterns. On the computer, areas of three-dimensional geometries can be 'filled' with diamond-shaped, hexagonal, triangular or other structures.[24]

In addition, a classification was developed at 'Fraunhofer IWM' (Institute for Mechanics of Materials), that adapts the cell structure depending on the force distribution within a part. Thus, following a finite element analysis, a part can be specified and optimised in terms of the force distribution which, in turn can lead to a more efficient use of resources. In this case, lightweight structures can be upvalued by improving the material distribution.

The British company 'Within' has brought a software application to market that combines all aspects: lightweight structuring, FE Analysis and optimisation cycles. This application makes it possible to develop parts focused on the intended function; without any further limitation caused by interface issues and software limitations.[25]

Using such programmed lightweight building structures can improve the active control of supporting structures. If the lightweight building structures are linked to the algorithm of the machine software which controls the distribution of the supporting structure for a technical realisation of the AM process, then the necessary supporting structures can be integrated in better AM constructions. The geometries of metal parts can be optimised to avoid the need for supporting structures entirely by selecting certain orientations within the process chamber and modelling the form. This means that the quality can be influenced ahead of time; the form is designed according to AM requirements, and time expenditure to remove unnecessary supporting structures is eliminated.

Lightweight construction can also be functionally 'reversed' and thus used to form flexible areas within a part. This means that no secondary flexible material needs to be introduced (which, with conventional structures is the only means to create flexibility). A structural added value is created by accumulating different performances that can be modelled from one single material.

§ 2.5.2.4 Smart Materials

The use of the so-called 'smart materials' in combination with AM technologies can mean even more added value for functional constructions. But it also means another demand on system technology and materials.

Smart materials are materials that when combined with each other exhibit more functionality than the individual source materials. Such materials have reversible changing properties and react to influences such as light, temperature, and electric fields. They can change shape, colour, viscosity, and other properties.

With glass for example, the changeable behaviour is achieved by coating. The material senses signals from the environment (sensory function: light, dark) and reacts (actuatory function: more or less light-transmissive). The material's reaction is not based on a conscious decision as the materials are not truly intelligent, but they react intelligently by reflex when certain changes occur. Necessary controllers and energy supplies can be mounted independently from the material – it acts as sensor and actuator. If these controllers are teachable we talk about 'adaptive materials' (see [26]).

Shape memory alloys and phase change materials also belong to the group of 'smart materials'. In architecture, they can be used to realise applications such as self-acting kinetic façades that automatically create shading when the temperature changes or guidance systems that change colour or pattern if the ambient temperature changes and thus become visible in case of fire.

Integrating smart materials into functional constructions by means of AM methods further increases the performance of the resulting parts. It is also conceivable to use DMF methods to produce bimetals with integrated actuators, for example for façade structures, i.e. they can be realised in a single part without additional assembly. In combination with according software tools, individually set temperature ranges for bimetals can result in individualised location-dependent solutions.

Similar to the realisation of FGM's, the material setup of smart materials poses different requirements on material distribution, material mix and material change within the part, and therefore new demands on the system technology and the programmability of such parts.

Figure 40
Smart material used in toddlers' spoon to indicate too hot served food by colour change at the tip.

§ 2.5.2.5 Transferring AM materials to building technology

Only a few of the materials developed for AM technologies are perfectly suited to be transferred to architecture. Therefore the available materials need to be further developed.

Over the last few years architecture and interior design have seen a trend toward employing new materials. For interior design, this does not prove very difficult because usually there are no requirements related to weather resistance, humidity resistance, or the capability to endure permanent loads. It is therefore easier for this industry to be open to new materials. In architecture, building technical as well as security requirements often prevent a transfer of materials from other applications. For planners this means that the scope of tested and approved materials is limited.
But the hesitation is also due to the fact that building components are not subjected to regular revisions which results in a greater risk of unnoticed failure than in other industries. There is no established technical inspection agency for façades, meaning that the façade needs to function correctly for at least 30 years without major maintenance. This is different for components in other industries: Besides regular maintenance at the garage, the roadworthiness of a motor vehicle is tested periodically; the wheels of high speed trains are exchanged after a certain kilometric performance, and aeroplanes are completely overhauled after a specified number of hours of operation – none of which is done in the building industry! Thus, we can, of course, demand 'braver' initiatives; but these can only be based on reliable control measures so that they can be thoroughly tested by means of real projects.

All considerations related to applying AM methods to façade technology and architecture in general must involve further development of the materials currently available, according to the named criteria. Both sides need to approach the issue simultaneously: planners must be familiar with the new technologies, and the new technologies must meet the requirements of new applications.
There is a noticeable discrepancy when considering a direct transfer of the manufacturing principles. Current process chambers are dimensioned for components, not for entire building elements. The system technology is filigree and the results are therefore fine and precise. Material-specific issues must be considered if the know-how of these systems is transferred to large-scale equipment to manufacture building parts or housing (§ 2.2.4.1 Contour Crafting).

To transfer AM to façade technology we must not only consider the material properties of the final product but also a change in system technology caused by the different size of the components.

Hereby, the main criteria are:

- Material viscosity. The challenge of manufacturing larger structures is to ensure high quality. Problematic areas are the hardening behaviour as well as the stability of the structure during production. Processing self-compacting concrete, for example, poses a logistical challenge in terms of controlling the material flow at the construction site, i.e. eliminating sintered skins between the individual layers of different batches of material. Similarly, when using AM materials, care must be taken to have sufficient material available, and that the base material is formulated such that the individual layers can bond to one another yet cure quickly so that they become one monolithic form.
- Method of application. Technologies using extrusion nozzles designed for the millimetre range do not necessarily function as well when employed for larger sizes. Material properties change significantly from being applied in a thin capillary tube to a large diameter tube. Thus, changing material properties must be examined in terms of controllability and homogeneity of the printed structure. Minimum and maximum achievable resolution for large structure details must also be observed. It is critical to choose the appropriate material for large areas or small details (cement, aggregate, grain size, material mix). In general, the larger the extruded material quantity, the lower the resolution.
- Material behaviour of composite parts. Different melting temperatures, curing behaviour and curing times need to be considered when using different materials in one component. If there is a universal 'building printer' these criteria must be considered for each component when generating 3D data. Process temperatures and process speeds can vary as well, depending on the chosen materials. Appropriate software solutions for simulating deformation and tension during and after a building job are necessary to achieve consistent material quality.

(see [27] [3])

If all these factors are incorporated into the development of new materials, such materials are necessarily very specialised. The end use of the desired products determines the development of the various material groups. A development for direct application in the building technology does not yet exist. Currently, only the Contour Crafting method and the methods for direct fabrication of metal parts employ materials in raw material form (see § 2.2).
Functional gradient materials (FGM's) and metals offer the most potential for direct application in the building industry. Conceivable products could include electric lines, products with different material densities or hard as well as flexible areas, and the use of different materials in one manufacturing process. In order to achieve this, the material properties as well as the manufacturing systems must be further developed.

§ 2.5.3 Automated building construction

When talking about an AM Envelope we automatically think of large structures that cannot be realised with the methods introduced here. It is not sufficient to simply scale available AM methods to the dimensions necessary for a building. This step requires several other considerations in terms of equipment technology as well as material selection.
Still, several concepts following this approach have been developed; and the following describes technologies that might be a step toward a 'printed' façade. They provide answers to how current AM technologies can be modified to meet the demands of large structures.

§ 2.5.3.1 Building construction robots

Based on good experiences with manufacturing robots in the Japanese automotive industry, research and development of robotics for use in the building sector was started in the late Seventies of the previous century (see [28]). We can differentiate between two types of robots: systems that handle entire process steps of the building construction (for example to create the shell construction), or robots for smaller specialised tasks such as welding steel carriers or assembling dry walls.
In 1983, the first robot designed for flameproof coating of steel components was presented to the public. And from 1991 until 1993, the first system that built an entire building was realised by Shimizu Corp. in the city of Nagoya, Japan.

Figure 41
Robot system 'T-Up-System' by Taisei Corp.

Figure 42
Concrete robot by Takenake Corp.

The invented robotic systems are linked to a fix scaffold. High-rise buildings are constructed in layers, just like the models created with AM methods. There are two basic systems: either each story is manufactured on the ground and moved underneath the previously assembled stories (for example: Arrow-Up-System, Fujita Corporation), or a 'climbing' system stacks individual stories on top of one another (for example: SMART-System, Shimizu Corporation).
The initial goal of building robots was to increase the productivity and reduce the cost for high-rise building projects. These goals were not realised because the systems were too inflexible, and because high-rise building projects are unique in appearance and material choice. The main benefit of automation, as it is used by the automotive industry for repetitive process steps, for example, does not apply to building technology. Therefore none of the above mentioned systems are in use today. The technical problems lie in a time-intensive reconfiguration after one building segment has been completed as well as in the large space required in the vicinity of the construction site. And the change in appearance of high-rises today, from Euclidian forms to more free-form shapes is another reason for the discontinuation of the application.
However, one benefit that did result from applying these technologies in combination with pre-manufactured elements was a reduction of on-site material waste of 70 percent compared to traditional building methods.

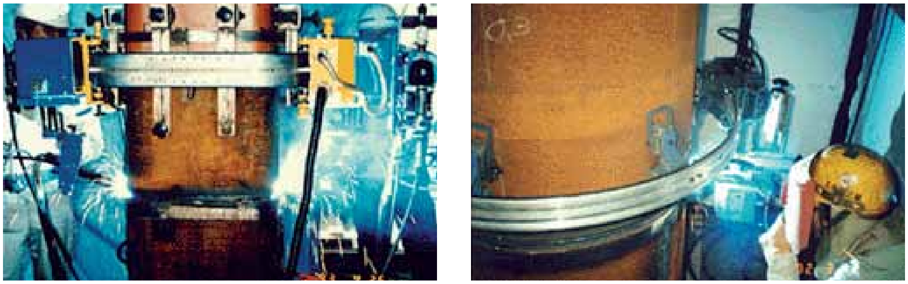


Figure 43
Welding robot, Takenake Corp.

Even though these systems are no longer in use; parts of their developments lead in a direction that could prove interesting when combined with additive methods (see [29] [3]).

§ 2.5.3.2 Digital Fabrication

The Faculty of Architecture at the Swiss Federal Institute of Technology Zurich (ETHZ) examines how modified production methods influence and retroact on architecture. It employs an industrial robotic system to create building components. Hereby, the research projects of Fabio Gramazio and Matthias Kohler follow different directions: one tests the possible use of robots for digitally controlled production of building parts, and the other examines the programmability of parts and the resulting level of freedom. This entails a discussion of the changed design and production methods in architecture and the influence additive methods have on construction, form and function. The department of ‚Architecture and Digital Fabrication' uses a research facility with an industry robot arm (Type: KR 150 by KuKa Roboter GmbH) for both basic approaches.

Because the robot can be used for different fields of application, the approach includes additive as well as subtractive methods. It is the goal of the people responsible to "examine the impact new design and manufacturing methods have on architecture and the building industry".[30] This encompasses a large spectrum of modern manufacturing methods.

a b c

Figure 44
Test facility @ ETHZ: a.) the range of the robot arm on the rails; b.) the tool to handle the brick; c.) the application of the glue to the brick. Imagery courtesy of Gramazio-Kohler, Switzerland.

The robotic system is used for defined projects: Brick wall elements were pre-manufactured for an exhibition booth and an addition to a vineyard building. Criteria such as load-bearing capacity, implanted information (ornament), reproducibility and programmability for digitalised production of wall elements were tested and applied in the projects. As a result, the traditional product portfolio could be complemented with a programmable and therefore reproducible level of freedom of form. The offset arrangement of the bricks alone significantly changed the appearance and the information content of the building components.

a b c

Figure 45

a.) Digital idea for the wall element with 'grapes in a basket'; b.) project application: materialising the idea with bricks into prefabricated wall elements; c.) the final façade design. Imagery courtesy of Gramazio-Kohler and Ralph Feiner, Switzerland.

Against the background of the other additive methods, this 'Digital Fabrication' is path breaking for the development of realisable printed façade components.[30]

It is a transfer of digital information to components, under consideration of the interface issue CAD-CAM and the added aspect 'construction site'.

All of the technologies shown in this section can be considered first steps in the direction of 'printed' façades:

- the japanese robotic systems are no longer in use; however, they have the potential to stimulate a new impulse when combined with other building construction methods or AM technologies. One possible combination is Contour Crafting, combining industrial techniques (crane runways) with AM technologies.
- The Digital Fabrication leads toward a new way of planning and realizing architectural ideas with digital tools. In this respect, AM technologies can offer new solutions in transferring digital ideas to physical reality.

§ 2.6 Summary chapter two

§ 2.6.1 AM Envelope?

The knowledge of the possibilities and limitations of the AM technology is essential for further development, particularly as it relates to applications for the building envelope. The benefits that, at first glance, make the use of these technologies seem sensible, such as lightweight construction, free form, material savings and integral functionality, vitiate traditional design strategies and thought models. They lead to radically new interpretations of existing systems, components, details and design approaches.
In addition, consistent realisation of AM designs annihilates the separation between primary and secondary structure. This highlights the fact that the development leads away from the clearly defined building component 'façade' toward an integrated functional zone, the 'dynamic building envelope'. It is the integration of the new design and production tools into the planning and realisation process that will determine whether or not the AM Envelope will become reality.
The fact that AM is particularly suited for the realisation of new façade ideas is supported by the nature of today's best (façade) architecture: Realisation always involves very small production runs (see § 4.4.3 Batch size one), and is set apart from the standard (see § 4.3.4 Mass Customization) by the demand for individualised building components. The fact that most buildings are very unique is usually a request from the customer, and it is this uniqueness why virtually every building is a prototype. Additive Fabrication is a suitable manufacturing method for such one-off solutions because it fulfils exactly these aspects. When a façade builder has familiarised him or herself with one of the AM methods, individualised solutions can be realised that are sure to fit in an existing façade system. Therefore, AM is suitable as an enhancement of known façade production methods.

§ 2.6.2 Changing the production methods

It is apparent that current production **methods will change** with the application of CAD and AM Technologies. But in order to accommodate such changes, our way of thinking needs to change as well. Developers and engineers are used to follow 'Design for Production' to identify solutions. But the new technologies offer a new approach of product development in the 'Design for Function'.[31] This new design will unite all of the available design and production techniques under one roof. Architects

will have the opportunity to use digital design as a means to re-participate in the production processes. The architect does no longer merely design but participates in the realisation process again – like the historic master-builder - but now as the "Information Master Builder" [32]. The architect becomes developer and data manager for functional components. Competent knowledge of the possibilities with which ideas can be realised brings with it greater freedom for the actual realisation. A first intermediate step on the path to this scenario will be to compile an appropriate multi-disciplinary planning group. It should include the expert planners necessary to master the increasingly complex details and realisation that come with increased freedom of geometry. Close collaboration is needed when trying to realise such 'liquid designs', i.e. the perpetuated designs in free form, blob und morph. "This type of building design dictates a very close collaboration between the participating designing, engineering and production [disciplines]. More than ever one could speak about 'High Collaborative' engineering and production."[33]
The original goal to employ AM technologies for more cost efficient and faster production has been replaced by the added value that they offer in terms of freedom of form. Amongst other aspects, this could include improved component properties or individual design. If building parts are manufactured with AM, they might offer an added value that would justify the use of methods.

It remains to be seen what added value AM technologies can bring to the building envelope. As described in chapter 3, the development of AM for the façade industry will consist of several steps. It is important to change the technologies along with the development of new applications (see § 2.5).
For the most part, the AM systems available today derive from the initial Rapid Prototyping developments; meaning that the original purpose and motivation behind the conception of the systems was never meant for 'real' production. Therefore, there are still restrictions and limitations that need to be improved upon to achieve the capability of serial production.
The restrictions lie in the material properties of the available AM process materials, the realisable surface quality (as compared to the quality standards for example of die cast components), accuracy and resolution and therefore detail fidelity and dimensional accuracy after the CAD file has been transferred into the AM process, and consistent reproducibility with fixed quality standards (see appendix A I / Standardization).
In spite of these limitations, Additive Fabrication offers great potential to fundamentally change building technology.
The conceptual ideas introduced in § 4.1 show that applications that promise added value can be conceived and planned even before the technologies are actually available.

Metals are an interesting group of materials when considering a realistic application of the AM methods to the façade technology: Since their material properties are well known, metals are easy to evaluate and assess by planners and manufacturers. Materials are already used for many technical solutions in the building industry and

thus complement existing systems and constructions when used with AM. It is to be expected that they will be accepted for new applications because the handling of and the trust in the second oldest building material in history has grown over a long time. However, when seeking to employ direct fabrication of metal parts (see § 2.2), one has to be aware that DMF methods still involve more complex manufacturing process than the methods for manufacturing plastic products.
Metal as base material for additive processes is still a specialised field, and a combination with plastics is not possible due to process limitations. The great freedom of form and construction that AM Technologies seem to offer is still limited for complex metal applications. Thus, functional components (articulated joints, bodies-within-bodies, etc.) cannot be formed entirely freely as is possible with plastics.

Another limitation when transferring the technologies to the building industry is the fact that regulations or quality standards for products manufactured with AM technologies have not yet been established. A catalogue of traceable criteria must be developed so that products can be compared to each other and to conventional mass products. A rating system for the manufactured parts, quality standards for the available methods and materials as well as quality control for the individual methods are key requirements when developing a mutually accepted manufacturing method (see [7]).
System manufacturers have been working on this issue over the last few years. Increasingly, quality management systems are integrated in the manufacturing equipment; the production steps for each job are documented; thus making the process steps, i.e. malfunctions, traceable. This aspect is critical when manufacturing ready-to-use products because the products are sold under warranty. The company EOS calls this process 'Part Property Management (PPM)', established to ensure the standardisation and comparability of building processes and building results. Specifiable building parameters can be used to achieve reliable component properties across different systems.[34]

The fact that the development of using AM for ready-to-use parts is fast progressing, infers quick improvements, because AM itself is a development that was not foreseeable 20 years ago. And even if Additive Manufacturing is developing in markets other than the building market, the general requirements and conditions remain the same.

A good example to highlight the **fast-paced development** of AM technologies by comparing them to another technology is the development of Mass Customisation (MC) in the building industry (see § 4.3.4): 20 years ago, it was inconceivable to economically create glass façades that did not feature homogenous glass areas. The development of CAD-CAM production techniques made it possible that façades with glass panes that are completely different from one another are commonplace today.

Equally, in retrospect the integration of AM methods into building production will prove just as natural.

§ 2.6.3 Challenges

The challenges of further developing AM for façade technology can be categorised in 'material', 'technology' and 'production':

- Material:
  - the physical properties of AM products: they need to mimic generally accepted mass products;
  - the materials used under consideration of cost, properties, reworkability and standardisation;
  - accuracy of the fabricated products in terms of product properties such as surface finish and dimensional accuracy;
  - programming and fabrication of Functionally Graded Materials (FGM).
- Technology:
  - the possibility of exact reproducibility of identical parts across different production batches and with different yet technically identical equipment;
  - producible product size: in macro as well as micro range;
  - process speed;
  - achieved resolution with largest possible form, smallest printable detail.
- Production:
  - software access for the user: intuitive processing of 3D data;
  - cost efficiency compared to conventional building products;
  - lower manufacturing cost with AM (equipment cost, maintenance, material cost).

Besides explanations about the development and functionality of the AM technologies, this chapter also established an understanding of the technical basics for future scientific considerations to apply them in façade technology. It became apparent that the AM technologies have evolved from a specialised branch for prototyping to a legitimate production method. Promising technologies for a transfer into façade technology were listed. Limitations in system technology that still exist today can be easily eliminated in the near future, i.e. the system suppliers will solve issues concerning component size, process speed and material choice for the Additive Fabrication.

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3 Toward AM Envelopes

This chapter answers the following research questions

- Which research approaches lead to first experiences with AM technologies in the building envelope?
- What are the effects of product-oriented project results on a general transfer of the AM technologies to façade technology?
- What means of assistance for planners and users of AM must be generated in order to guarantee AM oriented application in the façade?

In this chapter the core of the research work is introduced. The goal of the conducted investigations was a product-oriented research of details based on a post-beam façade, and the transfer of the findings to façade technology. The results are described by means of AM optimised components that can be achieved when applying AM to façade technology.

The description chronologically leads through the developments from small façade details to a complex façade component.

A summary of the optimisation results rounds off the chapter. It offers an intermediate result to evaluate the potential of AM for the building envelope.

§ 3.1 Building envelope requirements

Since approximately 20,000 years human beings create housing for cultic as well as living purposes. In short, our built environment as we know it today has developed from those origins in small increments. Analogically, building technical details evolved – from questions that arose and solutions that the relevant craft permitted. Openings were built into structures as access routes, for lighting and ventilation, and for the desire of the user to create comfortable living quarters. They developed from simple openings to covered frame constructions to the actual window and, at the beginning of the 20th century, to the façade as a clearly separated component of the building.

[1] [2] [3]

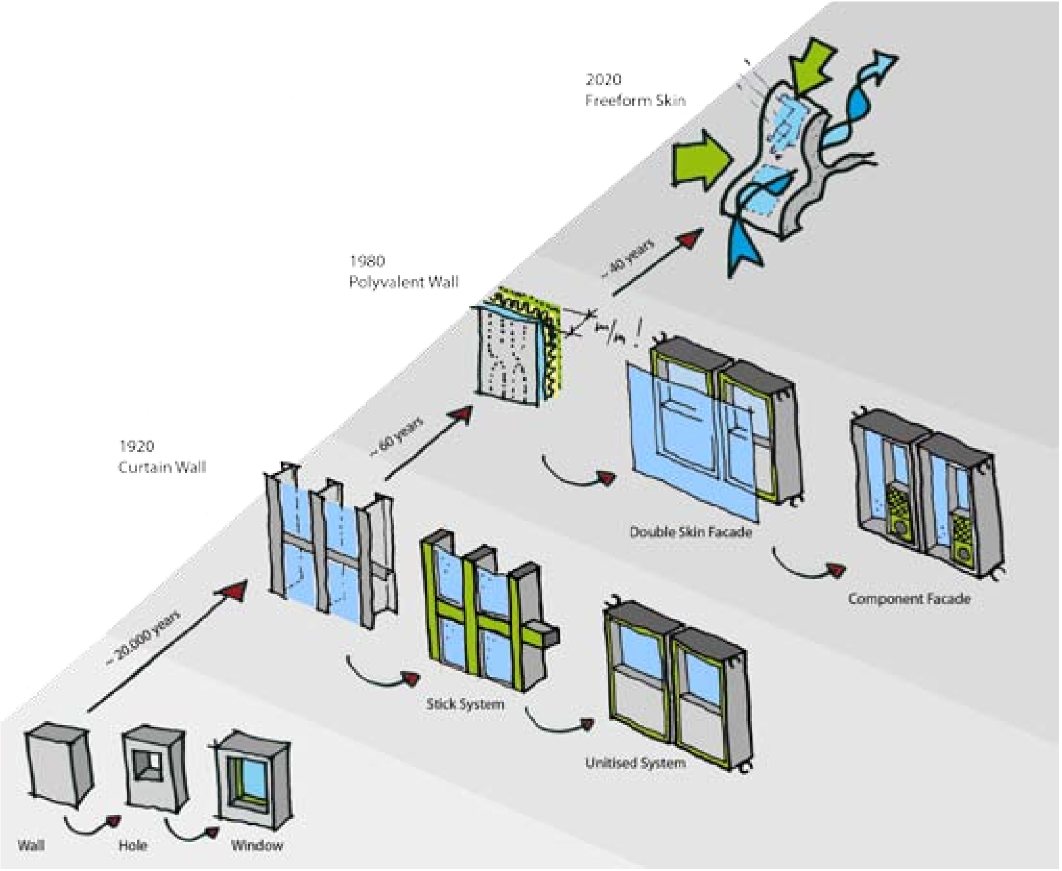

Figure 46
Façade development.

Developments always involved specialisation / fine-tuning: Simple drapes in front of wall openings evolved into operable windows; the curtain wall façade with single glazing casement windows evolved into the post-beam system, later element façades; the mere building enclosure turned into the vision of a building skin with all of the necessary functions that allow for a comfortable and energy efficient building, and as intermediate steps to a true skin the double façade, then the decentralised HVAC units and, still unsolved, the 'Polyvalent Wall' by Mike Davies.[1]

Each era had its own technological revolutions: Due to the development of the steam engine the handsaw evolved into a chainsaw, the smoothing plane into a planning machine – which made it possible to realise true to dimension parts and thus functional operable window sashes; the drawing board turned into a CAAD System (Computer Aided Architectural Design), which makes digital and networked planning possible – in the context of architectural design we also talk of the time 'before grasshopper' and the time 'after grasshopper' to manifest the massive changes in design that occurred since architects started programming (scripting); serial production turned into the parallel 'just-in-time' production that, through configuration, permits individual serial parts. And with this development came the desire to enable a seamless 'file-to-factory' process that allows to create manufactured structures from digital designs without interface losses on a 1:1 scale – and this is where we are today; new technologies push the boundaries of the feasible. With the aid of the production facilities available, digital designs can be realised up to approximately 90 per cent, accruing future technologies close the gap of the remaining approximately ten per cent, which includes Additive Manufacturing.

With AM technologies, functionally designed components can be realised that hold improved joints and material-optimised mechanisms. Of course, the initial goal is not to replace established and proven façade systems and to understand AM as the magic bullet with which our façades – and in a secondary step our buildings – are '3D printed' from now on out. Still, now is the time to begin improving upon the critical points and improvable details of façade constructions by employing the available new technologies – to which AM belongs. We will not be able to print entire profile geometries of a post-beam façade but the connection pieces for complicated joints of different roof pitches. With AM, such nodal points can be designed in different forms than hitherto known solutions, and allows for optimised solutions with fewer parts, less material and improved assembly; resulting in less labour. To directly 'print' entire façade structures with all functional connections can only be considered in a subsequent step.

It is essential to emphasise the importance of the building envelope as a neuralgic interface to the different requirements of the building [1]:

- climate;
- load transfer;
- comfort;
- technology and assembly;
- performance;
- appearance.

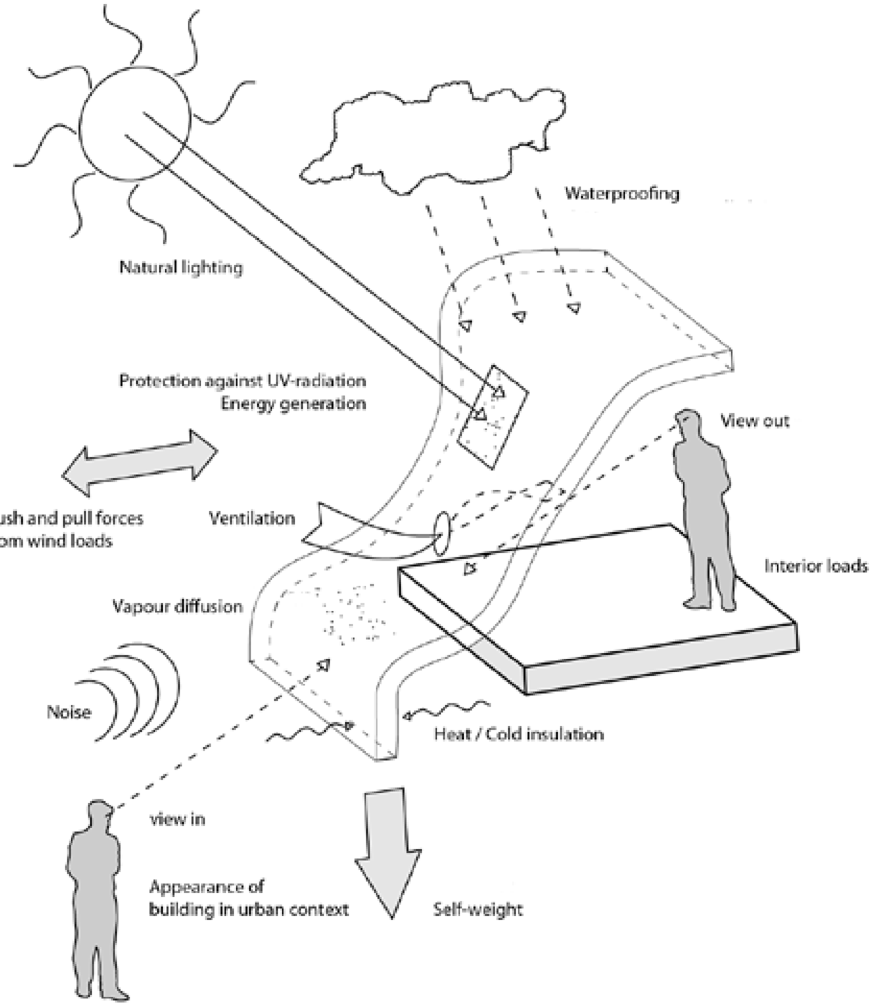

Figure 47
Façade functions

AM can improve the building envelope, and it can fulfil the demand for 'dynamic building envelopes'. The actual realisation of these improvements is closely linked to the developmental steps of the AM technology (see § 2.5). It depends on how intensely all participants discuss the potential of AM for the building envelope. The goals and visions specified pertain to all functional areas of the building envelope:

Optimisation of the room climate:

- by changing the geometry of the envelope depending on the 'load case sun';
- by integrating better building services (channelling, placement, more user-friendly control panels, amongst others);
- by reducing heat loss, i.e. optimising insulating properties;
- by improving passive energy management, i.e. energy gain, avoiding losses.

Optimisation of structural aspects:

- by reducing self-weight;
- by supporting a load adaptive load-bearing structure (wind, earthquake);
- by distributing material according to an optimised force path;
- by the reduction of self-weight in lightweight structures.

Comfort optimisation:

- with ergonomically designed components;
- by increasing the functional integration for the user (control panels, remote-free operation via voice control);
- with intuitive building services and automated activation (climate, system technology);
- with improved adaptation to individual circumstances, for example light directing, view, orientation of the openings;
- with a design-optimised appearance: 'true' representation of a free form (visual comfort);
- with a material-optimised appearance: Blob shapes are generated with Blob technologies, i.e. cast and injected rather than built as a post-beam system.

Façade technology:

- assembly optimisation with 'digital pre-fitting' and simulation;
- assembly optimisation with more detailed planning, i.e. improved because more detailed execution planning and early control in the file,
- assembly optimisation with functional connections;
- assembly optimisation by reducing the need for adjustment at the construction site, i.e. increased system security;
- assembly optimisation with integrated component identification (AM RFID, AM barcode, AM QR code).

§ 3.2 Research approaches

Individualisation, technology transfer, absolute freedom of form: These are the keywords that define the challenges as well as the charm of printed building envelopes. Which challenges in façade technology do we face in the new millennium? What demands will the user have on the future façade? If we are looking for an all-encompassing answer to these questions, AM alone certainly cannot provide the solution. But it can be part of it. This mind set, a curiosity about anything new, and possible technology transfers to other disciplines are the factors that generated the demand for an AM Envelope. How can we enter this new world while maintaining a practical orientation? How can we break up existing structures while remaining anchored in the planning task at hand? In this dissertation the path to answer these questions is based on product-oriented research. It shows the relevance of the topic in light of a commercial company. The result is connected to the restraints of the market and the demand for improvement – or even innovation. Completing the contract research must be followed by returning to be open for the more global aspects and broader horizons. Led by the goal not to actually print our buildings but to exploit AM to control the neuralgic interfaces and important areas of our buildings - technically secure and using the latest technology. Additive Manufacturing is one means to success – and a very fascinating one at that.

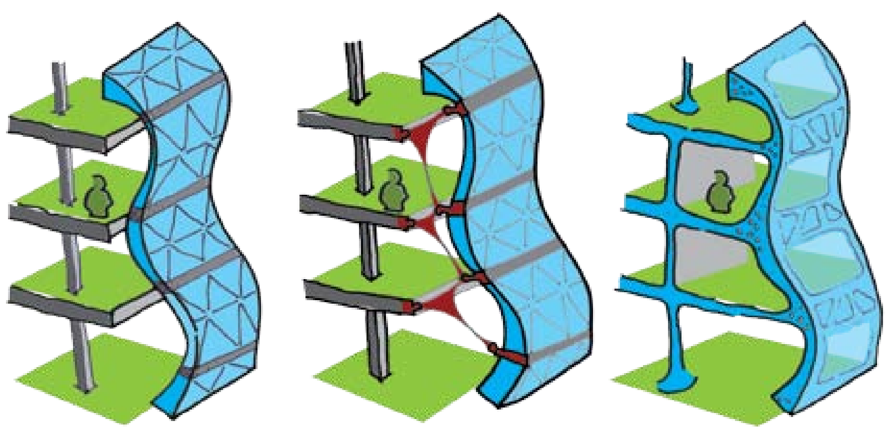

Figure 48
Consistent AM design

Considering the ever more creative designs for high-rise building projects, we must question the consistency of their realisation and the way the user interacts with them. At first glance, the most obvious applications for the new technologies derive from issues with known, advanced systems rather than from a fundamentally new approach to research their potential. This leads to the risk that developmental opportunities are not addressed because the drive for development originates in gridlocked, conventional structures. In order to assess innovations objectively, conventional opinions must be abandoned and the user must be conscious of the consequences of these innovations. If, according to contemporary taste, buildings are merely clad in a free-formed envelope (fig. 48, to the left), does a new technology improve the connections and details (fig. 48, in the middle), or can it even lead to a new understanding of the built environment as an integrally developed living environment (fig. 48, to the right)?

At the beginning of the research, different goals were defined as a starting point. These visions are linked to different levels of development of the current standard façade systems:

- semi-finished product level;
- component level;
- system level.

To limit the expectations, these categories were linked to time periods: applications that can be realised over the next one to five years with currently available technologies (semi-finished product level); results that seem realisable in a period of five to ten years (component level); and lastly applications that cannot be realised with the currently available technologies, expected in a time period of 25 to 30 years (system level). This chronologic categorisation makes it possible to create a direct link between today's production and the requirements of modified designs. What begins with a simple change in standard components will, according to the project participants, evolve into a holistic approach – to a 'printed' façade, and in a broader sense to a dynamic building envelope. Potential for optimisation and or modifications were identified by means of an analysis of the currently available façade components for a post-beam façade under consideration of the frequency of their application. The individual products were selected based on how often they are used, as well as against the background of production optimisation and, partially, in terms of their development history in the façade system (semi-finished product level). The ultimate objective of the work was a façade node (component level) that represents the state of the art in 2010 in the field of 'Direct Metal Fabrication' (DMF) – the application of additive methods to create metal parts.
The developments in the semi-finished products and component level highlight that AM has a strong effect on the development of new parts in building technology. It became apparent that actually designing such parts to a satisfactory level takes up significantly more time than expected. The component and system levels were examined by means of written out visions and first visualisations (see § 4.1).[4]

§ 3.3 Influence of AM on the development of façade constructions

The following describes optimised parts from the system portfolio of Kawneer-Alcoa (façade manufacturer) that were examined during the research project. All parts are evaluated in terms of their potential for optimisation, the result of the optimisation attempts and their ranking after completion of the research project.

The first approach was to examine connecting elements that are rarely used. The goal of the optimisation was based on the great potential for 'on-demand production'; which, with AM can be executed directly by the user. An integration of additive methods into the façade manufacturing production cycle could eliminate cost intensive stock keeping. Parts are produced for each order individually in the quantity required.

Various components from this part of the product portfolio were analysed and evaluated in terms of their potential when manufacturing, stock keeping, performance and ease of assembly are changed. This type of evaluation must include not only the component itself but the entire process chain.

§ 3.3.1 Corner cleats

Working on the semi-finished part level means to optimise the individual product. As a first case study, corner cleats for frames and window profiles from a current production series were examined. Typically, these components are used to stiffen profile corners as well as a connecting piece for gluing and grouting the profiles.

Figure 49
Principle application of corner cleats for window-frame mounting.

Figure 50
Corner cleat gluing, @ Kolf en Molijn, façade manufacturer, Netherlands

Due to the increasing number of different window profiles available, the corner cleats also differ slightly in thickness, leg length or boring. They are created from extruded aluminium profiles, produced with a matrix as yard goods and cut to the desired length in the workshop.
Each article must be available at all times; the increasing number of different systems offered by one supplier results in a large number of different parts that need to be in stock.

Figure 51
Corner cleat aluminium profiles; corner cleat cutting with circular saw, @ Kolf en Molijn, façade manufacturer, Netherlands

Figure 52
Storage boxes for the various types of corner cleats, @ Kolf en Molijn, façade manufacturer, Netherlands

Ordered quantities of the extruded profiles can be better quantified in kilometres than in metres. This in turn means that these kilometres of profiles are bound capital and inventory until possible future use, independent of the actual demand. This problem could be eliminated if single parts of rarely used product groups are manufactured just-in-time, made possible by the AM methods.
Due to their size, corner cleats could already be manufactured with AM today. The small dimensions make it possible that several parts could be produced simultaneously, which in turns points toward a possible integration into façade production.
Additionally, possible improvements on the parts can increase their performance. With the currently used method of production, the corner cleats are merely pushed into the frame profiles where they stabilise the corners with bolts or grouting. However, the main factor providing stability for the corners of the frame is the additional PU glue that needs to cure for up to seven hours. During this time, the frames are subject to twisting and shifting, i.e. they must be carefully stored during the entire curing period. If, on the other hand, a click connector was integrated into the corner cleat, a pre-tensioned connection with offset borings could be created that is self-clamping and torsion-free. In addition, a larger surface would allow for more effective gluing.

The following describes three different variants of corner cleats that were subject of this research project.

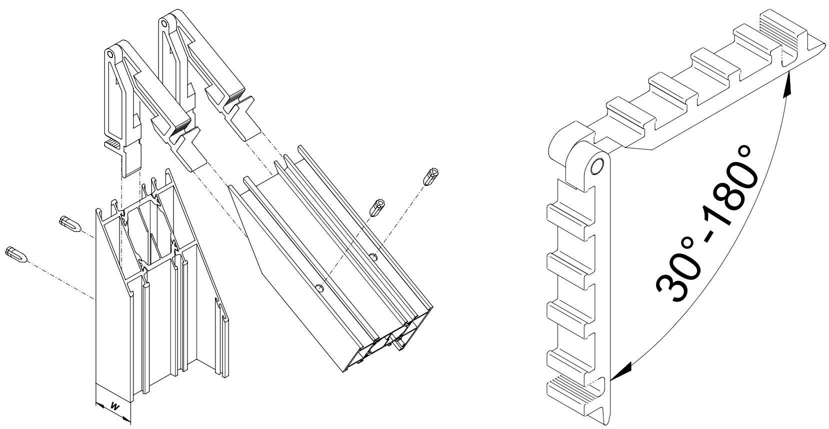

Figure 53
Corner cleats for non-orthogonal window frames; angle manually adjustable; Imagery and illustrations from Kawneer-Alcoa digital catalogue, Issue 10/2010

a. Potential for optimisation:

The part was used as a starting point. Optimisation potential is given by the fact that the angle (from 30° to 180°) has to be adjusted manually. A higher degree of stiffness of the corner connection could be achieved if the part was printed with 'digital' angles.

b. Result:

The angles of a window system could be digitalised and transferred to the necessary CAD files for production. The corner cleats could then be printed individually for one entire window or façade system, in the exact quantities needed for a particular project. The cleats would be more rigid and stiff due to the fact that the loose pivoting joint is eliminated.
Material savings are achieved by implementing a lightweight structure into the massive area of the cleat.

c. Ranking:

The idea was not further developed in the project. The results were clear and the potential for an immediate application obvious, supported by the feasible size of the parts. The application and realisation with DMF is possible, savings can be achieved because there is no more tied up capital for infrequently used products.

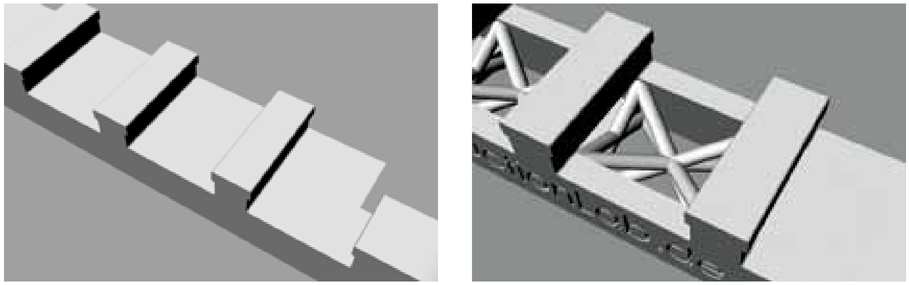

Figure 54
Rendering of 271.xx, detail; left: standard solution digitally drawn from e-catalogue; right: AM optimized solution; digitally reduced material and light weight structures. Digital branding on the side of the part: this could also be used for part identification.

§ 3.3.1.2 272.xx

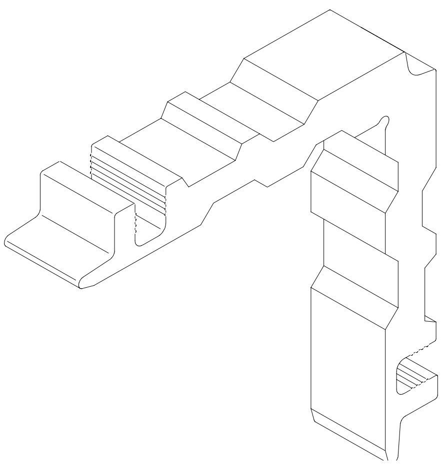

Figure 55
Drawing of standard corner cleat 272.xx from Alcoa e-catalogue.

Figure 56
Original aluminium corner cleat and a first prototype with integrated snap-on functions and leightweight structures (right).

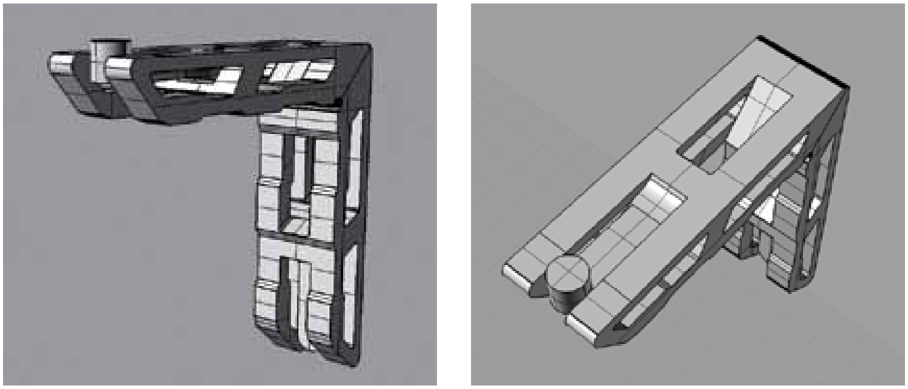

Figure 57

Rendering of part detail: 272.xx, AM optimized solution; digitally reduced material and snap-on features for additional fixation in the Aluminium profiles; digitally drawn from e-catalogue.

a. Potential for optimisation:

The second corner cleat was optimised in terms of advanced functionality. The frame corners are manually mounted in the workshop. The profiles are glued and fixed and need to rest after assembly before the corner can be subjected to stress. The optimisation is aimed at enlarging the surface for glue adhesion and the fixation of the corner by inventing snap-on fittings that eliminate the waiting period before the frame can be further processed.

b. Result:

The part was optimised in shape and function. The snap-on feature works well with plastics; it is not clear yet what modifications would be needed for DMF processes. The geometry of the part remained the same, but by enlarging the surface for adhesion, material savings were achieved.

c. Ranking:

A similar idea of screw-less corner cleats was invented in the 1970's and is protected by patents pending. Therefore this concept was not further pursued; however, it offers potential for future investigation.

§ 3.3.1.3 210.xx

a. Potential for optimisation:
The third approach for corner cleats was developed to test the functional implementation in a window frame. The original part differs slightly from the previously introduced part #272.xx. Two different kinds of cleats need to be used for the chosen system: One for the outside, another one for the inside of the frame. Again, the snap-on function was implemented; results and ranking are similar to #272.xx!

b. Result:
The part was optimised in shape and function. The snap-on feature works well with plastics; it is not clear yet what modifications would be needed for DMF processes. The geometry of the part remained the same, but by enlarging the surface for adhesion, material savings were achieved.

c. Ranking:
A similar idea of screw-less corner cleats was invented in the 1970's and is protected by patents pending. Therefore this concept was not further pursued; however, it offers potential for future investigation.

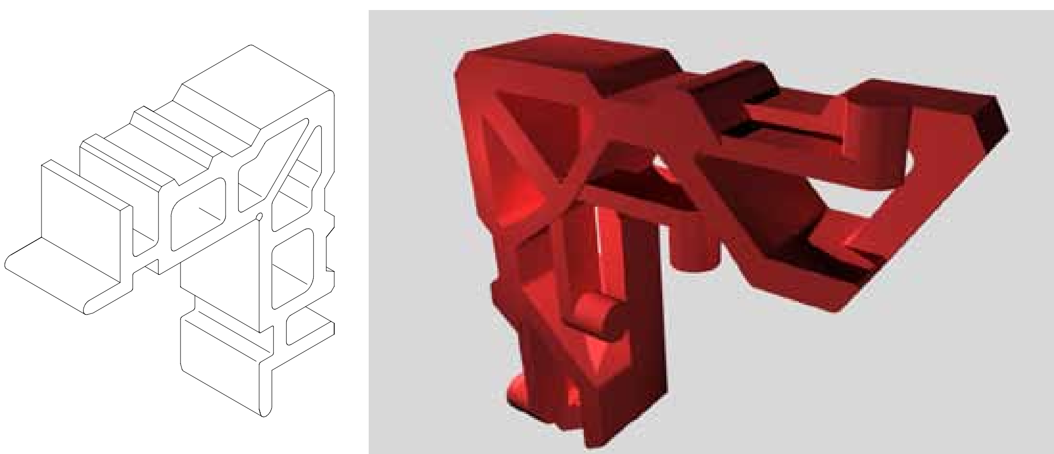

Figure 58
To the left: standard corner cleats made from aluminium profiles; to the right: AM corner cleats made from ABS plastic with the FDM technology.

Figure 59

To the left: standard corner cleats made from aluminium profiles; to the right: AM corner cleats made from ABS plastic with the FDM technology.

§ 3.3.2 T-Connector

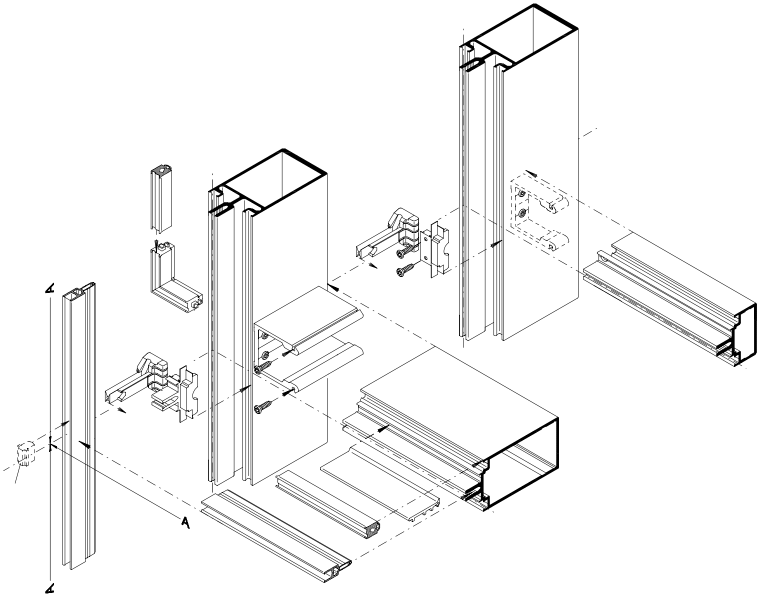

Figure 60

T-connector for orthogonal connection in AA-100 mullion and transom façade system by Alcoa; Imagery and illustrations from Kawneer-Alcoa digital catalogue, Issue 10/2010.

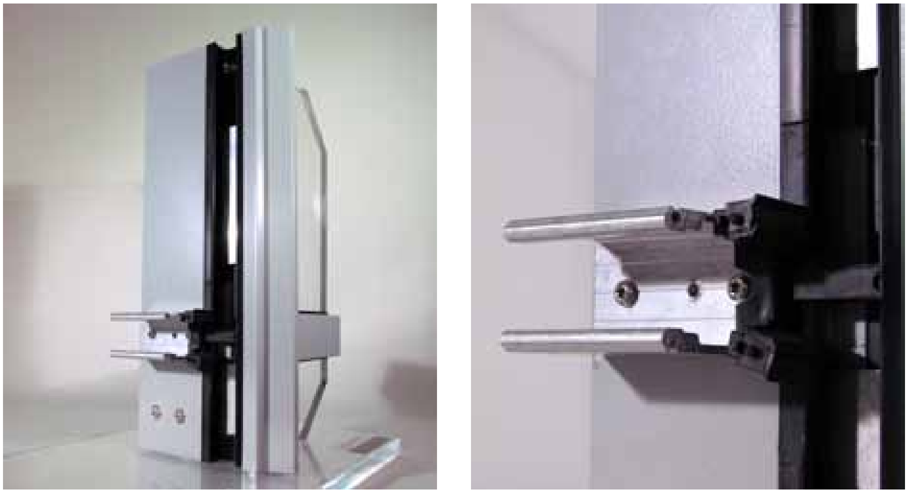

Figure 61
Standard T-connector mounted to AA-100 mock-up.

Based on the initial approach to examine the product group corner cleats, the focus of the project lay on a T-connector of the post-beam façade AA-100. Hereby the considerations not only included the benefits of prompt production but also the performance characteristics within the façade system.
The optimised component therefore is an improved 'digital' façade joint that, in combination with digital planning tools enables individualised façade geometries, and offers a structurally optimised system.

A 'digital' connector:
The availability of additive methods adds one more link to the chain of true 'file-to-factory' production. In an ideal scenario, the digital planning stage would be followed by a CAD-CAM production process; which would enable us to create parts for a free-form façade with all angles and adaptations of the same quality than those of an orthogonal solution with standard products. In this particular case, a connecting piece between post and beam would optimally transfer the loads via the beams into the pillars. Orthogonal façade or not - it would ensure a force-fitted connection of the components.

There is a standard connector for today's post-beam systems that also works for non-orthogonal façades. However, it does not fulfil all of the requirements of a post-beam connection, and, due to the limitation of the extruded sections, is limited in shape to a multiple of the same geometry defined by the used matrix.

Figure 62
To the left: standard free-form element, @ Kolf en Molijn, façade manufacturer, Netherlands;
to the right: standard free-form connector, @ Kolf en Molijn, façade manufacturer, Netherlands.

For the advanced AM part, all necessary angles and borings are digitally integrated into the design. Therefore perfectly fitting connections can be planned and manufactured for each nodal point of the façade. Additionally, added value is achieved through material savings and force path optimised shapes, even for such small parts. Assembly is done analogous to the orthogonal connection using the standard post-beam system components, all of which can be pre-manufactured with CNC milling equipment with exact angles.

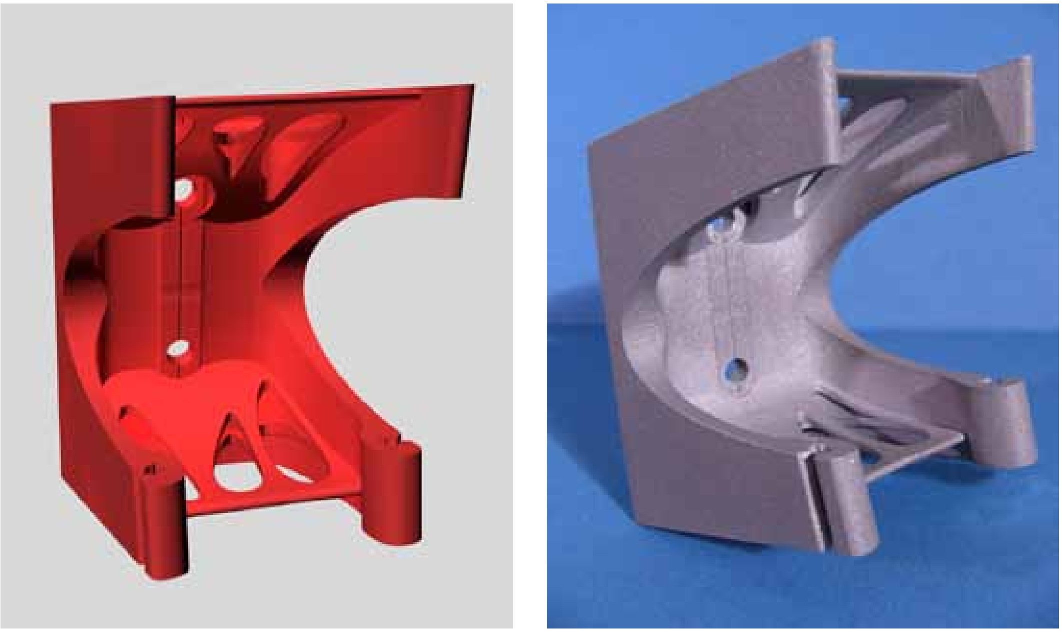

Figure 63
3D connector: rendering (left), printed part in stainless steel (right), realized on a DMLS system by EOS @ FKM Sintertechnik GmbH

Figure 64
Digital T-connector mounted to AA-100 mock-up.

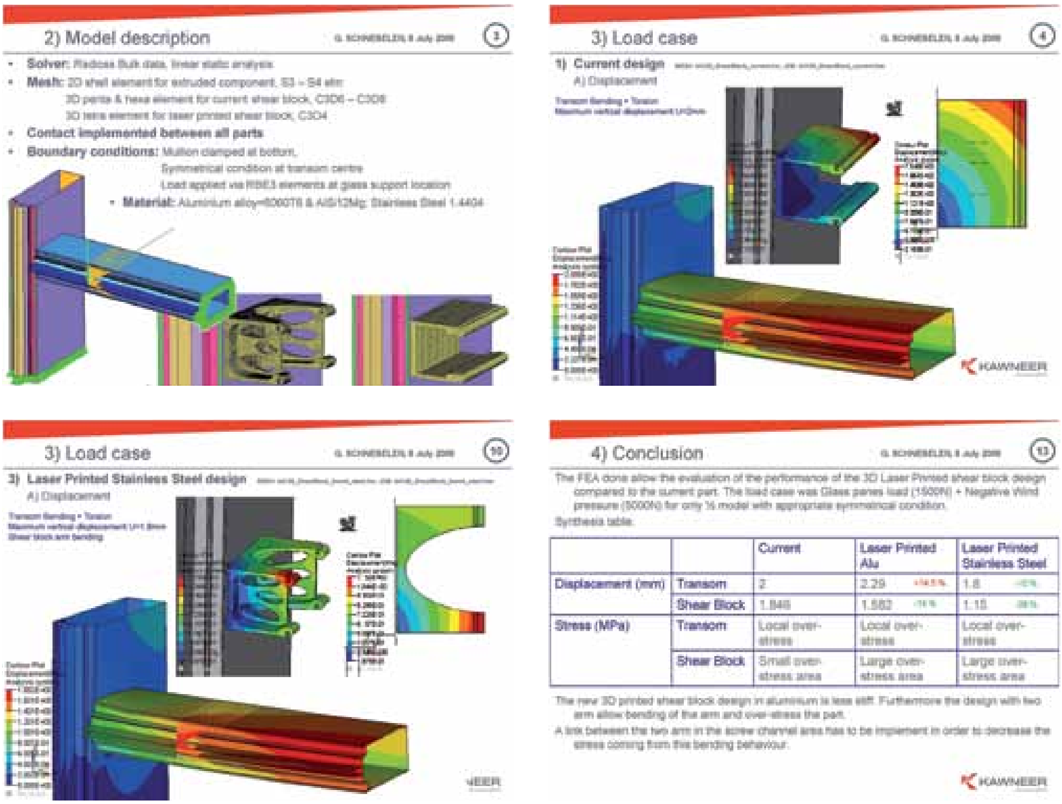

Figure 65

FE-analysis results; conducted by Kawneer-Alcoa during the project.

Figure 66

Evolution from Standard (left), to ABS Prototyp (middle), to 3D connector in Stainless Steel (right).

a. Potential for optimisation:

This part offers good potential for optimisation because it has different designs to fulfil the free-form task of the AA-100 system. The digital integration of angles and the possibility to save material and enhance performance show how the system benefits from AM improvement.

b. Result:

Material savings of 25 per cent were achieved compared to the orthogonal standard connector by digitally 'cutting off' the material where it was not needed.

The mounting system remained the same. Therefore all tools and accessories of the standard AA-100 system can be used.

c. Ranking:

The advanced connector is the first part of the project that was 'printed' in stainless steel. It shows the possibilities and the change in design and performance, even if it lacks further engineering. The potential for AM optimisation is more obvious with this component than with the corner cleats. Improvements in the performance characteristics for deformed façade geometries are easy to retrace. Therefore the connector is an important milestone in the development toward an AM Envelope; it can be seen as the first important intermediate result (for further details and technical drawings see appendix A I / Additional information on the research results).

However, initially the digital connector is only a very first suggestion on the way to a true AM connector. Therefore, during the project was tested in terms of its structural performance within a façade system.
The modified connector was digitally simulated and evaluated by means of a FE analyse. Due to the new requirements originating from the different, non-orthogonal component geometry, the simulation with currently available software could only be done for a slightly modified component. The FEA analysis on the following pages shows that a second optimisation run has to be conducted according to the results of the numeric simulation.

The results show that, if applied to the façade, the component would fail. The material savings at the component shoulder results in less stiffness in case of wind loads and tensile stress. In order to avoid such deformation, a cross-tie behind the screw hole would need to be added to enclose the shape, and thus be able to transfer occurring loads. Several optimisation runs would have to be conducted to achieve an operational component (see § 3.5). But a digital approximation of the component can be done anytime. The approach of the 'Bionic connector' was not continued during the project. The current state of development highlighted the most important issues, and was further examined as part of the following project goal: the combination of post and beam geometry in a nodal point.

§ 3.3.3 Nodal point

§ 3.3.3.1 Nematox I

The third approach was to realise a one-off solution for a deformed post-and-beam façade system. The result shows the development and realisation of a digitally planned and additively manufactured façade node – the Nematox.

Figure 67
Non orthogonal façade construction, resulting in a joining detail that is inadequately solved with silicone.

The idea to construct arched façades by using a hybrid construction method of standard sections and accessories with additive manufactured '3D façade nodes' came up as one intermediate result of the research at the University of Applied Sciences in Detmold. In order to avoid imprecise cuts caused by free-form angles, this approach resulted from the first optimised components described above. Sometimes free-form angles lead to undesirable leakages due to the complicated geometries that appear in the joints. Afterwards sealing is done by using wet silicone on the construction site.

To enhance such a free-form façade joint, all benefits of the previously developed 'digital connector' were further developed and combined into one integral nodal point. The resulting nodal point is, in terms of its dimensions, directly manufacturable with AM. All the needed angles can be digitally implemented in the dataset by software settings of parameters (parametric design). This digital design allows for the optimisation of different aspects: maximum length of transoms according to loads, minimum deformation in the joints according to glazing requirements, maximum needed number of joints according to near net shape geometry.

By digitally merging the post and beam profile, only rectangular saw cuts are necessary to assemble the façade. This reduces cutting scrap and facilitates assembly. In addition, the critical issue of water transfer from the beams to the channels of the post is defused and the system thus technically improved. Also, all accessory parts from the existing façade system can be used, even for a deformed façade.

Digital planning and generative fabrication allow for such solutions and facilitate the difficult situation in the workshops and on-site. While, until now, sections and cover strips had to be manually adapted to non-orthogonal angles, the new system uses only right-angled cuts – easy to accomplish for the contractors at both the workshop and the construction site. The façade can be pieced together easily, because the individual parts could be equipped with unique digital identifiers.

Due to ever increasing demands in terms of tightness and thermal transfer, the development of sections over the past years has led to increasingly complex node solutions. When eliminating the need to connect at node level and connecting parts outside of this 'critical zone' where all seals, water ducts and fixings come together, the potential for defects is greatly reduced. One result could be a system-fit execution of all seals without the need to cut non-orthogonal angles on-site and add wet silicone.

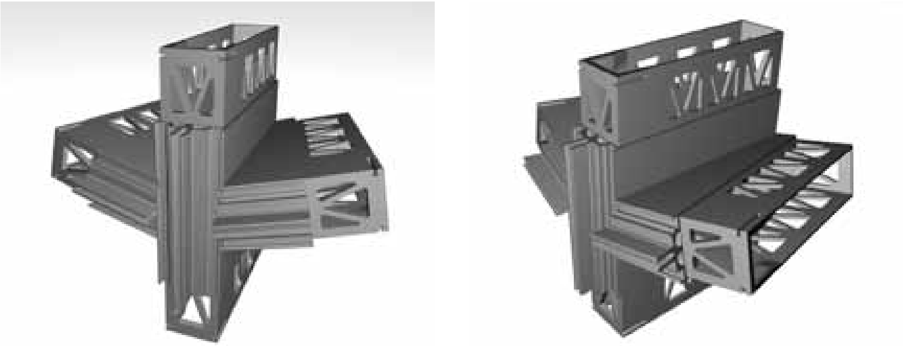

Figure 68
Rendering, NEMATOX I, 3D façade node for Alcoa 'Next' façade system.

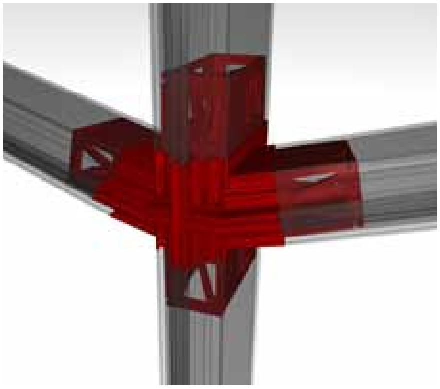
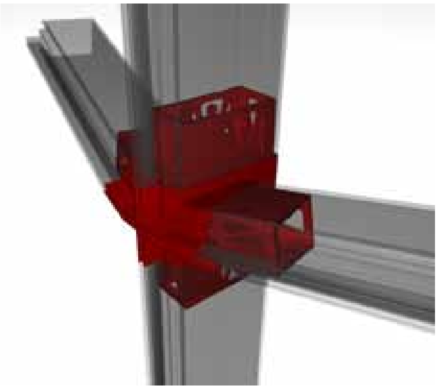

Figure 69
Principle of construction for façade node within a façade system; all angles can be digitally adjusted to the desired geometry and deformation.

With this approach a combination of applied standards and digital enhanced node solutions was realised for today's façade technology. By blending new 'high tech' parts into tested and verified systems, advantages from both can be combined to an even better solution. By only re-designing the critical points with AM, the needed hybrid system is invented.
A hybrid combination of the digitally catalogued parts together with smooth logistics (On-Demand-Production) could result in optimised time management.

§ 3.3.3.2 Nematox II

The Nematox Node is the first printed façade node for a 1:1 mock-up. It represents the state-of-the-art of AM in façade systems in 2010. Hybrid constructions from system components and individualised AM parts show a realistic path that could be followed as a first step.

To produce this type of node, it takes a lot of effort and understanding of both the engineering aspects of façade systems and the great range of CAD tools to sketch and script the node. For the two versions of the nodal point - Nematox I and, subsequently Nematox II – 120 hours of CAD engineering were needed to generate a print-proof *.stl-file: 60 hours were needed for the first attempt with all joints and dimensions to fit the standard aluminium profile. This was followed by the decision to reduce the costs for the prototype by changing the dimensions of the profiles to a smaller size. These changes took another 50 hours of CAD work. Ten hours of computation and translating were needed to finalise the *stl.-file, and another two hours to place the part in the virtual building chamber of the AM system software.

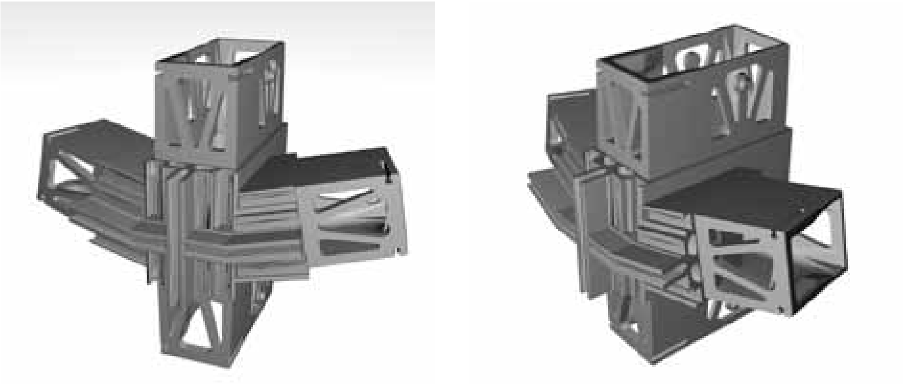

Figure 70
Rendering: NEMATOX II, 3D façade node for Alcoa 'AA-100' façade system.

Figure 71
Nematox II mounted to AA-100 mock-up.

Figure 72
Nematox II mounted to AA-100 mock-up; detailed view of the aluminium part.

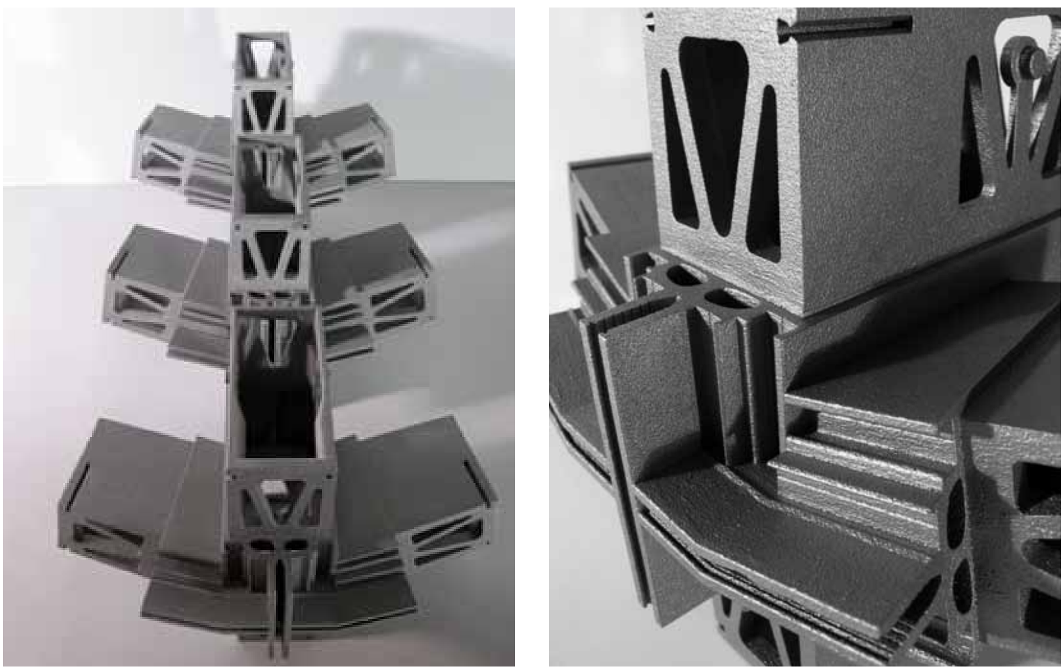

Figure 73
Printed nodal point in aluminium, realized on a ConceptLaser system by EOS @ FKM Sintertechnik GmbH

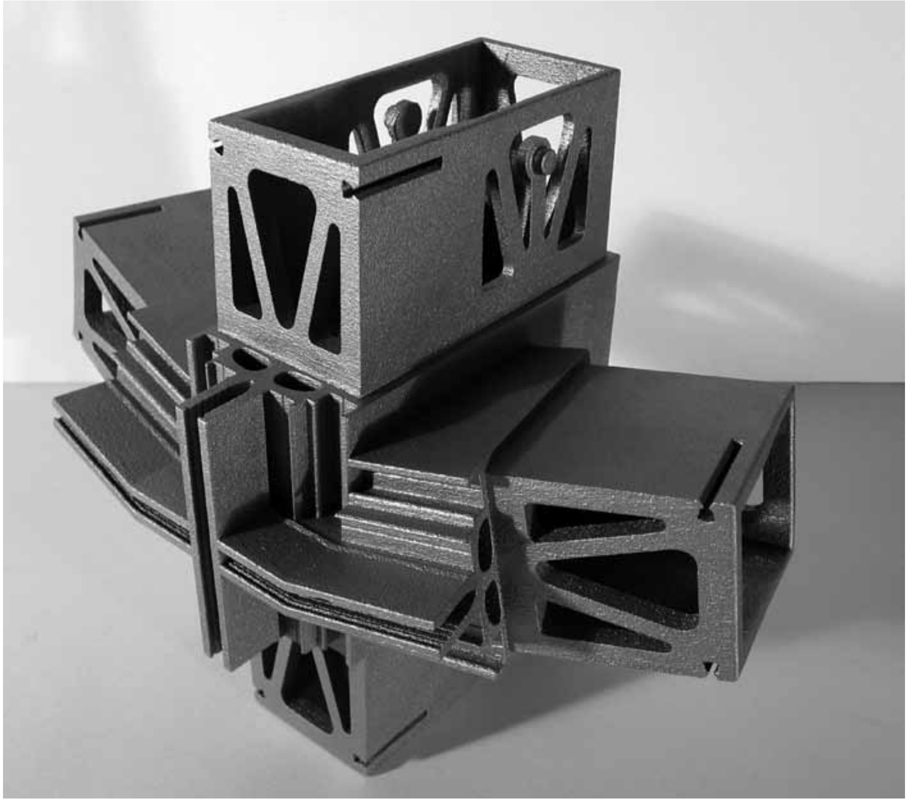

Figure 74
Printed nodal point in aluminium, realized on a ConceptLaser system by EOS @ FKM Sintertechnik GmbH

And finally, it took 76.5 hours of processing time to 'print' the nodal point in aluminium as a 1:1 prototype with LaserCusing (by ConceptLaser). Upon completion of the build job, the part was finished and post-processed in another four hours of labour.

The team that designs parts like this should be just as hybrid as the façade itself! The first idea emerged relatively quickly. After developing the t-cleat part, the next obvious step was to virtually merge the two connected profile geometries to get a nodal point with all needed connections. Even though this process sounds straight forward, a lot of thinking was required to determine all relevant objectives.

The first test-drive was very valuable for all aspects of the development, and opened up many new questions and fields of investigation.

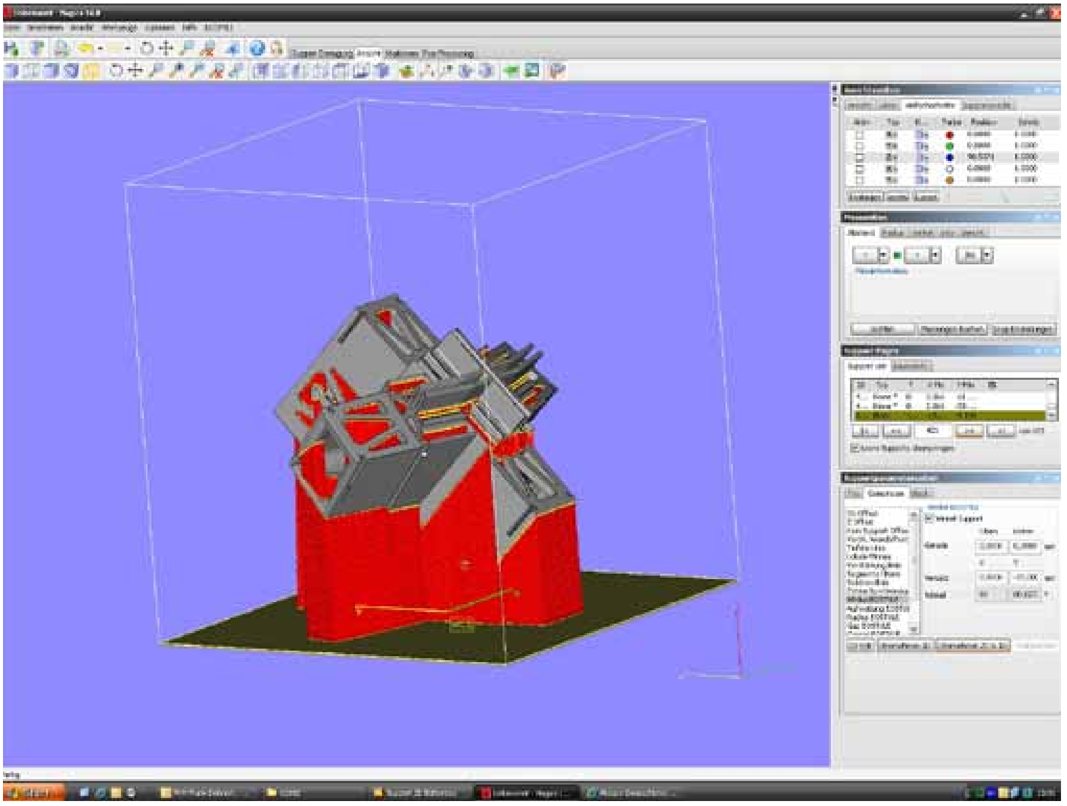

Figure 75

Build job preparation: screenshot of orientation of Nematox II within the DMLS building chamber representation; indicated in red is the needed support structure; @ FKM Sintertechnik GmbH

a. Potential for optimisation (both nodal points):

The intersection of a façade system is an area with high optimisation potential in itself. As all the different drainage, tightness and connection parts are joined in one neuralgic spot, enhancement can be achieved for all these performing aspects. This first attempt is one approach to an assembly-friendly system that combines standard solutions with one-off parts.

b. Result:

The nodal points show a way to realise free-formed façades with a standard façade system combined with parametrically planned components.

The optimisation potential stretches across different areas of façade manufacturing and assembly:

- reduction of cutting scraps by avoiding long mitre cuts; the angular deformation of the façade is solved with the nodes, the connections are realised with 90° cuts;
- 90° cuts also reduce the risk of inaccuracies during cutting at the construction site;

- the realisation of accurate joins is improved, and the use of later deposited permanently elastic sealing materials is reduced;
- a combination of several components in one nodal point minimises the number of work steps and therefore assembly time and reduces the risk of using wrong parts;
- a high degree of prefabrication can take place in the safe work environment of the workshop, which in turn reduces inaccuracies and other production risks on-site;
- regional manufacturing of the nodal points reduces otherwise necessary transportation expenditures.

Double curvature glass planes will be the result of digitally planning two different angles at the nodal points. For manufacturing, this is another challenge of the building envelope; however, in the context of solving the nodal points for the load-bearing structure, this issue is mentioned here, but not solved. In the case of glazing such a façade, digitally planned and load-optimised glass carriers could offer an advantage.

It was a conscious decision not to include articulating parts within the node geometries (adjustable connections or joints) in the development at this time. This is in connection with the already mentioned difficulties that the necessary supporting structures pose. Another reason not to add any further complexity to the node was the significant data volume, because the impact on generating the print file and processing the AM software program was unforeseeable. These functions should definitely be further investigated in a next step.

The Nematox nodes are worked out and engineered to a certain point; but the development should be continued to exhaust their full potential.

c. Ranking:
The task of a 'digital' façade node was fulfilled. The presented node is state-of-the-art in the field of AM production in 2010, with the support of a service provider instead of in-house technology. The presented node showed the boundaries of CAD engineering in the project. CAD engineers are needed for further evolution in collaboration with a façade planner.[4]

For further details and technical drawings see appendix A I / Additional information on the research results.

§ 3.4 Results from part optimization

Façade manufacturers offer several different window, door and façade systems. For many projects, these systems fulfil the needs and demands of architects and investors. But some projects require specific solutions with tailor-made products. Just-in-time production with AM could help establish a new balance between tailor-made solutions and system offerings.

In the research project presented here, the current limitations of the additive methods were consciously neglected to stay open minded to all possibilities. First concrete numbers for the production with additive methods must be generated using 'honest' calculations and by trying to quantify the constructive added value of improved parts. These numbers do not yet justify broad application, but they also do not negate it. Thus, generative methods have a development potential that reaches beyond a pure comparison of cost per unit. If assembly and manufacturing are optimised, the basis for the calculation changes substantially. And, with an on-going change in the markets, the flexibility of production as well as the reduction of the self-limitation to certain established manufacturing methods should be considered.

It was proven during the research that the large number of parts used for existing façade systems offers great potential to apply AM for the production or evolution of those parts. The findings can be subsumed as follows:

- generally, the parts are small and therefore meet the maximum size of current process chambers;
- the material used is mainly aluminium and can be realised with existing DMF processes;
- production batches can be planned in advance;
- with the existing CAD-CAM process, AM can be integrated into the production;
- most parts already exist in the digital catalogue of the manufacturer, which can be used as database for part optimisation;
- new functions and features can be incorporated into the parts using the design potential of AM, leading to better performance;
- further thought has to be put into the future design of and with AM. A design guideline (see § 3.6) is needed for each specified AM system that is implemented into the production chain.

It is foreseeable that with the growing knowledge of the possibilities of Additive Manufacturing its use in architecture and building construction will increase. Collaboration is essential when developing reliable solutions for future envelopes (and incorporated future façade systems) that will satisfy both the supplier and the architect/customer. As of today, AM solutions are not yet feasible for façades in a broader sense; however, it is crucial to begin to develop visions so that we can adopt

them as soon as possible. Everyone becoming aware of the fascinating possibilities that AM offers feels the potential they bear for future applications.
The availability of AM technologies might make it possible that individualised parts can be digitally designed and adapted in the near future. The façade industry in particular can benefit from the fast developments of 'Direct Metal Fabrication'; advanced parts are then 'printed' as a service to clients or as an enhancement of the façade suppliers' production. The potential of AM almost demands that each façade node is designed individually, thus furthering the idea of true free-form architecture. The presented results are only the first steps of implementing additive methods into the building industry. Further examination of the possibilities will offer even more options that will change our built environment.
First, we should try to identify possible applications between low-priced and established mass production and individualised 'one-off's'. We must find strategies for a sensible application of these technologies for different industrial areas; mere availability does not justify their use in all cases. On the way to every-day production with additive methods, perspectives must be identified for a step by step introduction of the technologies into the various markets. Research projects and ongoing examination of the possibilities are the first step; and future market demand will contribute to solving existing technical challenges.

It is important to change the technologies along with the development of new applications (see § 2.5). In spite of today's limitations, additive methods offer great potential to fundamentally change façade technology. The first optimised parts and conceptual ideas (see § 4.1) show that AM applications promise added value compared to traditional building methods, and that they can be conceived and planned even without the technologies being available to the full extend, yet.

§ 3.4.1 Potential for façade application

When considering future applications of AM in the façade industry, metals will prove to be interesting materials due to their well-known properties.

However, when seeking to employ direct fabrication of metal parts one has to be aware that DMF methods have not yet reached the same developmental stage as the methods for manufacturing plastic products (see § 2.2.3), and lead to a more complex technology.

Considering the possibility of substituting metal-only solutions by introducing high-end plastics into complex façade details is a crucial strategy if following the 'AM path'.

For the façade node described above, this would directly lead to the further development of Nematox II. To reach the next level, testing on a larger scale is required (1:1 scale). A life-size mock-up could be used to check the real effect of AM parts inside a mounted façade system with its multitude of dependencies. This would offer the opportunity to verify all necessary joints and connections. A next step would then be a real façade project, where the different levels of AM opportunities could be tested under real conditions (storage, manufacturing, integration into production, just-in-time management, logistics, fit and assembly, performance during long-term testing). Such a project would ultimately prove the feasibility of AM for façades - or not. It would also allow a more detailed look into a possible file-to-factory process for façade systems. And finally, all results could be combined into the requested AM design guideline (see § 3.6).

§ 3.5 Requirements for optimizing standard parts with AM

To encompass the findings of the research, a catalogue of requirements shows the key aspects for optimisation with AM in a condensed way.
The catalogue is divided into three parts: from the perspective as a façade system provider or façade installer (the future producer with AM), from the perspective as an AM user (engineer, designer or architect) and related to the parts themselves. At first glance the last aspect might not seem conclusive, but it is important to clearly phrase the requirements posed on the parts themselves. AM is only practical if the manufactured part reflects the technology applied to make it: it does not make sense to use AM to print rectangular massive blocks but rather to create AM optimised representations of the desired function!

Façade system provider / façade builder:

- it only makes sense for a system provider to become an AM producer if the high initial investment will pay back;
- one proper façade project might be sufficient to pay back the initial investment (AM system);
- it does not make sense to compare mass produced mounting accessories to printed parts – the price will always be a killer argument against an honest calculation;
- keeping the technology in-house gives the system provider a unique position in the field of façade system providers;
- specialised one-off solutions can be realised with a wide range of contractors/customers;
- expertise can be concentrated in one place;
- limitations and potentials of the AM system will be explored exclusively by the applying engineers.

AM user:

- ‘plug-and-play’ is a must: the use of AM should be as easy as using a tablet computer;
- the decision has to be made whether CAD engineering is done in-house or by an external service provider;
- the design of parts has to follow an AM design guideline to keep the costs as low as possible and achieve maximum extra value from the application of AM;
- better understanding of the process leads to better parts;
- combining different CAD systems to a holistic approach - numeric analysis, FEM, thermal simulation, load bearing optimisation;
- highly specialised expertise is needed to meet the complex requirements of façade systems;
- by following these rules the user immerses him or herself deep enough into the new way of designing to make it everyday business.

AM parts:

- material savings are crucial;
- design for AM is crucial - surface orientation, incorporated supports, minimum height;
- free-form is limited by the process – the method of production limits the practicality of certain shapes;
- smart use of support structures is crucial - for example ‘Selective Space Structures’, software to generate filigree lightweight structures and to integrate them into the production process with AM (to design parts that do not rely on supports, but are self-supporting);
- if required, incorporate support into the design to avoid material waste and issues with (surface) finishing during post-processing;
- extra value from better/new performance – requires further exploration and will bring change for many aspects of the existing systems;
- scripting and automation of complex façade systems has to be accomplished - BIM, parametrical design, adopting ‘mother’ files;
- the surface of the end-part is the only limitation – everything else can be reinterpreted.
- Standard parts can be optimised for different aspects:
  - number of parts sold during the year vs. min. number of produced parts – stock keeping;
  - standard parts vs. extra value – more strength, specific shapes with higher performance, better performance with less material;
  - extra value vs. production related limitations - for example transom with non-orthogonal solutions;
  - assembly process vs. time – optimise assembly by combining parts to fewer single parts;
  - manual labour vs. smart parts - for example implementation of snap-on features into fittings.

§ 3.6 The need for an AM guideline

The research results presented here highlight the necessity of a user guideline. Such a user guideline must include different aspects of applying AM in a production chain, and must enable different perspectives on a production with AM. On one hand this means a technical manual, but on the other it must also be a design aid for improved AM parts.

An AM guideline should cover the following topics:

- how to judge the AM process for a particular part/production;
- how to decide for a particular AM process;
- how to start a design development;
- how to respect the needs of other specialists in the process;
- how to design a 'mother file';
- how to implement the necessities of a prototyping idea into a 'AM proof file';
- how to optimise a *.STL or *.STEP file for AM production.

The structuring of such a guideline arises from the particular processing phase of the manufacturing process: In the case of the façade node Nematox II, it should be divided into the steps **'system check'** and **'production check'** which are further described in the following. The findings resulting from such systematic work can be used to develop **'design guidelines'**. Such a guideline must be developed for each of the AM technologies in order to exploit the full potential of each manufacturing method.

§ 3.6.1 System check

System check in this respect means: choosing an appropriate AM system, fitting the AM part into the façade system.

Considering the Nematox II as the starting point, adaptations in terms of engineering must be carried out to use the node in a façade system. The prototype is the result of an initial development, and has not undergone an optimisation cycle. Initial optimisation can be done directly in the CAD file:

- numerical analysis (FEA) for the performance within the façade system, related to dead loads, wind loads, heat transmission, etc;
- additional material savings with regards to the load performance;
- shape optimisation for accessory fitting;
- virtual fit-and-assembly tests.

The next step is to carry out a dedicated finite element analysis for the node that, over several runs, changes the geometry and therefore the CAD file. Hereby, the profile geometry of the connecting standard profiles as well as the angles selected for the façade form are the only parameters that are fixed. Wind loads, dead load as well as thermal and hygric properties can already be virtually tested.
Ideally, the CAD file is parameterised accordingly, i.e. the boundary conditions for setting the parameters are specified in accordance to the standard parts but are also influenced by the performance aspects (loads, span width, angle of deformation, a. o.). In a cycle of optimisation, the changes in the CAD file, the FE analysis and the boundary conditions result in an adaptation of or approximation to the optimum structure and shape of the part in the CAD file, according to the required performance. Such structural adaptation leads to modified material distribution, formation of compression and tension zones as well as stress-less areas that are merely influenced by the specified surface geometries.

After the file has been optimised, the most appropriate AM technology for the part in question must be selected: due to the great variety in systems, an intensive market research should be conducted for a first assessment. Certain demands on the desired properties of the product further limit the choice. In all cases, it is important to research alternative manufacturing methods as well to identify the best possible method for the task. Hereby the main criterion is the part geometry. When selecting production processes, there is always the possibility to achieve a better result when combining AM with other manufacturing methods, than by using AM alone.

If elements or components need to be adapted to an existing system, their suitability for the system must be evaluated. How high is the degree of specialisation of the desired component and the system used? Can all system-dependent accessories be used? Does the application of AM lead to further changes in the components or system elements?

If the development is based on an existing prototype, a realistic assessment must be done after this initial process, and preparations must be made for further optimisation. In this regard it is very important to select the proper inter- or multi-disciplinary team of participants. The following specialists/consultants are needed for a satisfactory optimisation:

- CAD experts;
- FEA experts;
- parametric designer;
- structural consultants;
- AM system providers;
- material producers;
- AM service providers;
- providers of alternative processes (for example fine casting);
- façade system providers.

A thorough examination and discussion of this approach to product development can aid in establishing the necessary processes.

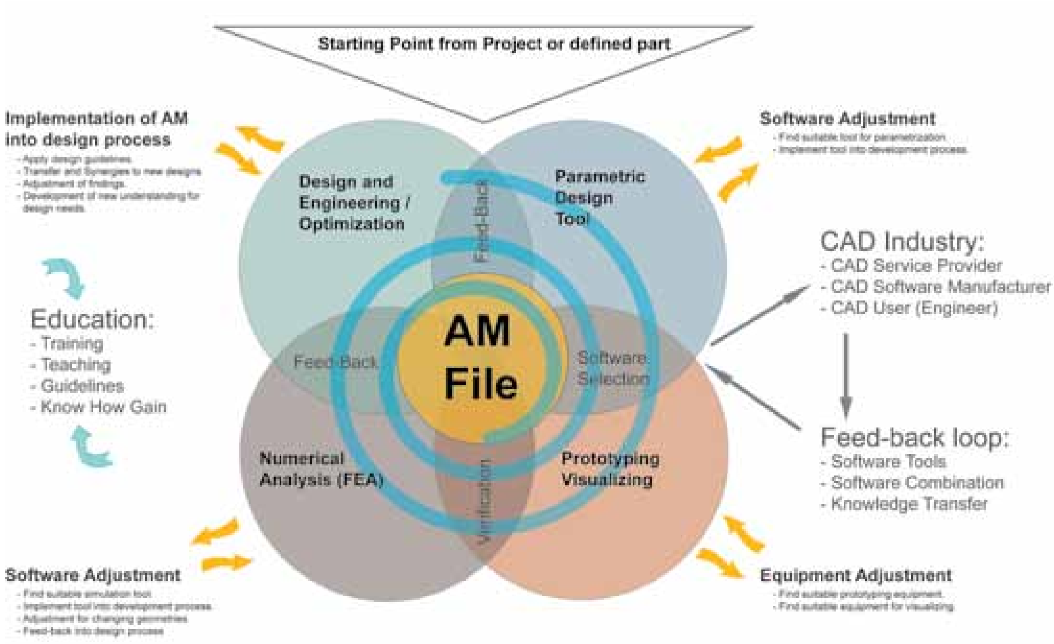

Figure 76
Representation of file optimisation in several cycles

§ 3.6.2 Production check

Production check in this respect means: fitting the new AM parts into the production of façade producers, optimising the AM file for the production of the part.

The shape and appearance must be checked if an AM part is to be integrated into an existing system (design check). If the part file is modified after initial optimisation, the geometry of the part might also change. In this case, the design and function of the part must be discussed and possibly readapted by means of physical prototypes and simulation (system fitting). Geometric changes might result in changes to the fitting of accessories. This highlights the multilayered interdependencies between the changes and results from optimisation runs. The graphics below show a simplified representation.

The following optimisations steps would run for further development of the Nematox façade node:

- generate new *.stl file for the production of Nematox III;
- first prototype of Nematox III (FDM, STL);
- reassessment of desired performance;
- review with technician concerning the fitting of necessary accessories;
- re-discuss the prototype;
- conclusion of first and second optimisation;
- generate final 'mother file';
- identify a suitable method to produce AM parts;
- decision on material, process, shapes;
- adjust AM parts after first assembly accordingly.

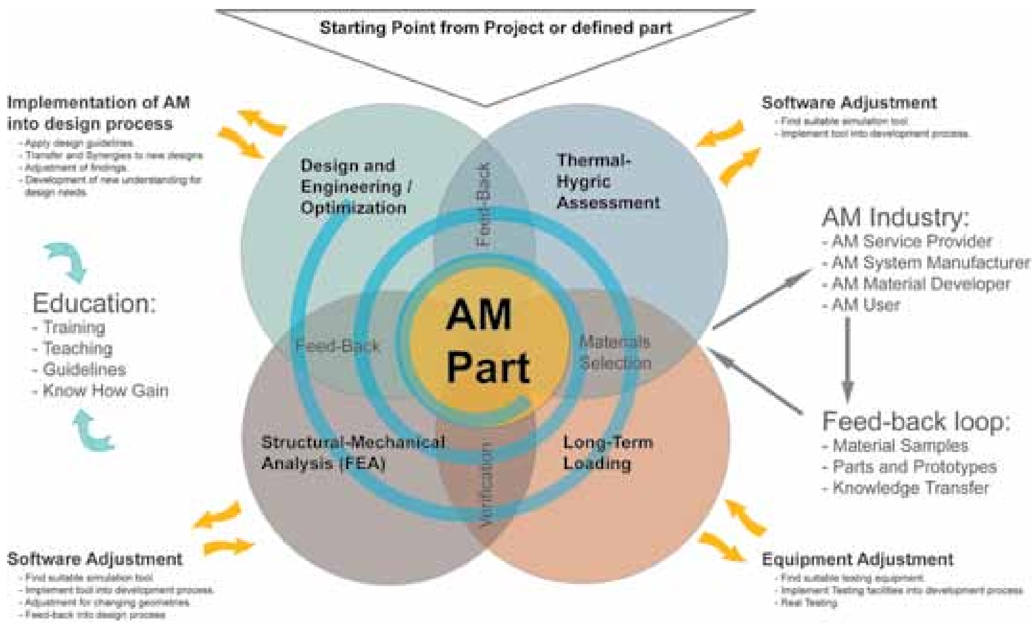

Figure 77
Representation of AM part optimisation in several cycles

§ 3.6.3 Design rules

The objective for a design guideline must be to establish target-group specific, universally accepted statements that support the user in the decision making process in the different areas of functional constructing. The dependencies between the participating disciplines must be clearly visible to enable seamless decision making.

Hereby, the different interests of all of the parties involved must be considered: those of the AM system operator as well as those of the user who wants to generate ready-to-print files, as well as those of the customer who wants to use AM as a service provided to him.

§ 3.6.3.1 Optimization aspects

Considering the necessary progress of optimisation, there are also different points of view that need to be taken into account: **'engineering aspects'**, **'design aspects'**, **'system aspects'**.

Similar to the different levels of a component or file optimisation, different criteria will influence the resulting optimisation. Hereby it is important to weigh the aspects against each other and to select the appropriate method for the particular product / project.

The decisive factor of this new manner of designing is the complexity of the areas touched upon and the expertise involved. The difficulty will be to name one primarily responsible "master builder"[5] who consolidates the decisions and bears the final responsibility (see [5]).

If the different aspects are optimised together, they will have to be weighted, which will lead to the favour of one and disfavour of another. The decision making is complex since a great number of different parameters and criteria can be specified for each aspect. Consideration of all aspects during optimisation requires the designer, engineer or architect to have expert knowledge in all areas involved, or at least the ability to properly communicate all occurring problems and necessary decisions.

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5 Citation: Branko Kolarevic, „... as the opportunity for architects to reclaim the lost ground and once again become fully engaged in the act of building (as information master-builders)." in Reference [5] Kolarevic, B., Architecture in the digital age: Design and Manufacturing. 2003, New York: Spoon Press. Page 27.

Possible engineering aspects:
- minimal wall thicknesses;
- maximum possible component size;
- orientation within the process chamber; accordingly, the changes in surface quality and the resulting process speed;
- strategy 'hatch – offset – contour', weighing component density, material use, geometric accuracy and process speed;
- reduction of notch stress by sensibly rounding out notches.

Possible design aspects:
- form and appearance of filling elements in a grid system (glass fillings: straight surfaces, single curvature surfaces, double curvature surfaces);
- joint design and arrangement;
- appearance of the component in the system (accentuated, exposed, subsidiary, integrated);
- surface design (quality, structure, materiality);
- formative integration of structures and geometries.

Possible system aspects:
- determining the reference lines;
- optimising cutting scraps for standard components;
- further development of sealing layers and arrangement;
- integrating the technologies into development and production;
- adjusting the connection points and joints in iterative steps.

The main objective of the guideline must be to simplify information. The user as well as the engineer must find the necessary information to successfully apply AM to their specific application.

Recommendations about the cost for the use of AM technologies cannot be provided in such a guideline because they are subject of strong fluctuation and change.
The question whether AM is used as a service or an in-house process is another fundamental process decision that influences the cost calculation.

Just as components and data sets can only be optimised with several optimisation cycles, the guidelines must also be fine-tuned and adapted.

Figure 78

Representation of the optimisation aspects and related areas

§ 3.7 Summary chapter three

The presented components and parts show one side of the range of results that the project brought up. One of the most important results is the fact that the project does not conclude the research, but rather opens up an array of questions and new starting points for further development and future approaches toward the use of AM in building envelopes, building construction, and architecture in general.

So all of the limitations mentioned here do not represent the end of this development but offer the chance to conduct targeted research in those areas on the basis of the knowledge gained here. The involved project partners did not only gain knowledge about the currently available technologies in AM; the questions that arose would not have been identified without this first approach.

New input from AM but also strong hints about the limitations of the DMF processes regarding our current standards in façade systems became apparent during the project. To make use of the opportunities that AM generally offers, and that originally led to this project (free-form, lightweight, material savings, integrated functions …), make current strategies and ways of thinking obsolete and lead to a radical reinterpretation of the existing systems, parts, details and designs of building envelopes.

"Historically, architects drew what they could build, and built what they could draw […]. The straight lines and circular arcs drawn on paper using straightedge and compass have been translated into the materials made by the extrusion and rolling machinery. This reciprocity between the means of representation and production has not disappeared entirely in the digital age. In the realm of representation, the modeling software based on NURBS has infinitely expanded what could be 'drawn', while the digital fabrication technologies have substantially expanded what could be manufactured and built. As a result, the geometric complexity of buildings has increased dramatically over the past decade."[6]

The results of this research activity can be categorised as follows: the advantages of AM (generally, status 2012), the disadvantages of DMF (generally, status 2012), the effect of AM in component design, and the effect on digital design with AM.

1. The advantages of AM:
   - freedom of shape and form;
   - lightweight constructions;
   - force following shapes;
   - material only where it is needed;
   - manufacturing on demand;
   - no tooling-related limitations during production.

2. The disadvantage of DMF:
   - expensive if purchased from service providers;
   - costly as investment;
   - time consuming with current production speeds;
   - support for overhangs and undercuts as well as heat control are required;
   - any shape with an incline of less than 45° needs to be supported;
   - different orientation in the process chamber leads to different surface qualities. (This means a limitation in taking advantage of AM as stated above!)

3 Effect on current design:

- it might be quicker not to enhance existing façade solutions for AM, but to start engineering from scratch;
- parts and fittings of façade systems need to be reinterpreted against the background of the given limitations of DMF (if DMF is the chosen manufacturing method);
- example: support structures required for the DMF process need to be integrated into the structural design of façade parts (turn a disadvantage into an advantage; support structure turned into a lightweight internal structure of a DMF part;
- current 'design for production' has to be specialised to 'design for DMF';
- a 'design guideline for AM in façades' has to be developed.

4 Effect on advanced parts:

- only the geometrical 'outside' (surface) of the part must be specified, everything else is open for reinterpretation;
- all components other than the surface (see aspect above) will be executed according to the 'Design for AM' code;
- things will change!

This chapter described possible first steps for an integration of additive fabrication into production, and introduced and assessed results of an application in a façade system. Aspects are listed that are important results of the project: they open up additional questions that can be used to pursue this research beyond the scope of this work. In terms of façade technology, results were found in the individual components. And a first building stone was developed for a complex façade construction. At this point is becomes apparent that an optimisation of existing components alone will not allow us to fully exploit the potential of the new technologies. New development originating from the functions of a part leads to freer results, but it also requires a radically new method of thinking by the developer.

The necessity of a design guideline for additive methods was discussed; content and structuring were introduced. The facets of an intensive discussion about the manifold aspects of a consistent application of AM were formulated and evaluated.

This part of the research work made it possible to observe the influences and effects of the application of AM technologies on the production of system components. Information to better assess the AM technologies as they relate to an AM Envelope were gathered, and the results help in evaluating the potential of additive methods.

References chapter 3

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[5] Kolarevic, B., Architecture in the digital age: Design and Manufacturing. 2003, New York: Spoon Press.

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4 Use and application of AM in façade technology

This chapter formulates the open questions concerning a continuation of the research results. Defined suggestions for an application in different areas of the façade are given and evaluated. The end of the chapter describes the steps necessary to continue the efforts to further the application of additive fabrication in the façade technology.

- Which developments of the AM technologies for façades are conceivable?
- Which façade applications can result from these developments?
- What effect can an integration of high-tech technologies have on building technology?

§ 4.1 Technological developments in the (near) future

Additive Manufacturing, as a consequence of its definition, describes the production of ready-to-use products. But since the AM technologies available today cannot yet deliver this capability economically and technologically, concept ideas based on the status quo were developed. Therefore, from the point of view of the current state of knowledge the results of this research project must be seen as 'true' Rapid Prototyping approaches, even if Rapid Prototyping describes only a part of the generative methods. They are insufficient for a long-term prognosis of the potential of the technologies. Ultimately, all considerations lead to a 'functional building construction' and the development of 'dynamic building envelopes'.

These thoughts about the future of AM for the building envelope round off the discussion: The development of AM is an evolution running in upward spirals that, based on similar approaches, will lead to a new level of realisation. The developed prototypes pioneer this evolution, even if they do not represent today's manufacturing reality. All of the components shown are prototypes that can only be elevated to the next level of realisation after they have been tested in a real façade project. Only after such real object testing can the prototype evolve into a product for (individualised) mass production.

For façade technology – and consequently for architecture in general – this evolution can be executed in individual steps:

Step 1:
An AM façade detail that can be realised with currently available AM technologies. Combined with established façade products, this AM façade detail features advantages in terms of production, assembly and/or construction.
The planning process is similar to that of conventional manufacturing: AM parts are optimised on the basis of existing products and are manufactured on demand. Only one tool is added to the manufacturing process; it is one additional link in the production chain of the façade supplier, the façade builder or the AM service supplier. The final product 'façade' is the same as those created with conventional methods; the potential for optimisation is on the part of the manufacturer, not the user.
Hereby, AM is a possible enhancement of the production.

Step 2:
A modular part that complements conventional façade technologies. The functional added value lies in the combination of conventional façade systems with individually fabricated AM parts. The size of the parts depends on further development of AM systems (see § 2.5.1).

Compared to conventional manufacturing, the planning process is enhanced: the classic approach depends on adapting the design to the tools and products available. The solution is an approximation to the initial design, and is therefore always a compromise.
Therefore, AM extends the process: realisation is only partially based on available system components; certain areas of the task are reinterpreted considering the possibilities of AM and are solved based on the desired functionality. This means that the planning and execution part of the process chain needs to be extended to encompass AM. For execution planning, this is a significant step because AM does not only change the performance properties of the façade but also influences the production process itself. The product 'façade' distinguishes itself from traditional solutions with newly won freedom of form and performance. The user benefits from advantages related to the realisation possibilities of the design ideas, and technically improved solutions resulting from the CAD-CAM process.
AM is a possible solution approach from the series of digital tools available.

Step 3:
The AM Envelope that migrates from design to building construction in one step
There will not be any AM systems for these concepts in the near future. However, contemplating such encompassing AM applications stimulates the continuation of the AM development.

Compared to conventional manufacturing, the classic planning process is abandoned: To realise an AM Envelope, we no longer need the system solutions currently available but a combination of all available products enhanced by AM. The planning process is based on the desired performance of the building envelope. It materialises the necessary parts by exploiting all available production tools. This change requires a hybrid planning team that develops the optimum process chain for the design together with the façade builder.

By coupling the possibilities of the AM technology with the requirements of the building envelope, the implementation of AM into the production process can be estimated. The development of semi-finished goods consisting of small parts to a dynamic building envelope becomes comprehensible.

[1] [2]

To illustrate the potential of AM for the building envelope, the following lists the expected changes of the development steps over the next 30 years.

Within the next five years: ...

... AM will change existing component details. The technology will be integrated into the production of distinguished architectural projects. It will bring the façade one step further toward an AM Envelope.

The development of the applications over the coming years is clearly foreseeable: In principle, all necessary technologies are available. If not certain metals, then high performance plastics will be used as building materials in building technology. Components will improve because engineers will examine the potentials of the technology in greater detail. Initially, AM parts will be integrated as parts of existing systems – improved joints, integrated components, combined functionality. AM is available as a production method – AM is reality.

The AM services that, over the past ten years – have been established to produce everyday items – fabbing (see § 2.2.2) – can be conceived for other areas as well. If a company cannot afford the initial investment for an AM system, special purpose associations can be formed to reduce the cost for the individual partner. Similar to the development in the craft trade following the introduction of CNC machining centres (for example CNC trimming and joining systems for carpentry). Following market adjustment, the use of CNC technologies is now common practise; we no longer ponder its practicality. Likewise, an increasing number of service providers will spread the matter of course of the use of AM.[3] [4] [5]

In five to ten years: …

… AM will have found its way into the workshops of façade builders due to improved system technology. An intuitive approach to the technology will lead to numerous uses as a natural part of the production process.

Considering the rapid development since their invention in the Eighties, it is to be expected that subsequent development and consequently application will take place just as rapidly. Dealing with 3D data comes more naturally, and therefore the understanding of the method and quality of the necessary data related to the different manufacturing technologies and the design. In ten years, the discussion about data formats, quality assurance and further development of AM applications will have reached a level that will annihilate today's concerns about the integration of the technology. Good economic prognoses as well as a noticeable shift in the AM market point toward increasing strength of the AM industry. And lastly through mergers of the big players from the different AM segments to effective corporations that consolidate the entire bandwidth of AM technologies under one roof (for example the announced merger of Stratasys and Objet in the beginning of 2012). Such pooling – and thus monopolisation – will influence the technological evolution as well: larger corporations require greater revenue, i.e. 'real' production throughput and revenue in number of systems. This in turn demands opening up new markets. It can be expected that building technology will be recognised as one such market.

But new markets also mean new requirements: for example technical limitations in terms of system size and process speed need to be overcome. In the coming years, current attempts to establish norms and quality management will lead to a consolidation of the trust in the performance of AM products. And therefore even the conservative building industry will discover the technologies – with current participants becoming early adopters.[6]

In twenty five to thirty years: …

… the manufacturers of large (façade) components will use Additive Fabrication with various materials for combinable hybrid processes, to produce dynamic building envelopes and the according primary structures. 'Fluid Design' will turn into a natural 'Cross-Over Design', analogous to the required functions.

System technology will further develop toward hybrid manufacturing. The combination of different disciplines is as important as the combination of different manufacturing methods. The process of choice will depend on the product, not on the availability of particular means of production. Production will be democratised; everybody will be a producer, the monopoly of mass products will be replaced by a conscious choice of individualised (and therefore intensively planned) products. In the building sector the borders between interior and exterior space will have shifted. The dynamic building envelope will fulfil far more functions than expected, which opens up new options for design and use of interior spaces. The design of our built environment will be partially parameterised; production will be based on practical automation. It is no longer relevant whether individual spaces are designed according to the Blob or Bauhaus style – there will be suitable manufacturing methods for both approaches. The implicitness of the functionality of the generated components will have changed: Energy efficiency, sustainability and functionality are fundamental parameters of fulfilling individual needs; only the choice of the production means and the diversity of design options will have increased.

Following efforts to question the necessity of the designer, a societal consensus was formed that design is no longer a random product of independent algorithms but rather an expression of targeted considerations.
The same considerations were verified by trying to generate buildings with purely automated manufacturing methods – in addition to 'Information Master Builders', today (2040) there also are 'Digital Craftsmen' who comprehend their work as a virtual and analogous craft.

§ 4.2 Principles for AM Envelopes

Concept ideas were worked out into 'principles' to illustrate the above described development of AM for façade construction. Some of these are closely related to an AM Envelope, some not so close; but they all illustrate new approaches for further development with the new technology. Therefore, all principles were subjected to an AM ranking which differentiates between and evaluates six parameters of the idea potential:

- the time frame of a possible realisation (yesterday – tomorrow);
- a differentiation between different part sizes (micro – macro);
- the probability of realisation (Yes, we can! – can we?);
- an allocation of the part category in façade construction (detail – system);
- the type of application (interior – façade);
- the type of execution (craftsmanship – High-Tech).

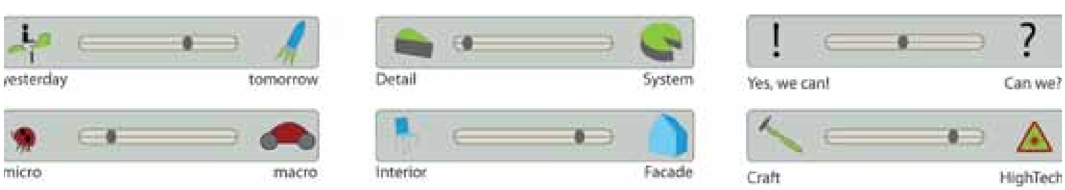


Figure 79
Evaluation schematic for AM envelope principles.

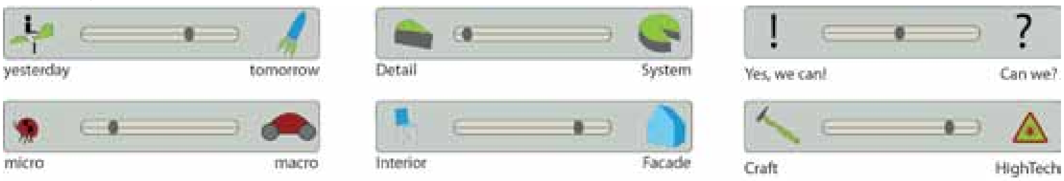
The evaluation facilitates a comparison of the ideas and offers a distinct assessment of whether the ideas are suited for AM or not.
The principles are categorised as follows: Façade applications (§ 4.2.1), the new work material glass (§ 4.2.2) and targeted AM developments (§ 4.2.3).

§ 4.2.1 Façade application

Energy Cavity

Imagined by: Holger Strauß

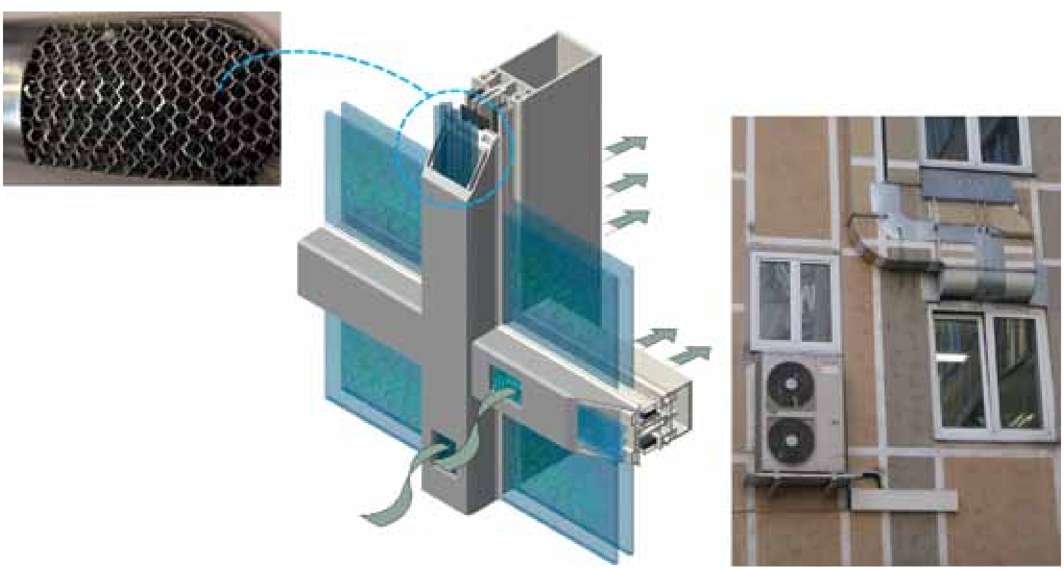
AM ranking



Description

Here, an AM product substitutes the standard cover caps and parts of the extruded façade profiles in glazed facades. A high-tech part with integrated heat exchanger offers energy gains within an existing part of the building – the post-and-beam façade. The advanced cover caps and profiles can be used for refurbishment projects or for partial upgrades during refurbishment. They can also be deployed as part of a green energy concept for up-to-date buildings.
An energy generation component is implemented into the - so far unused - cavities within structural profiles in both cover caps and post and beams. If the profiles are used for air-conditioning, no additional AC units need to be mounted on the façade, eliminating these unsightly devices.
All required ducts and pipes are printed onto the inner walls of the profiles. Additional optimisation, such as pollen filters can also be integrated.

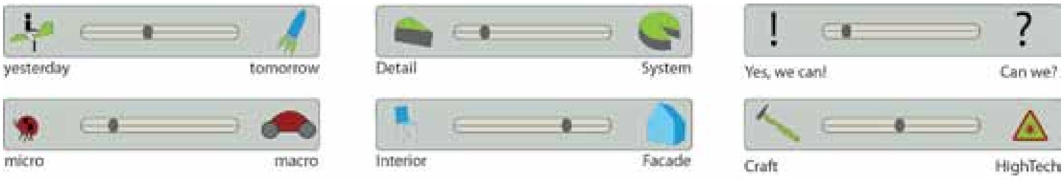
The principle of a heat exchanger is used to gain heat or cold by exchanging energy between different surfaces. The efficiency depends on the amount of surface area created. Standard heat exchangers can be created by mounting thin plates together, similar to the radiator in a car. Extrusion methods can generate large surface areas which in turn are used to transfer the heat to the surrounding air. By using 3D printing technologies, huge additional surface areas of any shape or size could be produced to exchange heat or cold. The method can also be applied to gain sun energy and/or to easily create heating and cooling devices.



Solar Kinetic Bi-Metal Façade

Imagined by: Daan Rietbergen, Holger Strauß

AM ranking



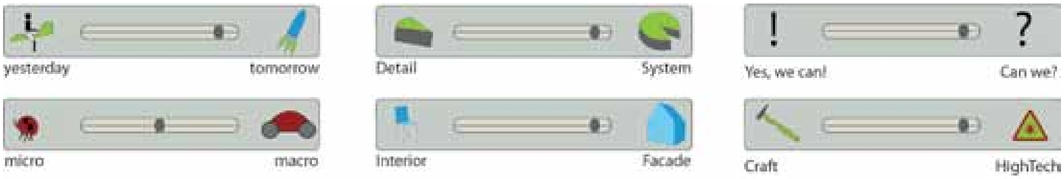
Description

Functionally Gradaed Materials (FGM) made from two metals can be used to produce parts that deform at precisely predictable rates. An accurately calculated mixture of two different metals is implemented into one single part using CAD. Changing temperatures control the behaviour of the bimetal parts, thus making the façade change accordingly. There is a broad range of possible designs: inspired by shingles, slate cladding, fish scales and many more, smaller or bigger parts of the façade could be heat-adaptive. Application in the façade could be used for shading, ventilation or as visors.

Wind Adaptive Façade

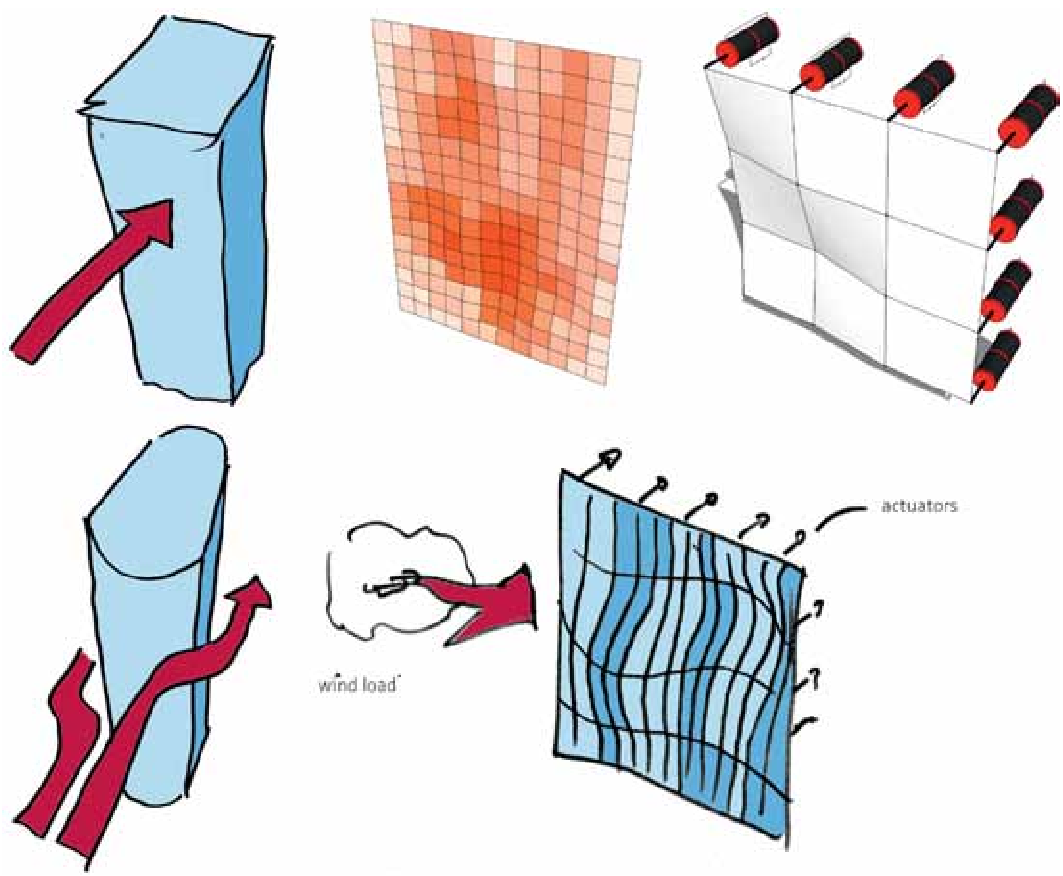
Imagined by: Ulrich Knaack, Phillip Meise, Marcel Bilow, Holger Strauß

AM ranking



Description

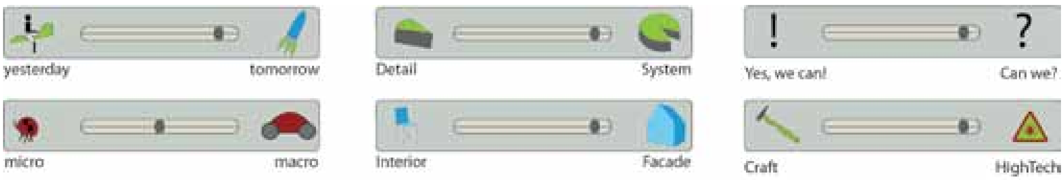
This idea features integrated piezo spring point holders inside the façade construction. When wind loads act on the façade, these piezo springs generate energy via piezo ceramics. The energy can be used for building services such as shading, ventilating etc. In addition, integrated actuators let the façade respond to varying wind loads: With moderate wind speeds, it generates energy, with heavy wind speeds it self-adjusts to minimise wind resistance by optimising its shape. This prevents major damage and deformation, especially in high-rise buildings that are often subjected to heavy wind loads.



Fully integral Façade

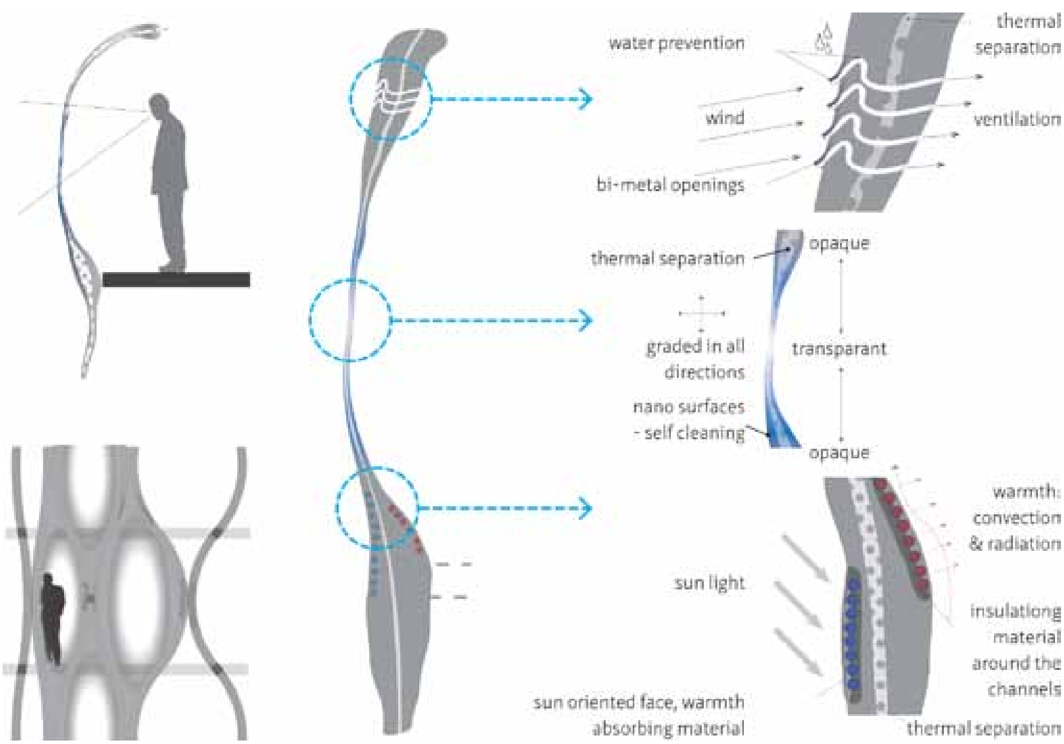
Imagined by: Nathan Volkers

AM ranking



Description

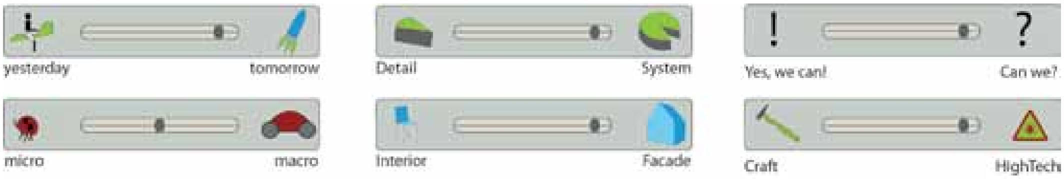
In this conceptual vision, the façade is made of a printed multi-material gradient structure that fulfils all functions in one continuous façade layer. Principally, this façade could seamlessly evolve into a fully integral building. The 'Fully Integral Façade' (FiF) vision uses the benefits of 'graded materials' and 'free-form design' related to Additive Manufacturing. It covers most aspects of façade design, although 'free-form' and 'function integration' are the most important criteria. The FiF fully benefits from 3D CAD software with finite element methods built into it. Engineers design these façades with parametric models that can be fully optimised in terms of structure and functionality. For example, structurally the façade can 'mimic' nature's solutions for structural optimisation such as bone structures. In terms of functional optimisation, gradient materials could be used that function as a hinge to open parts of the façade. Thus, one material provides both stiffness and flexibility. The FiF is the result of a complex mathematical 3D model that determines where structural strength and other functions should be positioned. Mastering complex 3D modelling becomes a required skill to design façades or buildings. The future fully integrated façade might be a complex formula, for which the context and the user requirements define the parameters.



Sphere within Sphere

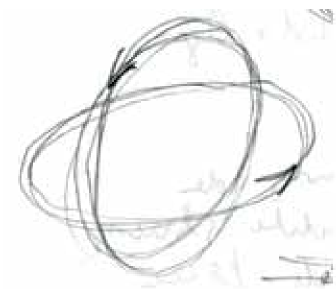
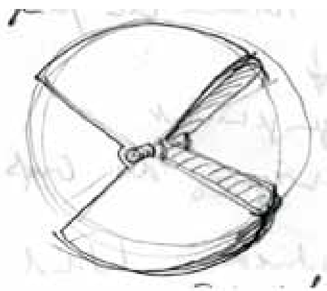
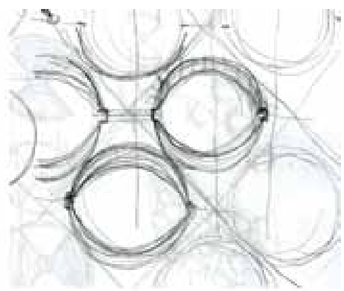
Imagined by: Holger Strauß

AM ranking

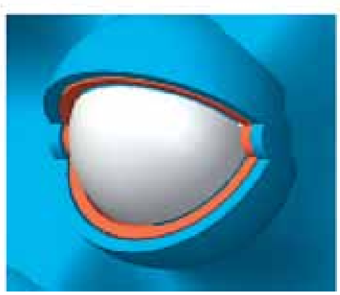
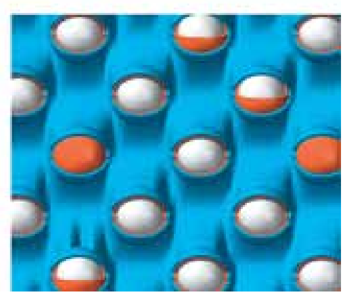


Description

Derived from the Chinese 'sphere within sphere' idea of turned wooden spheres, this sketch elaborates the concept into a functionally integrated façade system. Scaling the modules provides extra freedom in creating applications with this feature – designed in CAD, the size of the printed module is irrelevant; reaching from micro to macro.
Features integrated within the spheres could be pollen filters, phase change materials to store energy/warmth, insulating materials, shading; a layer of printed photovoltaic foil could even generate electricity… Layering functions is a benefit for multifunctional façades.

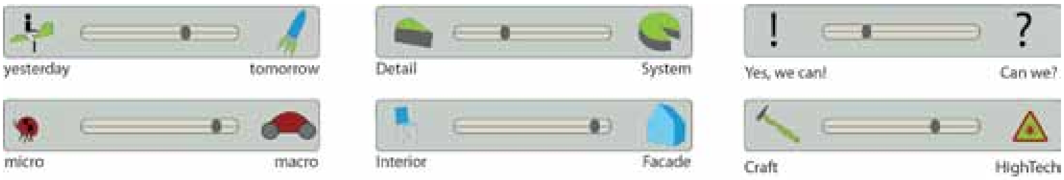


Mono Material Recycling Element

Imagined by: Holger Strauß

AM ranking



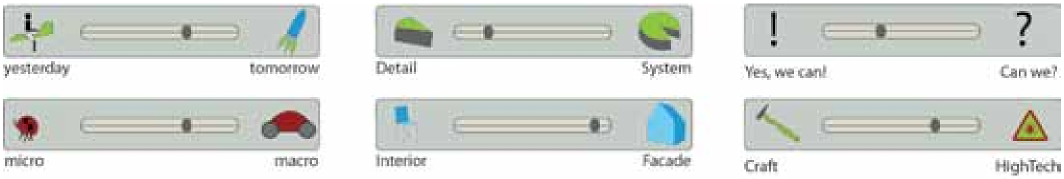
Description

Houses can be constructed from a mono-material, e.g. aluminium. Depending on the processing method, the material can exhibit a great variety of material properties: foam, lightweight structures, solid, free-form. A house printed from a mono-material can be fully recycled because only one material was used. Aluminium can be shredded and reprocessed as Rapid Manufacturing material. Different ways of joining different parts on the surface will need post processing, such as welding, grinding, polishing, but this results in a smooth watertight surface with no gaps.

Active Insulation

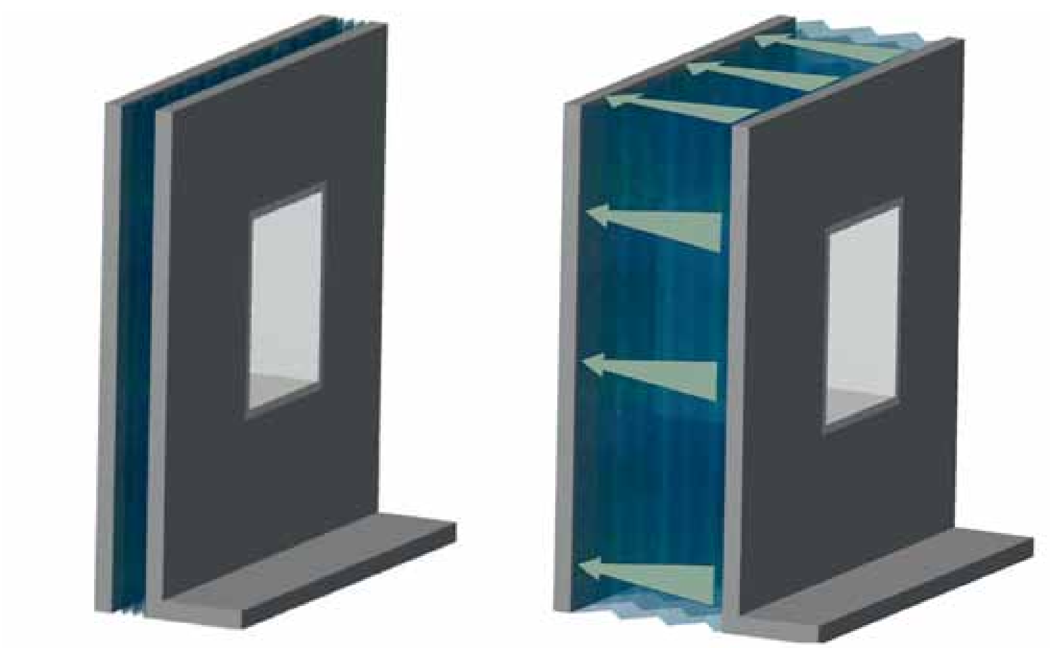
Imagined by: Ulrich Knaack, Holger Strauß

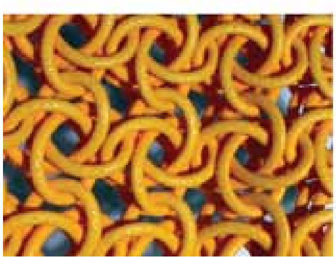
AM ranking

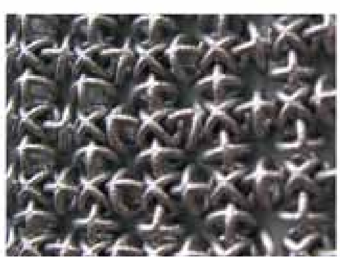


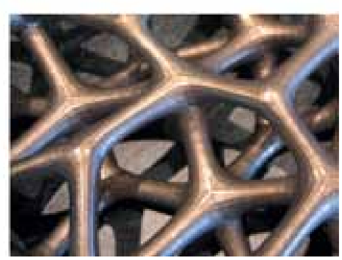
Description

The goal of this concept is to provide our houses with the necessary insulation at the exact time when insulation is needed. Similar to birds that fluff up their feathers to create an insulating layer against the cold, building structures could extend in wintertime to achieve better insulation. Printed micro-structures could be used to fulfil this goal.





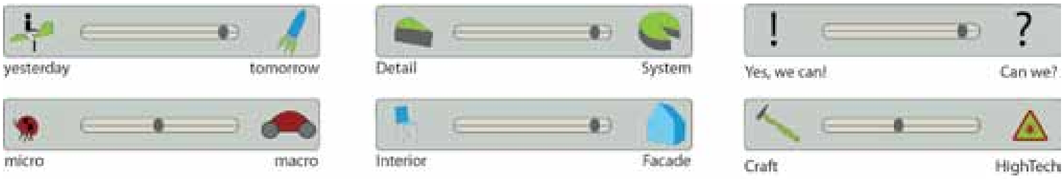




Tissue Engineering Skin

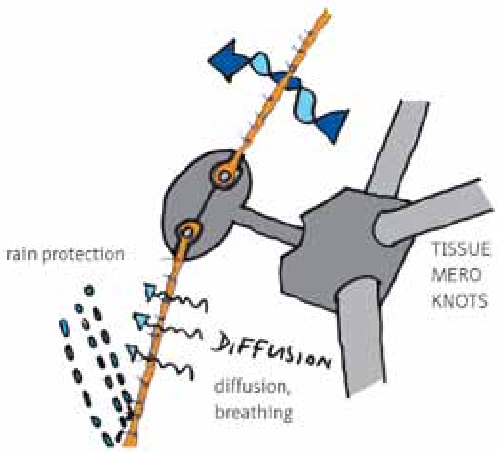
Imagined by: Holger Strauß

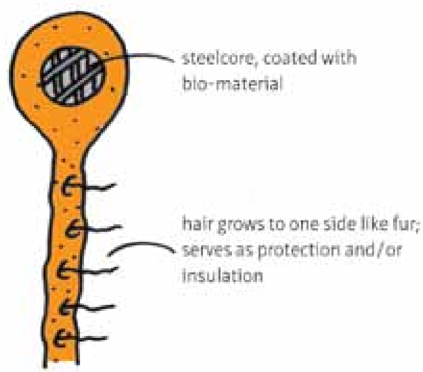
AM ranking

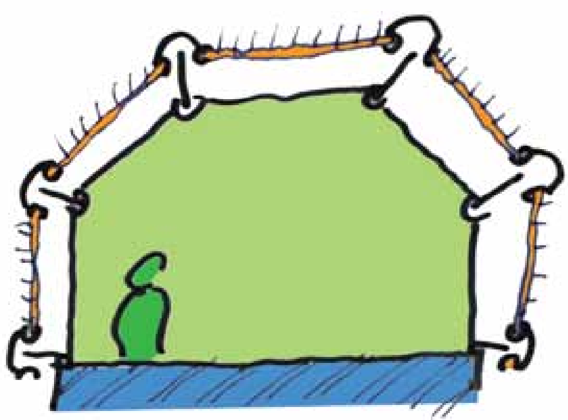


Description

With the newly developed material of 'printed' human tissue, real skin can be generated from bio-organic material. The idea is to employ the perfect performance of the skin for a building envelope. Water tightness, wind tightness, breathing and evaporation could be achieved with one layer of skin. And insulation could be provided by growing hair on one side of the façade. By storing organic material, the skin could even be self-healing.
The skin is mounted to a substructure (Mero-like system) with a terminal block and interlinked steel cables.





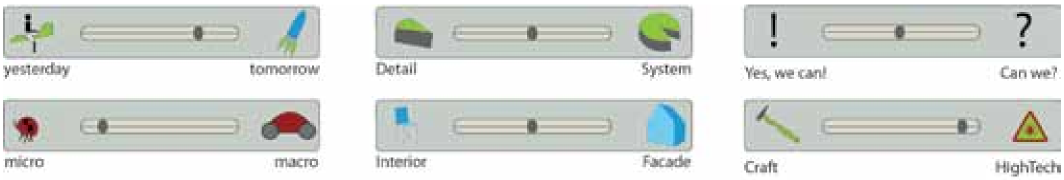


§ 4.2.2 Direct Glass Fabrication

The Idea

Imagined by: Ulrich Knaack, Holger Strauß, Lisa Rammig

AM ranking



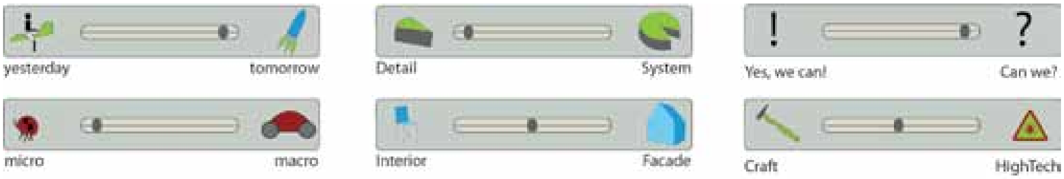
Description

While direct fabrication of materials such as plastics or metal is a sophisticated technology, Direct Glass Fabrication (DGF) is almost unexplored although glass is one of the most fascinating building materials we know. It is strong but brittle, heavy but appears light, and it is transparent. These properties have made glass into an important component of our built surrounding. It protects us from weather influences, but it is not a barrier that cuts us off from our environment.
Today's architecture is very much influenced by digital media and tooling software that enables us to create almost anything. However, it also poses increasing requirements on the building materials. For certain designs, free formed glass panes, each different from the next, need to be cut to perfect dimension so that they can be joint accurately. This brings up the question as to why not use additive fabrication methods for glass production. Additive fabrication with glass would enable the production of free formed transparent building parts while eliminating the need for the traditionally very complex processing steps.

DGF-Joint I

Imagined by: Holger Strauß, Lisa Rammig

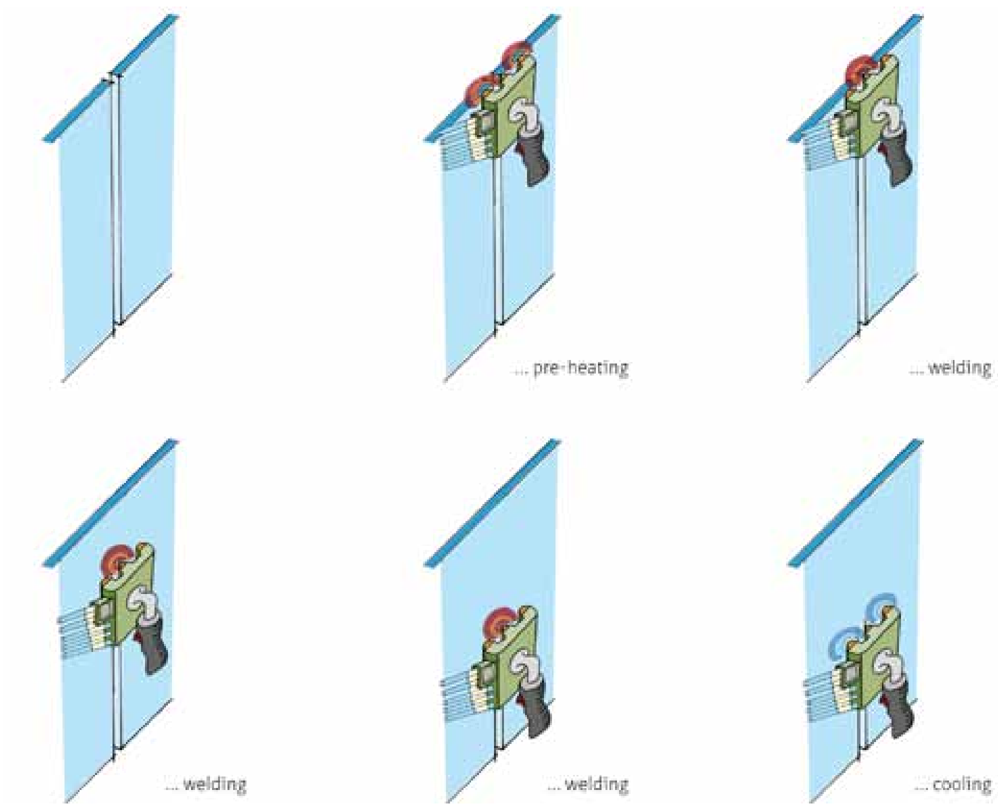
AM ranking



Description

One step in the evolution of DGF would be the welding of glass panes instead of gluing them. The gap in between two panes is then filled with a heated glass-rod in the same way as if using a hot-glue-gun. To assure a proper connection of the material, they have to be preheated and then brought to a processing temperature. With this method jointing could be achieved, which leads to an increase of design quality and to better maintenance conditions: a homogenous surface would allow for faster cleaning with less effort and also bears less danger of leakages caused by bad sealing materials.

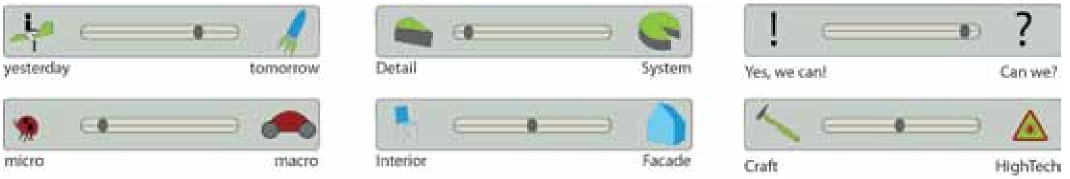
Another advantage is to be able to weld the glass panes on-site: to do so, small hand-held devices need to be developed. These tools than need to be able to preheat, weld and anneal the glass structures. At the beginning of the process, the glass panes get heated, the viscous glass is brought into the joint layer by layer and directly fused with the edge material. The heating and cooling parts should lie flat on the glass surface.



DGF-Joint II

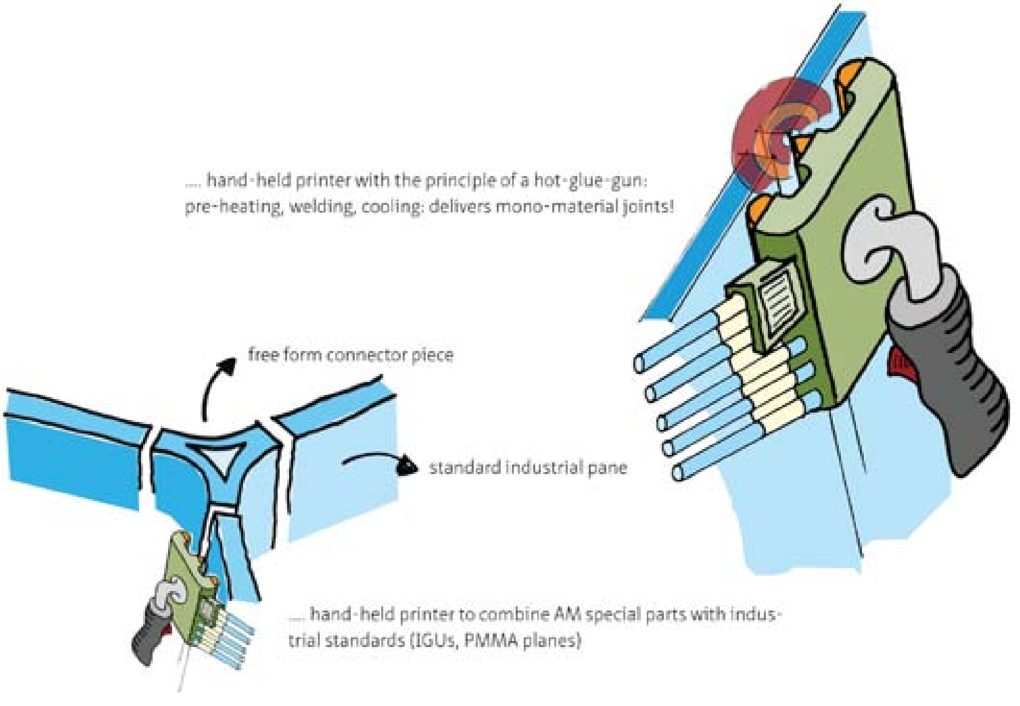
Imagined by: Holger Strauß, Lisa Rammig

AM ranking



Description

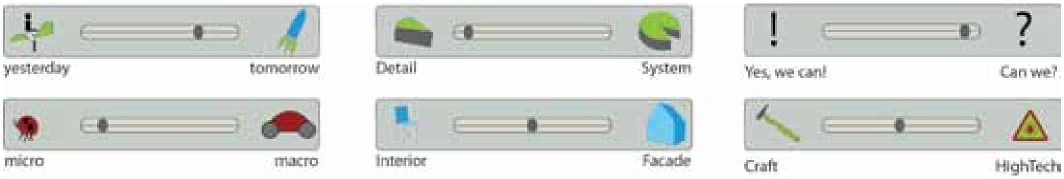
With the priciple of DGF joints on-site also free form structures and shapes could be assembled in a mono-material way. To do so, special free form connector pieces would bear all the complex deformations for the over all shape. In between those connector pieces standard float glass could be filling the gaps. With the DGF-on-site handheld device, the joints would be done in-situ.
For glass, the tool has to be somehow able to heat the whole glass pane with a temperature difference smaller than 190 K in all spots of the pane, which is a challenge. Alternatively another tool for heating the material could be deployed. The cooling part helps to accelerate the process of hardening. It has to be relatively big, to guarantee a proper heat declension and avoid material deformations caused by 'rest viscosity'.
This technology can also be applied to more materials: PMMA is already an available material for AM-Technologies. So a mono-material joint for large scale acrylic-glass structures could be achieved by employing the joining-method of the DGF-principle to PMMA. A hand-held tool is today used for PVC flooring, whereas a filament material is being fed to a cut-and-glue device and perfectly cuts, joints and seals the flooring.



DGF-Fishtank

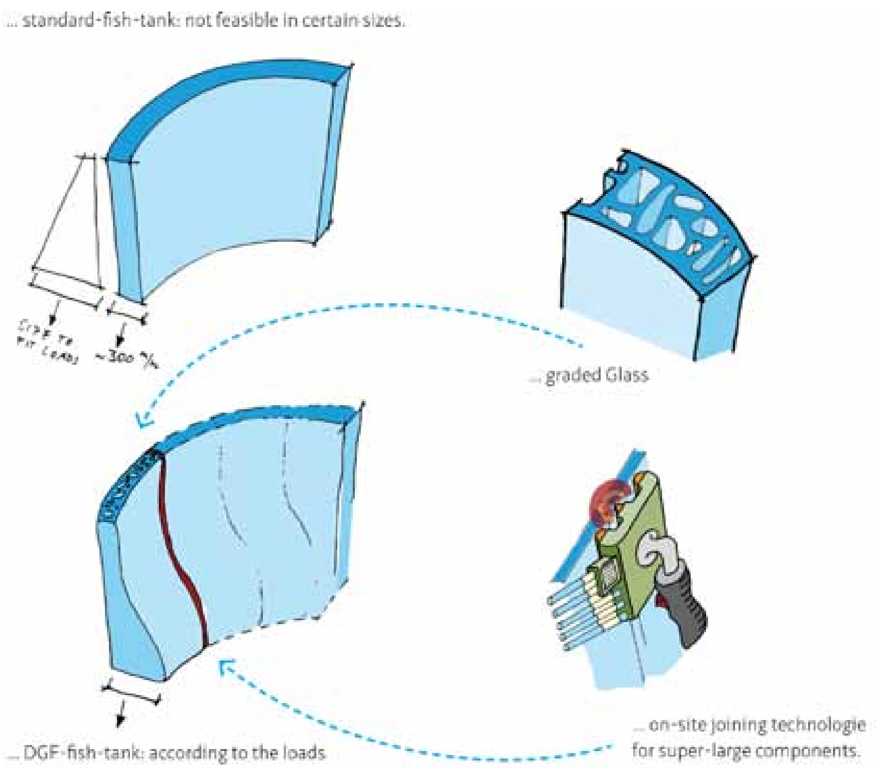
Imagined by: Holger Strauß, Lisa Rammig

AM ranking



Description

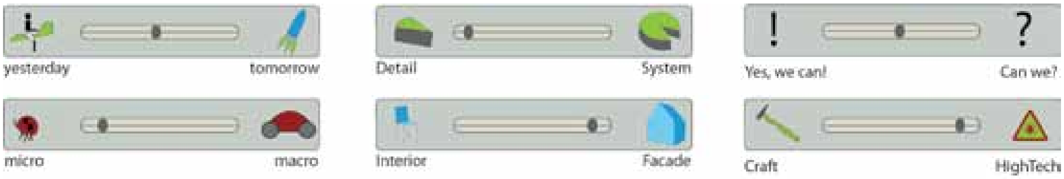
If the requirements for large transparent structures demand the use of glass, but the structural capacities or production feasibility do not allow for such large glass components, Direct Glass Fabrication might offer a solution:
In the case of an extremely large fish tank, for example, that requires 300mm thick glazing elements of specified dimensions, there are no current production methods available. Acrylic glass could be used instead, but it does not offer the pure visual qualities of glass. The better solution would be to use 3D printed glass to build up structures that withstand the water pressure. Optimised structural shapes would offer material savings, and the load-bearing structure could be determined exactly according to the real pressure load of the water, not according to the given limitation of traditional glazing element fabrication. Internal cavities could be used either to reduce the amount of material needed, or to fill the structure with water to obtain the required weight. Digital shaping of the glass could provide special effects such as fish-eye lenses or focal points that offer extra value for the viewer – e.g. a 3D porthole, made from a mono-material structure.



Biomimicry Skin

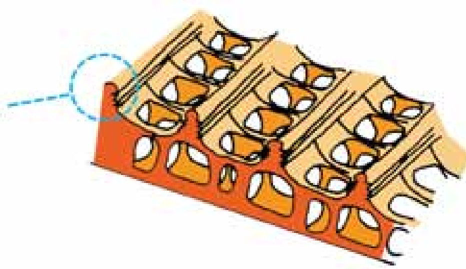
Imagined by: Marcel Bilow, Holger Strauß

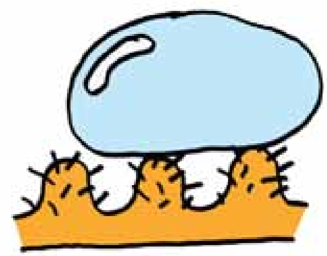
AM ranking

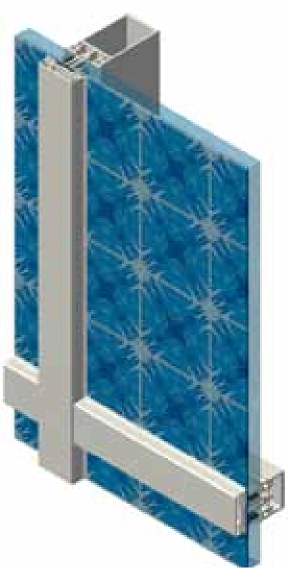


Description

Extra value from digitally implemented information can be gained with a bio mimicry façade. Interference structures on the surface make logos or designed images appear on the façade. During planning, the desired design can be dragged-and-dropped onto the façade with a special CAD tool (pattern, grid, logo, and lettering). A printed micro structure creates the interference on the surfaces similar to how certain colours appear on butterfly wings. The light is emitted by the structures and the design appears through light refraction. In combination with a lotus effect layer, the façade can be long-lasting and easy to maintain. The designs are not painted but rather printed onto the façade surface.



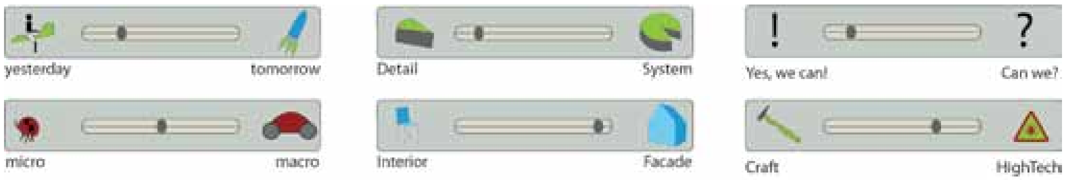




Zero-Tolerance Refurbishment Façade

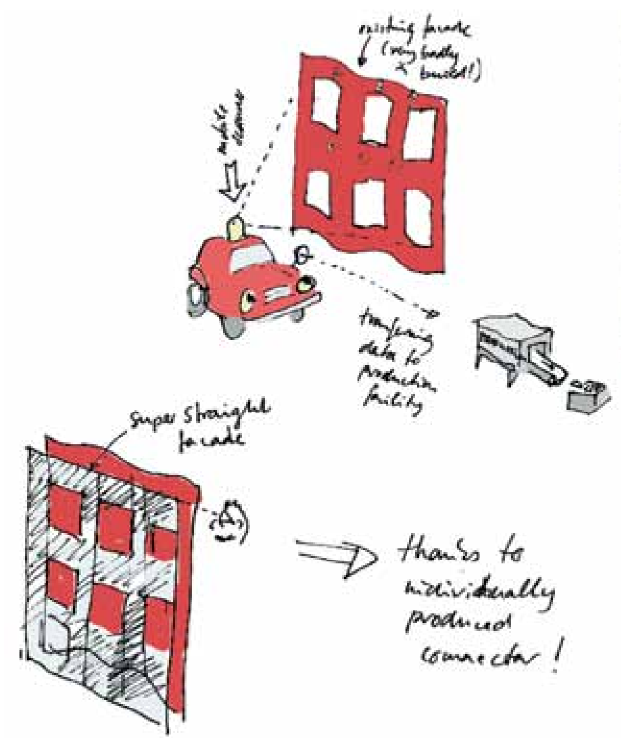
Imagined by: Tillmann Klein

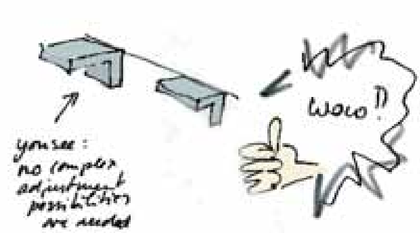
AM ranking



Description

In refurbishment, tolerances are commonplace. Individually adjusted connectors for the new façade could be created with a mobile 3D scanner. The technology for 3D scanning of entire buildings and complex structures has long been used in industrial applications – such as the assembly of mega-scale structures for power plants or bridges. The data is transferred into 3D point clouds that offer the possibility of reverse engineering of detailed information. Sophisticated software and computer hardware are capable of handling large amounts of data; thus, hand-held applications for on-site scanning and engineering are available for existing buildings or façades. By transferring the exact geometries of the building/façade with all its deformations and settlements now offers the opportunity to individualise all necessary connectors and components for refurbishment. Such virtual planning means to eliminate complex adjustments on-site, the new skin fits perfectly and therefore carries less risk of failure.

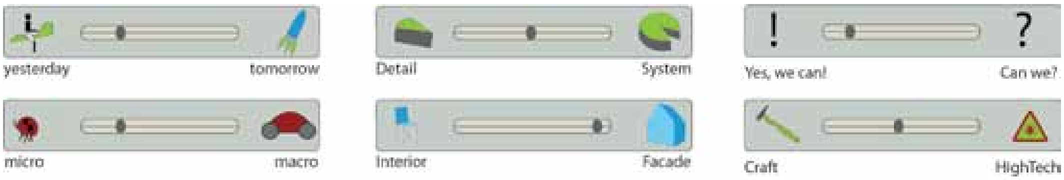




Rotating Sunscreen

Imagined by: Marcel Bilow, Leonie Van Ginkel, Holger Strauß

AM ranking

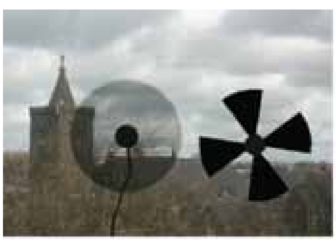


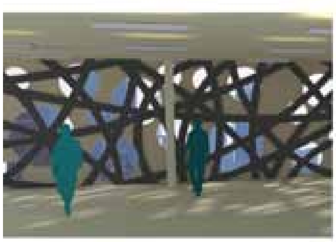
Description

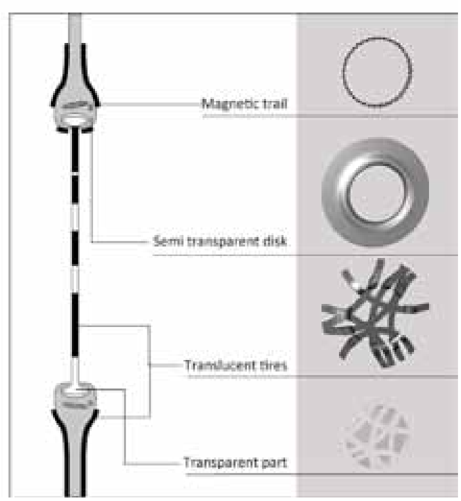
Avoiding heat transmission into our buildings is one goal to reduce energy consumption used today for conditioning of buildings. Sun shading is one key to do so: by applying rotating disks with transparent and non-transparent materials, distributed in a controlled pattern, leads to distinct shading but still allows to have the look to the outside.

Using AM to print the rotating shading device changes the boundary conditions. The problem of replacement and maintenance due to wear can be solved by designing a device where the moving parts do not touch each other at all, using the geometric freedom of the process. Thereby, a magnetic trail would be implemented in the perimeter of the disk. If switched on, the disks float in the casing. Each disk can be different in scale and pattern, because the design is independent of the production method.

Printing this device means that transparent, load-bearing and insulating material in the shape of glass, metal and glass fibre could be printed in one process. The behaviour of these materials makes it reasonable to presume the development of this graded product.



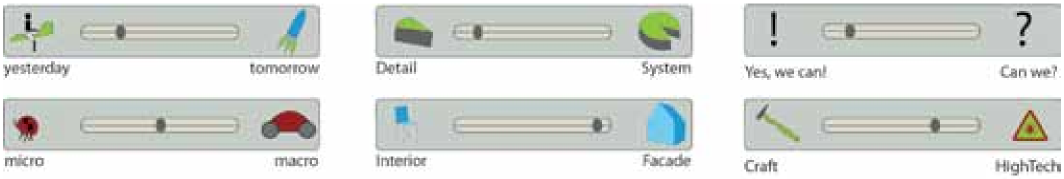




Snap- Façade Joint

Imagined by: Anna-Lena Waldeyer, Florian Winkelmann, Jasmin Lövenich, Katarzyna Kiersnowska, Rebekka Tegelkamp, Tina Schuster, Holger Strauß

AM ranking



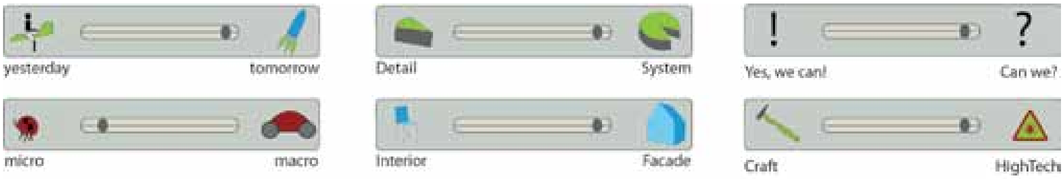
Description

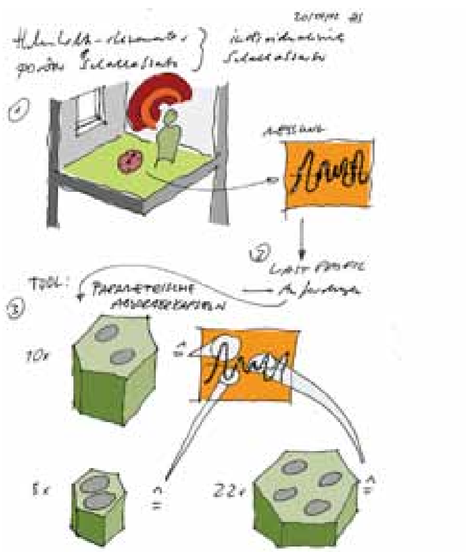
The idea behind this sketch is the combination of 'snap and lock' products from well known applications with AM performance for facade joints. Facade panels could be mounted by a single person, because they are made from lightweight material and feature an improved mounting system. This mounting system was developed from the basic adoption of the 'snap and lock' features and further developed for various rear ventilated façade variations. The evolution in shape and function comes from engineering with the AM possibilities.

Customized Sound Absorber

Imagined by: Foteini Setaki, Holger Strauß

AM ranking





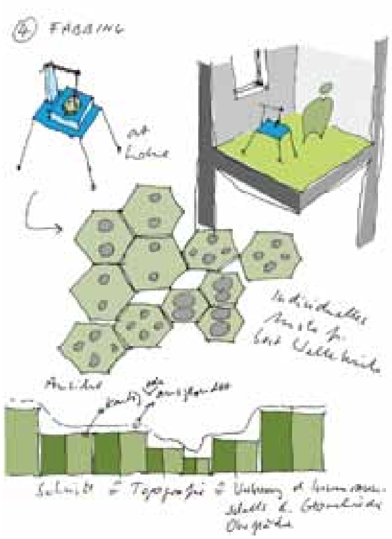
Description

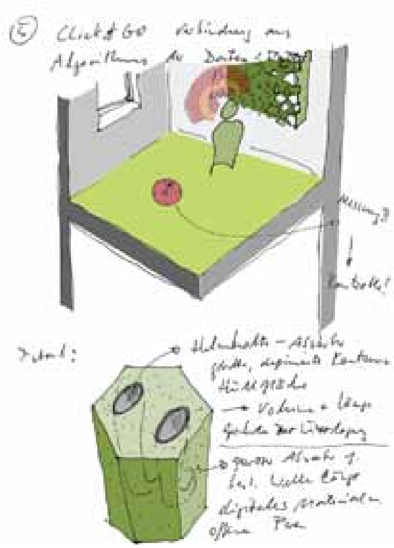
The principle 'Customised Sound Absorber' fully exploits the possibility to individually adapt products by using Additive Fabrication and a parametric design: After measuring the sound load in a space (1), a unique profile of required absorbers is generated with a software tool (2).

By changing certain parameters, the user can adjust the sound performance of the space to his or her individual needs. An algorithm is used to determine the required number, size and shape of sound capsules (3). The design can also be based on pixelated graphs that serve as an abstraction base for the module. Various basic geometric shapes are used as originating shapes for the absorber capsules, and are automatically joined and adjusted.

The modules are based on a coded building plan that, similar to a puzzle, can be put together in only one manner. Thus, in addition to the required surfaces for the Helmholtz resonators and the necessary volumes of porous absorber materials, the topology of the module which acts upon the sound reflection in a space is determined.

Using a fabber, the customer can 'print' the individual absorber capsules (4) and join them into a decorative, highly individualised sound wall (5).





§ 4.2.4 Summarising assessment of the shown principles

With increasing depth and complexity, the probability of realising the sketched principles moves into the far distance. However, they offer a sense of the 'realistic potential' of applying AM; even against the background of the fact that technologically they are currently not feasible. The ideas are complex and take a stand concerning the new manufacturing methods, changed planning fundamentals, desired part properties, the control of climatic influences and a new materiality of the façade.

§ 4.2.4.1 Façade technology

A more specified consideration is the hybrid 'Snap Façade Joint' where available lightweight materials from the automotive and aeronautic industries serve as the basis for a transfer into architecture. Assembly and load-transfer optimisation and therefore resource friendly building comes within reach by optimising the joint technology. This development challenges us to rethink the design of building technical details. But it also requires an integrated use of design and simulation tools when developing such components. And thus, this idea does not only change the product 'façade' but at the same time planning processes, areas of responsibility and the role of the architect.

§ 4.2.4.2 Climate and comfort

As described by Bilow ([7] 2012), changing demands on the building envelope lead to changing requirements for better building products. Against the background of the economic and ecologic shifts over the coming years and the legal obligations for energy neutral building[6] ([9] [8] article 9: "almost energy-plus-houses as of 2020"), technical solutions can find their place in the market that could be better or more effectively realised with new technologies. Thus, the sun shading device described here was

6 The information was taken from: DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings;

Reference [8]: EU, Directive 2010/31/EU on the energy performance of buildings T.E. Parliament, Editor. 2010, Official Journal of the European Union.

conceived and developed as an integrated component that can only be realised with technologies that are not yet available. But the effects and the functionality can already be formulated as an intermediate step so that an initial prototype could be built with current manufacturing methods.[10]

Figure 80
Bilow, Ginkel: manual prototype 'RSS'

If developed strictly on the basis of AM, the product can be even further optimised.

An AM Envelope is generated from a seamless gradient material with numerous properties. Simulation and functionally constructed components eliminate unnecessary use of material and oversizing – with a creative freedom that is independent of predetermined material properties and standard building products.

Against this background, the implementation of the Rotating Sunscreen in an AM façade is the logically consistent application of these principles. The benefits that AM offers demand that we create integrated functionality. For the Rotating Sunscreen this means the possibility to use an optimised drive method, which, similarly to the Transrapid train, is based on friction free magnetism.

For now, the RSS remains an AM vision exemplified in a small illustrative model that does not feature technical performance properties. The prototype is a non-functioning representation model because the relevant technology is not yet available.

Figure 81
Left: rendering of the integrated sun shading device; middle, right: Images of the AM prototype; realized in different materials with the PolyJet technology.

§ 4.2.4.3 Glass as a basic material for AM

The continuing desire for ever more transparency in our façades leads to further development of the use of glass in combination with AM technologies. The fascination of the material is unbowed – even while the discussion about energy savings continues. The applications shown and the underlying principle are convincing; however, AM should not be understood as a universal remedy but must be considered in a sensible combination with sophisticated glass technologies. 'In situ glass' [11], 'seamless glazing' and a 'hand-held printer for glass applications' are items that designers and architects understandably wish for, and that drive further development.

§ 4.2.4.4 Individualisation

The 'Customised Sound Absorber' is a first in combining the ideas of mass customisation, democratisation of the production and the future of AM technologies in that it is based on a Do It Yourself (DIY) application to create an integrated (building) product that enables improved building technical situations with freedom of design. But this idea also shows that even in the future expert knowledge will be needed to realise creative ideas. Programming accurate software tools with an intuitive user interface that allows laymen to apply them correctly will remain expert knowledge. Controlling the algorithms to achieve reliable results will also remain an expert task. Using such expert knowledge by means of a fabbing system imparts a playful simplicity that is also required for larger (building) projects. In the shown form, this idea is an application for interior spaces. But the topics noise and sound are becoming a façade issue: Why should we not use a sound absorbing layer on the outside of a building to help reduce noise loads?

An evaluation of the ideas demonstrates that they are all based on current thought processes and the status quo of today's technology and engineering. Thinking beyond those boundaries proves difficult, and if done results in 'wild' ideas that seem unrealistic. However, the potential of these ideas can be evaluated if looked upon in retrospective and assuming technology advancements.

§ 4.3 Influence of AM on architecture

AM technologies open up a new world of product development. 'Funktionales Konstruieren' (functional constructing) makes it possible to work from the desired functions rather than having to realise an idea with products that are currently available. Such paradigm shift turns the approach to product development on its head. It is no longer critical to design according to available production methods ('design for production'), but rather possible to consequently realise a functional construction ('design for function'). This new way of designing should also be applied to the design and the production of architecture. By doing so, architecture itself will change, so will the processes of planning and realising it.

§ 4.3.1 From design to built environment

In traditional architecture, a large structure such as a building always emanates from the smallest structural parts. Thus, an 'uninhibited' design is followed by the fact that the future shape and execution of the 'vision' will be subjected to material building construction related limitations: different areas of a glass façade, for example, are divided into main, secondary, sub, and support structures.

Any structure has its own requirements and necessities; and only as a whole they form the overall image that lies at the basis of the design. There is not one functional envelope that fulfils all of the demands of client, planner and user, but rather a complex, multi-part building element. What was designed as a homogenous whole disintegrates into a conglomerate of (too) many individual parts due to narrow boundaries in materiality and numerous realisation-related restrictions.

And this consideration does not end with a separation into different layers, but is continued to the component parts of the individual layer: a ventilation wing, for example, consists of fixed as well as movable parts, must be opened as well as locked, must fulfil load transfer and requires a certain degree of freedom that will allow its functionality.
These functionality related requirements bring with them an increasing complexity of the components.

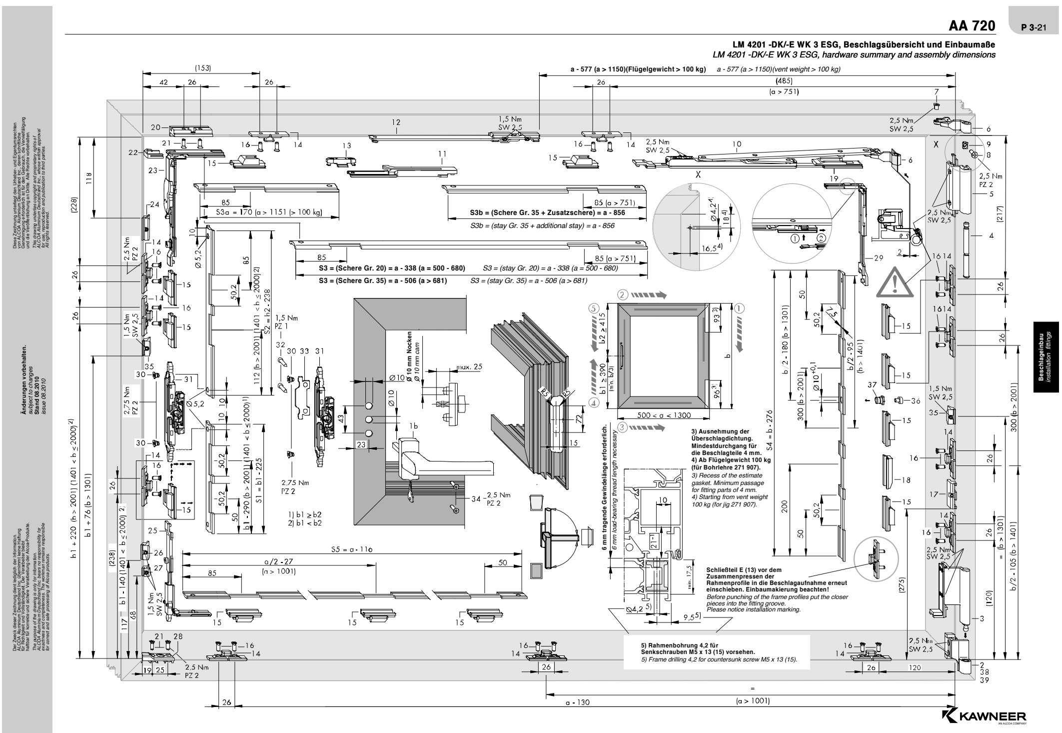


Figure 82
Mounting details for a standard window by Alcoa 'AA-720'. Imagery and illustrations from Kawneer-Alcoa digital catalogue, Issue 10/2010.

When looking at a high-rise building project, this same segmentation can be found in all building parts. From the building shell to interior finishing, the highly technological material mix brought together at the construction site hardly bears resemblance to the distinct components shown in the original design. Simple attributes such as surface design, chromaticity, joints and edges are realised with great technical effort. Complicated composite parts are created that combine numerous individual parts, materials and properties.

The examples of recently built architecture have in common that the realisation of the underlying visionary CAD designs are still coined by today's technological restrictions. Thus, after creating a unified, homogenous overall design, the structure must be divided into transportable small components. The requirements for the individual building parts such as roof, wall, foundation etc. are broken down into small components in the planning process, and then reassembled at the construction site. The result is one large unit that, upon closer inspection, can be broken down into its constructive parts.
The conventional nodal point of a typical system façade also consists of a multitude of individual parts. Assembling all of the components requires a large number of fastening devices which in turn results in a high number of process steps during assembly. Many parts mean many sources of error and increased maintenance requirements. During optimisation, more and more functions were added to façade systems; leading to more and more complex parts.
Considering the much emphasised shortage of natural resources, recycling plays an important role in this context as well. It can speak for or against establishing new manufacturing methods – AM is not a 'green' technology. However, developing functional parts with AM can result in material savings and reduced material diversity. [12]

§ 4.3.2 Toward built representations

The development of CAD and CAAD software is critical for today's architecture.

Architectural designs from around 1920 show parallels to current CAD architecture. On one hand this is due to a recurring stylistic vocabulary, such as is known from fashion. On the other hand, the reason is that architects of all times have thought of buildings as organic analogies. All eras show similarities to 'grown' structures, sculptural shapes and inspiration derived from flora and fauna. However, the majority of these designs remained utopian designs that were never realised. Noticeable examples are the utopian city crown ('Stadtkrone') designs by Scharoun and Taut, as well as the drawings by Hermann Finsterlin and Erich Mendelsohn (see [13]), but also the 'Walking Cities' by the architect group archigram in the 1960ies, none of which were ever realised as a large building project.

Round, curved, free forms are difficult to plan, realise and assemble. On one hand this is due to any material's tendency to try to maintain its original directionality, for example during bending. On the other, because a two-dimensional representation can never capture or show all aspects of a given building part. Rafael Moneo speaks of “forgotten geometries lost to us because of the difficulty of their representation” (citation from Branko Kolarevic: “Architecture in the digital age” [14]).

Another factor is the human being. Most constructions are joined and assembled at the construction site. The craftsmen involved and the machines used can better handle orthogonal components. Maybe this is the reason that only a few of the utopian designs of the last century have been realised.

§ 4.3.2.1 Mendelsohn, Einsteinturm

One of the built designs of expressionistic, free form is Mendelsohn’s ‘Einstein Tower’ from 1920-1924. It resembles a free-formed sculpture more than a functional building. Mendelsohn skilfully combines the necessary spaces with lively, amorphous shapes. Conceptionalised as a reinforced concrete structure, the part of the tower above the plinth was built with conventional brick building methods however, due to problems when trying to create the unevenly curved formwork. The surfaces were then plastered with rendering to create a uniform surface. The inconsistent use of the materials caused the building to deteriorate early. Building humidity and varying material thicknesses and expansion properties led to chipping off and cracking. As early as in 1927, metal plates were applied to counteract the problems. But even after various restoration measures the building continues to require constant renovation. (see [15] [13] [16]).

Figure 83
Left: Erich Mendelsohn, Einstein Tower, Potsdam, 1920-24;
right: elevation after the restoration in 2000; b.) detail of the entrance.

Today, the development and use of new planning tools and new materials enables us to realise designs that were difficult to execute at the beginning of the twentieth century. Particularly the field of building with reinforced concrete has greatly improved, for example in the areas of concrete with non-metal reinforcement [17], self-compressing concrete and high performance binding agents with diverse properties. Thus, realising Mendelsohn' design in monolithic fibre concrete would be less problematic today. Almost all material groups have been further developed and therefore offer greater architectural freedom of design. Building parts made of glass fibre reinforced plastics (GRP), carbon fibre reinforced load-bearing structures and the use of sophisticated specialised plastics (for example PEEK) open up unimagined possibilities.

§ 4.3.2.2 Cook & Fournier, Kunsthaus Graz

To create striking large-scale structures that serve as a branding opportunity for a city has become known as "Bilbao effect".[18] Form a formative point of view, these extraordinary architectural designs play with long and close range effects, or the disintegration of a large-scale shape into a conglomerate of building stones when viewed from close up. This is also true for Kunsthaus Graz by Peter Cook and Colin Fournier. The Kunsthaus, in popular parlance called the 'Friendly Alien', is an example of the so-called liquid architecture - an amorphous, free-form design [19]. Some see the building as a late realisation of the visionary archigram designs of the sixties, with Cook and Fournier having realised their visions in a 'new building' icon.[20]

Figure 84
Left: view of Kunsthaus Graz in the middle of Graz, Austria. A 'Friendly Alien' in a historical setting.
right: close-up of a 'Nozzle'; cladding was done in PMMA panes with point fixations..

With its eye-catching shape and extraordinary appearance the Friendly Alien attracts a great deal of attention. The design clearly shows that it was conceptionalised in virtual space. The building does not want to fit in, but rather distinguish itself with its unique free form.

For Colin Fournier, the predetermined step into the 21st century is the change of architecture into 3D architecture in combination with 3D production.[21]

But because this process is not yet complete, the realisation of this project required dealing with current production realities.

The façade appears to be the skin of the Kunsthaus and, on closer inspection, dissolves into a multi-layered, complex and fragmented structure. It consists of more than 1000 individually shaped acryl glass panels and 6000 here for necessary point fixtures as well as an elaborate load-bearing structure.

The components for such a construction are produced individually from available mass products. Often, financial reasons prohibit the use of individual building products. It is expensive to get certification for a new building material, and the process entails great administration effort. Therefore, tested products are typically used, which however results in compromised solutions for particular building projects.

§ 4.3.2.3 Gehry, Walt Disney Concert Hall

A pioneer in applying digital information to depict and realise complex buildings, Frank O. Gehry showed that the way in which architecture is conceived, projected and built has been changed by the digital revolution.

His project 'Walt Disney Concert Hall' in Los Angeles is the example that shows the planning office's most advanced technical development. Deriving its first projects such as the Guggenheim Museum in Bilbao, the planning team around Gehry created a digital workshop. This digital workshop was necessary to realise complex projects without analogue drawings and the continuous transfer of information between the parties involved in the realisation. Irrespective of the design quality of an architectural project, the method of execution by means of digital tools is a consequent step toward a new method of realising an architectural task – all of the information is compiled in a parent file; all changes, adjustments and tests are done on the same model. The architect manages this file – analogous to the historic master builder – and thus returns to be a central institution of the building project, even if in a more abstract manner than was the case conventionally. By using the data for planning as well as directly producing the work, the architect returns close to production and can control and influence it and possibly adapt it to architectural demands. Transferring technologies between hitherto unrelated industries becomes easier, and promotes a more accurate representation of the design idea into built reality.

Paradoxically, in its renaissance approach of unifying planning and craft, the new type of collaboration leads via free-form and Blob architecture back to the ideas of Bauhaus; with an architectural expression that consistently promoted clear, straight lines and repeatable elements for the benefit of serial production and that in its 'Gestalt' directly opposes the seemingly random forms of Blob (or liquid) architecture.[22]

Figure 85
Left: view of Walt Disney Concert Hall, Los Angeles, California;
right: Close-up of the primary structure that was built in order to allow for the free form shape. Cladding is done in metal plates, fixed to substructure.

§ 4.3.3 Potential for improvement using new technologies

The free-form possibilities that CAD software offers not only change the method of designing but also the design itself. In most cases the 3D data records are very large because they usually include specifications for materiality, type of execution, prefabricated parts as well as lighting, shading and ventilation. Some offices already use this data for immediate realisation, for example to process formwork drawings for in-situ concrete constructions, or to create cut plans for façade cladding.[23]
But realisation is still based on the limited possibilities of today's production techniques. The designs are translated back into realisable components, meaning that production determines design instead of design determining production. In spite of the changes in the design process, daily routines on the construction site have not yet undergone fundamental changes. Naturally, the possibilities of accurate and complex processing of execution planning are reflected in the increasingly impressive

results. But a design can only be as good as its later realisation on-site. The building industry employs ever more high-tech products to cope with the greater challenges of digital designs. Even though some industries segments already employ advanced technologisation and therefore simplification of the production process, the building industry does not yet offer a simple translation of design data to product. The possibilities of the new technologies are merely used as a means to make conventional building construction easier; not to fundamentally change the building task.

The examples show that the digital design directly influences the formative vocabulary in architecture: modelled free forms are realised into buildings – creating Liquid Design. Without computer simulation and precise CNC manufacturing, these forms could not have been realised.
With the increasing use of 3D applications, Additive manufacturing (AM) also comes to the fore of architects and others concerned with building. The applications in this field are still limited to the generation of printed 3D architecture models. But the advantages of AM to produce models, façade elements or entire buildings are the same: production without manual screwing, gluing, joining and fitting.

Seamless production from the digital design, meaning a true CAD-CAM work process is not yet possible. AM technologies might be a solution to do justice to these designs. Relevant AM methods must be made usable for serial production and large-scale applications in order to be applicable to the building industry.
Extraordinary architecture is in the public eye. It benefits from new developments. It represents approximately only three to five per cent of the overall building volume; but will always be the motor for innovation of design and construction.

§ 4.3.4 Mass Customization

An examination of the developments in the digital world shows a close link between the different consumer goods markets. CAD and CAM also change the working methods in architecture. In order to illustrate the connection between information technologies and AM technologies, we must examine a development that is a result of these new fields: Mass Customisation (MC).
Mass Customisation is a composition of the terms 'Mass Production' and 'Individual Customisation'.[24] It is the goal of the consumer goods industry to use MC to offer individualised products at the price of mass products. MC fulfils increasing customer demands for personalised products. However, due to cost issues, true individualisation (so-called "Core Customisation" [25]) cannot be realised with the manufacturing technologies commonly used today. Therefore, MC offers a certain degree of individualisation, which, however, upon closer examination is a modification of mass

products. One such example can be found in the automotive industry: when ordering, the customer chooses an individual combination of numerous available options. The selection of colour, wheel rim, accessories and extra equipment results in a product that is specially configured for a particular customer. All cars of one series are based on the same base modules, but there are many variations within the series of a model. However, the customer has no influence on the actual design or function of individual components because they are conventional components that were prefabricated with conventional production methods. This leads to the usual high cost levels (production means, inventory) that can only be regained by selling large quantities.

(see [25]).

Such limited individualised fabrication can be enhanced with AM. Assuming that the difficulties still inherent to AM methods (material comparability, processing speed and component size) could be eliminated, MC could evolve into true individualised fabrication. With regards to the example from the automotive industry this could mean that individual body scans could be used to make customised seats. These seats could be produced individually with AM. Not only the colour and the type of item could be influenced but also the shape and form.[25] With AM it will cost approximately the same to produce two different seats, if the quantity of seats produced is similar. But the overall effect is added value for the customer.
CO2 emission is another topic currently discussed and evaluated. One of the arguments for introducing AM as a production method is to possibly reduce the CO2 footprint by exploiting regional production. Currently, the shipment of consumer goods accounts for five percent of global CO2 emissions.[26] Also, the new method of designing that is inherent to AM and the resulting products make it possible to manufacture in a more resource friendly manner. Light weight structures, for example, can reduce energy and resource consumption while maintaining equal component performance through the use of less material, less weight, and shorter processing times (theoretically dependent of the necessary building volume). Still, it remains to be a theoretical comparison because we do not yet have an overview over all of the production parameters of AM. Current estimates are that AM production is up to 50 times less effective than comparable building volumes produced with die casting (per kilogram, per component). The same is true for a comparison of DMF components with turned metal parts. The potential advantage only becomes visible if we consider the overall energy consumption in a life cycle analysis. Lighter components in aeronautics, for example, can lead to less fuel consumption and therefore energy savings. Also, the new technologies could be used to conduct hitherto impossible repairs of high value parts; resulting in less waste. In terms of sustainability aspects, this shows an advantage for the AM technologies. Some research projects even assume that they enable a development toward production with a reduced CO2 footprint (research project 'ATKINS – Rapid Manufacturing a Low Carbon Footprint' [27]).

Initial results show that it is possible to reduce CO_2 emission by employing AM. Hereby, metals show the greatest potential; while the SLS technology also shows potential if the issues concerning recycling of un-used but heated material are solved. We must follow a holistic approach and therefore it is essential to fully exploit the freedom in geometry and design for part optimisation. In terms of shape and weight further CO_2 reduction is possible by designing slender geometries. Also there is a great economic interest in optimising processes with metals, but repeatability and process speed must be further optimised.[12] [28] [26]
The sustainability of intensively individualised products still needs to be evaluated in the market, for example in terms of a potential resale of such items – the perfectly customised car seat might be difficult to resell. A product can be customised to the demands of an individual buyer, but aspects relating to return warranties or exchange/ return policies will be challenging.

All areas of the consumer goods industry offer input programs, so-called configurators that allow the customer to individually configure a particular product. This is done under the assumption that a number of customers are willing to pay more for the advantage of being able to individualise the product. Standard products remain available for all other customers. The companies benefit from immediate market access by offering such active customer involvement through feedback and monitoring of the individual products. Exploiting the customer's input ('Open Innovation') enables the manufacturers to lower the cost for development and provides them with the assurance that their products meet the demand. MC aids in reducing the required inventory and the risk of unprofitable investment caused by an unaccepted product. (see [29]).
But a growing number of architectural mass products and prefabricated houses is also a development that results from the possibilities that CAD, CNC and ultimately AM technologies offer.[30] The client chooses dormers, gazebos, porches and carports from a variety of options to create his or her personal dream house. CAD allows for marketing via a webpage, and a combination of CAD and CAM facilitates production. The houses are built to order in a modular manner following the principles of Mass Customisation. With these individual configuration options, the design quality of such buildings can only be controlled by offering only high quality options and limiting the degree of individualisation. This is done with the so-called Black-Box System.[25] Hereby, the system controls the configuration with certain parameters (for example maximum, minimum) and resets a value to a predefined default if the user has entered values that are too low or too high. The user uses the configurator to configure a product according to his or her wishes; however, the influence he or she has on the individual parts is limited. In order to achieve a certain level of quality, we will continue to need designers and planner whose expert knowledge distinguishes them from the home user. For buildings, this is a necessity not least because of the required stability, usability and feasibility. Individualisation without such a controlling authority would lead to over-individualisation.

Even though future developments of 3D systems will lead to easy and intuitive use, the complex processes of translating a 3D model into a physical building are specialised services that cannot yet be satisfactorily accomplished by laymen.

"The implications of mass-customisation for architecture and the building industry in general are profound. As Catherine Slessor observed, 'the notion that uniqueness is now as economic and easy to achieve as repetition, challenges the simplifying assumptions of Modernism and suggests the potential of a new, post-industrial paradigm based on the enhanced, creative capabilities of electronics rather than mechanics.' In the modernist aesthetics, the house was to be considered a manufacturing item ("machine for living"). Mass production of the house would bring the best designs to a wide market and design would no longer cater to the elite. That goal remains, albeit reinterpreted. The industrial production no longer means the mass production of a standard product to fit all purposes, i.e. one size fits all. The technologies and methods of mass-customisation allow for the creation and production of unique or similar buildings and building components, differentiated through digitally-controlled variation."[31]

New technologies can only come to common use if there is a large enough market for them. And it is easier to create such markets by fulfilling the demands of the general public (see [25]). Similarly, architectural mass markets break the path for an acceptance and therefore use of CAD and AM technologies in the façade and architecture in general. MC used for buildings can make high quality designs accessible to a broader audience and eliminate the exclusivity reserved for a elitist minority (see [31]). The creative freedom of design that CAD offers influences the appearance of our built environment.

§ 4.4 Economic efficiency of AM

This work has not answered the question of true economic effectiveness of AM technologies as they relate to façade planning and realisation. This aspect of a holistic treatment of the topic can only be examined peripherally because the realisations of the project results presented here depended on AM service providers.[2] If AM is to be integrated into real production chains it must be considered a customary application and overcome its image of an exceptional technology! Economic efficiency with AM can only be achieved if common use has brought all advantages and disadvantages to the surface. Only then can all savings potentials be exploited and a maximum utilisation of the entire potential ensured. For each façade project, this must be done for a specific AM system considering factors such as process chamber, production time, and optimum orientation within the process chamber.

Initially, the investment for an AM system in the production chain of a façade manufacturer disproportionally exceeds the production quantities achievable with the sytem. However, a longer production period would provide a truer calculation of the cost for AM. A direct comparison of today's standard building parts with optimised AM building parts is impossible. Opening up technological potential must be followed by a monetary evaluation of the performance characteristics.

Besides all aspects of technical feasibility, economic efficiency will always play an important role when deciding for or against integrating AM into production.
To justify the procurement of an AM system with the production of components alone that cannot be manufactured with any other method than AM is too narrow a view of the matter. Rather, considerations should include various aspects of one's own production: Where can a sensible application of AM technologies generate added value? Which other benefits besides realising free forms and geometrically challenging components can be achieved?

Motivation to procure an AM system can be driven by some of the following factors:

§ 4.4.1 Break-even point

The trend in AM market goes toward producing end use parts. Hereby it is important to conduct an economic efficiency analysis to be able to compare AM technologies to the conventional methods for mass production. Neil Hopkinson has been engaged in this issue for many years.[25] He has examined processing aspects related to defined quantities and a 'break-even point'. Such considerations must be conducted for each AM process separately; in fact, for each part geometry. In general, the prime reason for such considerations is to estimate the specific quantity at which it makes sense for AM to compete with die casting, for example. Initially, these considerations were merely based on the size of the part, not on the expected increased performance of an improved part made with AM, or the product benefits measured over its entire lifecycle. Independently hereof, such studies as well as their results must always be based on the newest methods and system technologies available. Thus, parameters and results change at the same rate as the system technology itself.

Finding about production output can only be provided by the large service providers in Europe. Manufacturing facilities are also known as 'Sinter Farm' with a 24/7 operation of AM production. The increasing relevance in the market shows in the fact that Apple, for example, lets service providers produce protective covers for its iPhone with AM. The initial lot size is specified at 27,000 pieces to be distributed worldwide. The required geometric shape of the protective cover does not permit any other manufacturing

techniques than layered, generative fabrication, and therefore excludes other methods of mass production.[32]
The fact alone that parts produced with AM are adopted by a market leading supplier allows a conclusion to be drawn about the future development of AM as part of the production process. This must be based on the assumption of great process reliability and according high repeatability of the individual parts. Market leader FKM Sintertechnik GmbH, Biedenkopf, Germany is one of the first companies to offer the SLS method as a professional service. Expert knowledge based on a deep insight into the processes running on AM systems offers the freedom to test new markets.[33]

§ 4.4.2 Possible savings related to material consumption and weight

Concrete improvements, for example in the area of performance properties crystallise in addition to the possibility of easily changing the shape and appearance of AM made parts. Possible savings related to material consumption and weight resulting from shape optimisation and the use of light weight structures (see § 2.5.2.3) opens up new markets for AM as a production method. In aeronautics, a reduction of weight is directly linked to fuel consumption. The technologies are thus directly related to the current discussion about preserving resources, CO2 emissions and environmental compatibility. The example of parts manufactured for the aeronautics industry shows possible fuel savings, even though the initial cost to produce such parts made of high performance plastics (for example 'PEEK' with the SLS method) or metals (for example aluminium with the DMLS method) are higher.[34]

§ 4.4.3 Batch size one

Another advantage is the possibility of manufacturing product series with a batch size of 1. This means that production of small series or even single pieces is economical. With traditional manufacturing methods such small batch runs are not realisable. AM allows for customised products according to customer specifications – single products without added cost, single products at the price of mass products (see [2]).

AM materials used today also allow to closely imitate the properties of 'standard' methods. This allows more freedom in the development of mass products. On one hand it is possible with AM to run more optimisation cycles in a shorter period of time, resulting in a modified prototype that continuously exhibits higher product quality; on the other hand a closer and more immediate collaboration allows for better testing and therefore more sophisticated development before launching a product. In addition, consumer surveys can be conducted at an early stage of the product development which minimises the risk of misdevelopment. This results in greater customer satisfaction because the very first generation of a mass product has already undergone extensive development. And marketing a new product using realistic prototypes can lead to higher acceptance and demand in the market.[35]

§ 4.4.4 Development cost for introduction to the market

In the consumer goods industry, AM is now being employed as a pre-marketing tool when introducing new products to the market. The very first edition of a newly developed product can be tested in the market without the traditional development cost. With sufficient demand the product can then be produced with conventional methods. Thus, with AM a product can initially be distributed in limited numbers, which allows for optimisation before investing in expensive tool sets for mass production (see [25] [36] [37] [38]).

It is true for all areas of Additive Manufacturing that the cost for product development is significantly lower than with traditional methods. With Additive Manufacturing, the price is no longer influenced by difficult product or tool geometries. Before, it was the complexity of the model that determined the cost. With AM, this is no longer the case.

Growing competition in all areas of the AM market results in lower prices. Ambitions to make the technology accessible to a larger audience are understandable considering the expected market for AM services and complementary market areas. It becomes increasingly attractive for producing companies to look into the technology and to invest in an AM system to complement conventional manufacturing processes.

§ 4.4.5 New markets

The awareness and understanding of the AM technologies has grown strongly over the past years. The consumer goods industry uses additive methods to individualise products, the movie industry uses them to create props and masks, the computer games industry uses them to support their marketing strategies, and the aerospace industry uses printed components in aircrafts. Many different protagonists in the development talk about the methods; the DIY market is booming. New trend and technology analysts have been watching the methods for some time now and adjudge it great potential.

On one hand it is good that the large renowned market studies and lists of "emerging technologies" finally include the AM technologies. On the other hand, these potentials must be exploited to open up a new market. In this context the architect's or planner/designer's position is weak. Actual decisions to continue the implementation of '3D Printing' must come from the industry itself. Ultimately, the decision as offered in Gartner's Hype Cycle [39] as a tool to determine whether and, if so, when a technology is considered to have a good chance of success, is based on economic factors. Economic efficiency always has to do with unforeseeable developments as well, and therefore involves a risk that can have a positive or negative monetary impact.

Investing in the new technologies poses a risk for any company. The capital expenditure for equipment to produce metal parts (DMF) starts at approximately €500,000 and is open-ended. One has to have a good reason or argument in favour of AM technologies to justify such an investment. It is not easy to find such arguments for a particular project alone; but while the building envelope becomes an increasingly important part of the building project, the share of the entire construction sum for the façade increases as well. An AM system might self-finance with just a few projects. An intensive discussion about such investments and the here form resulting pressure to ensure economic operation of the system can be another driving force to try something new.

Further information about economic efficiency and market relevance can be found in appendix A I / New markets from AM.

§ 4.5 Summary chapter four

Combining CAD designs with AM technologies enables digital fabrication, and the possibilities of digital production are adapted to the possibilities of digital planning. Design-oriented realisation using digital processes creates a direct connection between design and production ('file-to-factory' process, see [31]). In the beginning stages of digitalisation there was the question of the realisability of complex CAD shapes. Today, the question is no longer whether, but rather with which tools such shapes can be realised. Besides the subtractive and formative methods, it is the additive methods that allow for a variety of shapes and functions.

The sketched ideas show applications that generate a functional added value from the AM methods. Considering the current state of the art of AM, the open issues related to the technical developments of the principles remain. They offer a field of work for subsequent research into the future of the building envelope. The suggestions for AM Envelopes can be used to illustrate and evaluate the potential of AM for façade construction. Such building envelopes can be accurately realised with AM. The solutions can be individualised by simple changes of the data records while maintaining the quality of the realisation. The building technical risks when realising bespoke AM Envelopes can be minimised, because the assurance lies in the manufacturing process, not in the parts used.

Even if the economic aspects of AM technologies cannot be finally judged today, still the major developments in the AM market and in the changing building industry lead toward more effective solutions in building envelopes and building technology. Here the shown aspects of time-to-market, regional production or light weight parts highlight a few possible ways to combine new technologies to more responsible solutions.

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5 Conclusion

This work is aimed at fathoming the potential of Additive Fabrication to change façade construction.
In order to do so it documents the technological possibilities of the AM methods as they relate to façade technology. Based on the executed projects, the number of different methods available was reduced to five AM technologies that seam relevant for façade applications. But this kind of potential evaluation must be redone for each new project because the great variety in AM technologies brings with it an equally great variety in performance.
Based on these descriptions and evaluations of the AM technologies, requirements placed on the building envelope were formulated and put into direct context with available AM technologies. Subsequent developmental steps toward an AM Envelope were derived from a list of the required areas of performance as well as an examination of the historic development of the façade technology. It is important to clarify that these developments always require the potential for improved parts as well as for improved system technology, and therewith influence both directions of development.

As core of the research, a research project studying the production of façade components with AM was conducted. The results were documented and, after chronological classification, linked to developmental steps and their realisation (see § 4.1).
To link the AM theory to façade reality, convincing AM prototypes were developed and manufactured. The prototypes make it possible to make the AM methods accessible and – literally – tangible to a professional audience. The responses consistently confirm the power of the materialised ideas and thus support the core statement of this work which is that AM technologies bear great potential to change the construction methods of façades. The type of assistance that every participant requires in the process of developing an AM Envelope in order to fully exploit the potential that was described. It became apparent that a detailed documentation of the feasible and the impossible by means of guidelines for the different process partners is necessary. Hereby, the content must be matched to the different demands of the planning and production process. These guidelines are the basis for a subsequent scientific discussion of the topic 'AM Envelope' and the translation into built reality.

In order to examine the research results in terms of a possible built future, additional visionary ideas and conceivable applications were added to the product-oriented results. The possible impact of the AM technology on façade construction can be derived from an entire line of ideas – closely connected as well as further removed from the AM Envelope – by means of the established time line (see § 4.1) and an AM ranking showing six important aspects of the presented ideas (see § 4.2).

The potential was discussed and evaluated with future AM users, which in turn led to more ideas and specific visions.

§ 5.1 Answers to the sub-questions

Since the content of the chapters of this work is oriented on the proposed subordinate questions of the hypothesis, the following provides compact answers to each. The individual chapters provide more detailed information; but the following section offers a generalised summary that can be used to assess the potential.

Chapter 2:

- **What technical possibilities for façade construction are available today with AM?**
  The description of the status quo of the technical possibilities of AM (see § 2.2) shows the large number of different technologies, but also the large number of variants of basically similar technologies used for very specialised applications. Since its beginning in the late 1980ies, the development progresses very dynamically and shows strong and consistent growth. Two fundamental decision-making options can be derived from this consideration and the description of the most common AM principles: manufacturing components with plastics or with metals. Following this decision, appropriate system technologies can be found for any application under consideration of the relevant planning goals. The fundamental differentiation between the two large material groups inevitably leads to the demand of adapting existing technologies to a particular product task.

- **Which changes do AM technologies have to undergo to be applicable to façade technology?**
  In order to make an impact on building technical applications, the technologies must evolve from sophisticated 'prototypers' to reliable production tools. Batch-size independent production of precisely equal components is mandatory. As are certification and approval of the technologies to ensure safe and secure building technology. Besides these aspects concerning product liability, the system dimensions must be adjusted, processing speeds reduced, and manufacturing cost lowered. The last aspect is and will remain to be the decisive factor influencing an introduction in a new market. And at the same time it is the main criterion for exclusion when considering whether or not to manufacture with AM.

- **Which external influences can cause such changes?**
  Important stimuli for technology changes come from the industry: Rapid Prototyping technologies for example could only be developed after high

performance lasers reached marketability; today, new energy sources or a significant increase in performance of the laser can create new impulses. An AM independent development in mechanical engineering, material science, process development is also conceivable, as is a direct demand from a different industry.

- **Which technical requirements are posed on an AM Envelope?**
  To justify the development of an AM Envelope, the performance properties of the new building envelope must clearly supersede those of a conventional façade technology. Ideally, the demand for a dynamic building envelope can be fulfilled: Climate regulation with breathable materials, load transfer with slender optimised load-bearing systems, comfort with insulation and ventilation, integrated technology for the user, performance capacity for lighting and shading with adaptive transparency, design appropriate appearance.
  It is important not to understand the dynamic building envelope as a technological end in itself but rather as an opportunity to elevate the stagnating development of the building envelope to the next level. Still today, Mike Davies' vision of a 'Polyvalent Wall' in its complexity and slender execution could not yet be turned into a viable product. However, it does combine all requirements placed on the building envelope in one concrete formulation.[1]

Chapter 3:

- **Which research approaches lead to first experiences with AM technologies in the building envelope?**
  In an existing façade system, approaches can be found anywhere where conventional production methods will not provide sufficient results. Meaning where conventional production leads to excessive inventory, or where the desired component performance cannot be fulfilled. Such product-oriented approaches then lead via modified façade construction with AM to a re-interpretation of the building envelope.

- **What are the effects of product-oriented project results on a general transfer of the AM technologies to façade technology?**
  We can conclude from the specific project that it makes sense to identify and rework weak system components. The technological development and according cost reduction for components provided by AM service providers that occurred during the time to complete this work alone make it apparent that a targeted application of one-off projects is feasible (see § 3.3.3). Hereby it does not suffice to merely exchange production methods in order to justify the application of additive methods. Only an intensive discussion about 'Funktionales Konstruieren' ('functional constructing') and the according changes in engineering can do justice to the potential of AM for façade constructions.
  AM as an enhancement within a hybrid production chain is the next step toward the AM Envelope. With the goal being improved façade construction.

- **What means of assistance for planners and users of the technologies must be generated in order to guarantee AM oriented application in the façade?**
  In order to achieve 'Design for AM', planners and users must be provided with thorough aids for the AM technology. Such aid in form of guidelines provide target-oriented advice for a technically correct handling of AM: Component thicknesses, orientation within the process chamber, production strategies and many more support an AM conform design. This can support the economic and resource-friendly use of AM.

Chapter 4:

- **Which developments of the AM technologies for façades are conceivable?**
  An increasingly thorough discussion about the potential of Additive Fabrication leads to the demand to develop the AM technologies further. These demands can be linked to certain time periods:

  - **In five years** (2020) the technology will have caused changes in existing building details; AM will be integrated in the production process of extraordinary architectural projects.

  - **In five to ten years** (2025) AM will have found its way into the workshops of façade builders due to improved system technology.

  - **In twenty-five to thirty years** (2045) the manufacturers of large (façade) components will use Additive Fabrication with various materials, for hybrid processes, and to produce dynamic building envelopes and the according primary structures.

- **Which façade applications can result from these developments?**
  Technology transfer makes it possible to formulate the most diverse ideas and combinations. Progressing developments in the field of software tools, continuous CAD and CAM training, and a deeper interconnectedness of hitherto separate disciplines lead to the comprehensive development of hybrid products. In building technology, AM applications can still be categorised as follows: semi-finished product level, element level, component level, and system level. It is only the level of consequence in formulating the possibilities of AM that will replace the technical limitations prevailing today in the future. Over the coming years, the development and application of Additive Fabrication will be further separated into the two areas 'professional applications' (Additive Manufacturing) and 'Do-it-yourself applications' (fabbing). But professional product ideas that a user creates for personal use can be placed in the latter category as well. Important topics in this respect are noise and sound, material and recycling as well as climate and comfort.

- **What effect can an integration of high-tech technologies have on building technology?**
  New technologies offer new opportunities in the transformation of the long existing digital designs into built reality. From an increasing combination of digital design and digital manufacturing an ever greater precision will be the result. Significantly improved products can be the result, if the available tools - analogue and digital – are used effectively. For the building envelope, this means a more user-oriented and diverse performance, more reliable details, enhanced durability and reliability. However, with the implementation of new technologies the human factor remains a crucial part of it.

§ 5.2 Open questions

Some of the unresolved issues on the path to an AM Envelope are:
- the repair of enclosed parts;
- the recycling of high-tech composite materials ('Design for Disassembly');
- the replacement or exchange of individual functional parts (How can we repair structures made of printed glass from Direct Glass Fabrication?);
- the formal and technical enhancements and additions to enclosed structures (How can we add to a printed building?);
- the readjusting of customized products (How do integral structures respond to changes that result from modified usage? How truly flexible are perfectly integrated façade constructions, for example when the user changes?).

Based on today's knowledge, possible solutions are:
- hand-held units that can be used to repair small defects;
- lasers with different focal lengths that allow melting repair material inside enclosed parts;
- mono-material parts, where a separation of the different materials for recycling is unnecessary because the individual part is generated with one homogeneous material (see § 4.2.1 / Mono Material Recycling Element); after use, these components can be shredded to granulate and thus fully recycled;
- the use of self-healing materials ensures that the part repairs itself when broken or worn.

As already stated in § 2.6.3 the challenges of further developing AM for façade technology can be categorised in 'material', 'technology' and 'production':

- Material:
  - the physical properties of AM products: they need to mimic generally accepted mass products;
  - the materials used under consideration of cost, properties, reworkability and standardisation;
  - accuracy of the fabricated products in terms of product properties such as surface finish and dimensional accuracy;
  - programming and fabrication of Functionally Graded Materials (FGM).
- Technology:
  - the possibility of exact reproducibility of identical parts across different production batches and with different yet technically identical equipment;
  - producible product size: in macro as well as micro range;
  - process speed;
  - achieved resolution with largest possible form, smallest printable detail.
- Production:
  - software access for the user: intuitive processing of 3D data;
  - cost efficiency compared to conventional building products;
  - lower manufacturing cost with AM (equipment cost, maintenance, material cost)

In order to promote further considerations about the use of Additive Fabrication in façade construction it is necessary to:

- differentiate the use of AM between the different production stages of façade construction (production, component assembly, assembly on-site, inventory, performance);
- achieve a deeper understanding of the potential and possible added value that AM offers: performance, material savings (in production and the system), functional constructions (component reduction, snap functions, etc.), marketing of the technology ('AM inside'), optimised stock-keeping (on-demand production, just-in-time management), digital designing (freedom of geometry, technically improved joints, load-transfer optimised building parts, combination of different functions in fewer component layers;
- understand the potential and let it flow into better constructions aiming for a dynamic envelope;
- clarify everyone's expectations concerning the integration of the technologies into building technology, and to formulate realistic options in terms of realising customer wishes;
- test and evaluate the potential using a real project on a 1:1 scale, and to draw a realistic conclusion relevant to the herein stated theses.

(see [2] [3]).

§ 5.3 Explicit benefits for the façade

Wim Michiels, Executive Vice President of Materialise in Belgium – one of the market leading service providers in AM – states the following as his personal top 4 reasons to consider AM:

- added value;
- cost reduction;
- environmental considerations;
- cultural trends.

[4]

Initially, these benefits are explicitly related to the area of manufacturing parts in plastics. However, at the same time they are the main drivers to further promote the technology in general. The mentioned added value is related to the freedom of design and the benefits of the production process. Closely linked are the large possible savings related to different areas of production (stock keeping, shipping, material requisition, etc.). Environmental compliancy is a topic often discussed in the AM industry. But it must be noted that today AM technologies are energy intensive and therefore not resource friendly. However, when discussing primary energy, the facts that local production can eliminate long transport distances and that possible fuel savings by using light weight components particularly in aviation can lead to the conception of AM as a 'green' technology. The last item on the list addresses a change in society. It refers to the increasing demand for individualised products and personal influence on design and production that is supported by digital tools.

These arguments for a general growth of the AM technologies can be transferred to and are also valid for the façade technology: The named benefits are the driving forces for all economic changes and the adaptation of innovation to a business model.
Additionally, façade-related criteria can be added to the list of reasons above. They support the application of AM specifically in façade construction:

- independence of scale;
- mass customisation for one-off projects;
- rapid product development = optimisation with every new generation of a product; every new print allows for enhancements, based on user feedback and user demands.

§ 5.3.1 Nematox II – a realistic approach to system façades?

Related to the actual façade technology of a post-beam system, the following, already realised benefits can be drawn from the experiences with the Nematox façade node:

- digital deformation and digital fitting;
- cut optimisation;
- diffusion of building technical difficulties related to crossover points (water circuits, sealing joints);
- digital coding of building parts;
- possible parameterisation of complex geometries across the system;
- diffusion of assembly issues on-site (sealing, accuracy, material waste);
- individual façade geometries, with cutting processes that work for all projects worked on the system, that means all accessories and tools from the standard façade system can still be used.

The current version of the 'Nematox II' is a prototype. However, following the logical consequence of the initial developmental steps, it was further developed with smaller parts of the façade system. The above mentioned advantages are the result of an intensive discussion about today's façade construction and production. Combined with Additive Fabrication they break the path to new shores for the rather conservative building sector.

Even though prototypes clearly show the benefits, these benefits are not necessarily obvious at the beginning of a planning task. Often, the potential for optimisation can only be derived from an intensive use of a well-established standard. Potential only shows when alternative solutions to hitherto unknown disadvantages become available. Established ways of thinking cannot be changed overnight; new thought methods must be learned and trained. And they must be based on arguments; and such arguments are highlighted by a comprehensible physical representation of the virtual product. This is where we come full circle to the origins of the AM development: The initial goal was to illustrate ideas that needed to be discussed between designer and customer, for example colour, shape and feasibility. Today, a prototype made with such systems serves as the basis for discussion of the performance properties of the technology itself. Only when a technician can physically touch and thus comprehend a model will he/she start believing in the technology.
Initial conversations with and feedback from building envelope specialists consistently show that little explanation is necessary as far as performance goes – even though the presented node is only the very first step of the development. Possible AM solutions for failed projects become immediately apparent when viewed on the basis of the newly gained knowledge. And the initially high cost per item for the prototypes has dropped so far during the time of this study that this discussion-ending argument from four years ago is not truly valid anymore. The only thing lacking after the presented 'proof of concept' is a real-life trial in an actual façade project.

Therefore the Nematox II can be looked upon as a realistic approach to improve system façades with AM.

§ 5.3.2 AM Envelope as a tangible goal

AM will never replace established production processes but rather complement them where this seems practical. AM is not the proverbial Swiss-army knife that can resolve all of today's façade issues! But it is a tool that might be able to close another link in the 'file-to-factory chain'. AM allows us a better, more precise and safer realisation of today's predominantly free designs that are based on the algorithms of the available software. With such extraordinary building projects, the production of neuralgic system components will become reality in the near future – today, an AM Envelope is close at hand. Still, 'printing' entire buildings lies in the far future; for a long time human skill and craftsmanship will be needed on the construction site combined with high-tech tools to translate the designers' visions into reality.

If AM is to be used as an independent production method, then this method must open up an independent genre within the building sector that is autarkic and revolutionary; which consequently means that it is no longer limited to the façade, load-bearing structure or enclosing envelope. The new production method should, however, be solely based on AM in order to avoid watering down the large potential of 'printed architecture' by mixing it with conventional methods.

§ 5.4 The potential of AM for façade construction

What is the ultimate assessment of the potential of AM technologies for the building envelope?

Without focussing too much on one particular aspect of the 'new architecture', we must ask who will benefit from this discussion? Is the main underlying goal of these developments to change or improve design and appearance? Or are they also about changing the way we build, thus changing building technology?
The discourse who or what will benefit from implementing the new technologies is not the primary subject matter of this work. But we must have this discussion in order not to degrade the potential that these technologies offer to an end in itself, which would mean falling far short of the possibilities. Related to AM, the considerations must go beyond merely translating free-form designs into built structures – it is all about changing and improving building technology.

§ 5.4.1 Feasibility

Here fore, the first item on the agenda must be to ensure feasibility; feasibility of all aspects of production with AM because all areas of AM applications need to be considered:

- in terms of system technology. Technical limitations must be resolved in the foreseeable future. However, existing boundaries can only be extended if visionary approaches are developed that challenge the developers of the technology.
- in terms of an application in façade technology, and ultimately in architecture. However, a more important criterion is the feasibility of the designs: 'Clean files' are needed to realise 'file-to-factory' processes, a challenging task. Designs must reflect the differentness of their realisation in order to justify the applications of new technologies. Consequently, the change in designing must be preceded by a different way of thinking about construction, or at least this must flow into a growing knowledge base.
- in terms of changing the appearance of digital designs. 'The chicken or the egg?' Will the designs need to follow the new technology, or will we need to find technical solutions to realise free-formed designs? Obviously, this study was based on the latter assumption; there are great opportunities to generate new design methods based on a thorough understanding of the technologies ('Digital craftsmanship'). We are at a crossover point between historically grown engineering – with all of its advantages and disadvantages – and the digital age that has been promised for thirty years, and should have made 'flux capacitors' ('Back to the future')

and 'replicators' ('Star Trek – The next generation') common technologies. Even though AM does not yet allow us to dematerialise organisms in one place and re-materialise them in another, it is possible to send architectural drawings to virtually any place on earth via the internet where they can be translated from a virtual to a physical state by means of the technology. This means that our method of production and handling goods has already changed.

§ 5.4.2 Improvement of building construction

Improved building technology as a main consequence of the potential offered can be subdivided into several aspects:

the general requirement to improve building technology is related to its functionality and therefore the functionality of the building components. The overall technology can only be optimised if the sub-aspects are optimised. AM offers the opportunity to increase functionality (ease of assembly, component simplicity, system-wide functionality, flexibility). The functions of the individual elements can, in turn, be improved by the new way of constructing (integration, multi-functionality)

- in addition there is the connection of different parts of the digital production chain (file-to-factory). The challenge here is to improve the processes and the interconnectivity between the individual steps of the digital development and digital production. AM is an opportunity to fulfil this demand if it is used as one part of the process.

§ 5.4.3 Requirements for the future handling of AM

The potential of AM for façade construction is great if the necessary steps are taken to employ it sensibly. Requirements on how to handle the AM technologies from here on out can be derived from the findings:

- certification / standardisation of the methods;
- intuitive application of the technology;
- easier file generation;
- testing in the façade industry / building industry;
- demand for building-relevant materials;
- interdisciplinary teams for further integration into façade production;
- technology transfer to hybrid production methods.

§ 5.4.4 Quality standards

No quality standards or norms have yet been established for products manufactured with AM technologies. A catalogue of traceable criteria must be developed so that products can be compared to each other and to conventional mass products. A rating system for the manufactured parts, quality standards for the available methods, and materials as well as quality control for the individual methods are key requirements when developing a mutually accepted manufacturing method. The methods must be certified, i.e. authorised by building law in order to be used in façade technology. Thus, individual AM methods can obtain official technical approval based on a specification of the targeted material parameters.

In order to allow for wider spread use, the software should be even more intuitive. Similarly to Building Integrated Modelling (BIM), the user must be able to set parameters while generating the file that defines the realisable properties of the AM product and tailor it to a particular AM method. Expert knowledge is still needed for 3D modelling and parametric designing; however, after the next generation change this will no longer be considered a boundary.

Integrating AM into a façade system must be tested under realistic conditions. Only the experiences gained during a defined building project will yield the necessary knowledge.

Considering such testing, it is obvious that other materials than metals come into question as well if they exhibit the properties necessary for use in the façade. In this context, the often cited comparison between the innovative automotive industry and the building industry is very poor: Because, due to very different maintenance intervals and very different liability and safety requirements the often advocated demand to deal with new materials more courageously cannot be directly compared for the two industry sectors. On average, a car is checked by a technical inspection agency every one or two years, and often undergoes even more inspections between these intervals. After assembly, a façade, on the other hand, must function for thirty years and more without the possibility to conduct such inspections in an economically reasonable manner. Against this background the building industry's reluctance to test new materials in a real project is understandable. We can only plan reliably with AM products if the methods are certified as reliable production methods.

Therefore, an application of Additive Fabrication in façade technology must clearly be targeted toward complementing conventional production methods, not replacing them. A hybrid integration of various production methods leads to the desired – and economically reasonable – solutions. AM is one building block of a whole.

§ 5.4.5 Advancements

To finalize this dissertation, advancements need to be clearly stated, that are to be expected from Additive Manufacturing for building envelopes:

- a change of the production methods corresponding to the digital revolution - now also in the physical world;
- a change of engineering toward 'Funktionales Konstruieren' (functional constructing) – turning the known engineering upside down;
- today's protagonists in the building industry to turn toward 'Digital Craftsmanship';
- technical and formative added value;
- greater freedom in design and function integration.

Because we are used to think subtractive rather than functionally it is difficult to identify suitable AM applications for the building technology. Still, the general discussion and growing awareness resulting from the described benefits of additive methods will generate many new construction principles. This development is still in the beginning stage; but AM offers the potential to lastingly change design and manufacturing methods.

"The goal is no longer to design according to production method, but to produce according to design idea."[7] [5]

References chapter 5

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6 Summary

§ 6.1 Summary

This dissertation shows the potential of Additive Manufacturing (AM) for the development of building envelopes: AM will change the way of designing facades, how we engineer and produce them. To achieve today's demands from those future envelopes, we have to find new solutions.

New technologies offer one possible way to do so. They open new approaches in designing, producing and processing building construction and facades. Finding the one capable of having big impact is difficult – Additive Manufacturing is one possible answer.
The term 'AM Envelope' (Additive Manufacturing Envelope) describes the transfer of this technology to the building envelope. Additive Fabrication is a building block that aids in developing the building envelope from a mere space enclosure to a dynamic building envelope.

First beginnings of AM facade construction show up when dealing with relevant aspects like material consumption, mounting or part's performance.
From those starting points several parts of an existing post-and-beam façade system were optimized, aiming toward the implementation of AM into the production chain. Enhancements on all different levels of production were achieved: storing, producing, mounting and performance.

AM offers the opportunity to manufacture facades 'just in time'. It is no longer necessary to store or produce large numbers of parts in advance. Initial investment for tooling can be avoided, as design improvements can be realized within the dataset of the AM part. AM is based on 'tool-less' production, all parts can be further developed with every new generation.
Producing tool-less also allows for new shapes and functional parts in small batch sizes – down to batch size one. The parts performance can be re-interpreted based on the demands within the system, not based on the limitations of conventional manufacturing. AM offers new ways of materializing the physical part around its function. It leads toward customized and enhanced performance.

Advancements can for example be achieved in the semi-finished goods: more effective glueing of window frames can be supported by Snap-On fittings. Solving the most critical part of a free-form structure and allowing for a smart combination with the approved standards has a great potential, as well.

Next to those product oriented approaches toward future envelopes, this thesis provides the basic knowledge about AM technologies and AM materials.

The basic principle of AM opens a fascinating new world of engineering, no matter what applications can be found: to 'design for function' rather to 'design for production' turns our way of engineering of the last century upside down. A collection of AM applications therefore offers the outlook to our (built) future in combination with the acquired knowledge.

AM will never replace established production processes but rather complement them where this seems practical. AM is not the proverbial Swiss-army knife that can resolve all of today's façade issues! But it is a tool that might be able to close another link in the 'file-to-factory chain'. AM allows us a better, more precise and safer realization of today's predominantly free designs that are based on the algorithms of the available software. With such extraordinary building projects, the digital production of neuralgic system components will become reality in the near future – today, an AM Envelope is close at hand. Still, 'printing' entire buildings lies in the far future; for a long time human skill and craftsmanship will be needed on the construction site combined with high-tech tools to translate the designers' visions into reality. AM Envelope is one possible result of this!

§ 6.2 Samenvatting

Dit proefschrift toont de potentie aan van Additive Manufacturing (AM) voor de ontwikkeling van gevels: AM zal van gevels de wijze van ontwerpen en ook de wijze van construeren en produceren veranderen.
Om te voldoen aan de eisen van de toekomstige uitwendige scheidingsconstructie moeten er nieuwe wegen ingeslagen worden. Nieuwe technologieën bieden daarvoor de mogelijkheid. Ze openen nieuwe wegen voor het ontwerpen en produceren en voor nieuwe implementatiestrategieën.
De juiste technologie te vinden voor de bouwenvelop is een uitdaging – AM is hierop een mogelijk antwoord.

De term AM Envelope (Additive Manufacturing Envelope) beschrijft het overbrengen van deze technologie naar de uitwendige scheidingsconstructie van een gebouw. De additieve werkwijze is een bouwsteen, welke helpt bij de ontwikkeling van de gevel van een louter fysieke barrière naar een meer dynamische bouwenvelop.

De eerste toepassingen van AM in de geveltechniek, laten de mogelijkheden zien van relevante aspecten als materiaalgebruik en montage, maar ook de prestatiemogelijkheden bij individuele bouwdelen.
Vanuit deze uitgangspunten werden verschillende onderdelen van een bestaand "stijl- en regelwerk" gevelsysteem geoptimaliseerd, met als doel de productiemethoden van AM te testen, te optimaliseren en te verbeteren.
Op allerlei productieniveaus werden verbeteringen bereikt: opslaan, produceren, monteren en kwaliteit. AM biedt de mogelijkheid om gevels "just in time" te vervaardigen. Het is niet langer nodig om grote aantallen vooraf te produceren of in voorraad te hebben. Initiële investeringen van gereedschap zijn niet meer nodig, verbeteringen van het ontwerp kunnen worden gerealiseerd via de dataset van het AM onderdeel. AM is gebaseerd op productie zonder gereedschap, waarbij alle onderdelen in de toekomst verder doorontwikkeld en aangepast kunnen worden.
Gereedschapsloze productie maakt de weg vrij voor nieuwe vormen en functionele bouwonderdelen in kleine aantallen. De deelprestaties van onderdelen kunnen geïnterpreteerd worden op basis van de vragen binnen het systeem en niet gebaseerd op de beperkingen van conventionele productiemethoden. AM biedt nieuwe wegen van materialisatie van speelruimte tot individuele functionaliteit en een verbeterde prestatie.
Het leidt tot nieuwe mogelijkheden met betrekking tot klantvriendelijkheid en verbeterde prestatie.
Verbeteringen kunnen bij voorbeeld gebruikt worden bij het optimaliseren van halffabricaten: effectievere verlijming van kozijnprofielen met behulp van klikprofielen.
Het oplossen van het meest kritische onderdeel van een vrije vorm structuur en de

mogelijkheid van een slimme combinatie met goedgekeurde normen, geeft grote mogelijkheden.

Naast deze productgerichte aanpak in de richting van de toekomstige verbeterde bouwenvelop levert dit proefschrift de basiskennis over AM technologieën en AM materialen.

Het basisprincipe van AM opent een fascinerende nieuwe technische wereld, ongeacht welke toepassingen er bedacht worden: Het “ontwerpen voor de functie” in plaats van “het ontwerpen voor de productie” zet onze wijze van engineering van de afgelopen eeuw op zijn kop. Een verzameling van AM toepassingen geeft daarom, in combinatie met de verworven kennis, een blik naar onze (gebouwde) toekomst.

AM zal nooit gevestigde productieprocessen vervangen, maar aanvullen daar waar het zinvol is. AM is niet het spreekwoordelijke Zwitserse zakmes, dat alle huidige gevelproblemen kan oplossen! Maar het is een instrument dat misschien in staat is een slimme link te maken in de productieketen. AM stelt ons in staat om veel voorkomende vrije ontwerpen beter, preciezer en veiliger te verbeteren en uit te voeren, gebaseerd op de algoritmen van de beschikbare software.
Met dergelijke buitengewone bouwprojecten, zal de digitale productie van neuralgische systeemcomponenten in de nabije toekomst – nu – werkelijkheid worden, een AM Envelope is dichtbij. Toch ligt het printen van gehele gebouwen in de verre toekomst; nog lang zal menselijke vaardigheid en vakmanschap, gecombineerd met high-tech gereedschap nodig zijn op de bouwplaats om de visie van de ontwerper tot realiteit te maken. AM Envelope is hier een mogelijk resultaat van!

§ 6.3 Zusammenfassung

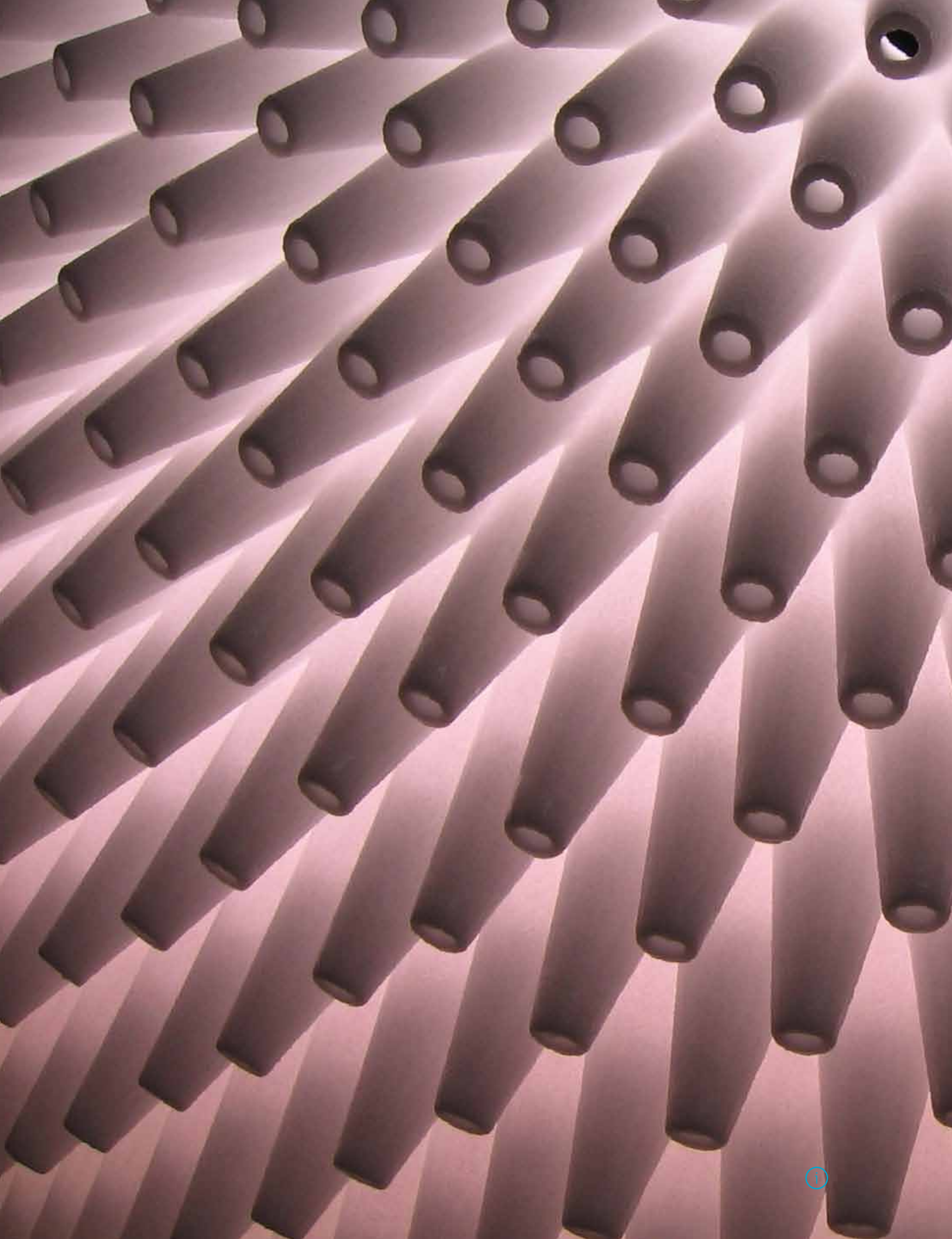
In dieser Dissertation wird das Potential der additiven Verfahren für die Entwicklung von Fassadenkonstruktionen aufgezeigt: die Additiven Verfahren (Additive Manufacturing - AM) verändern die Art und Weise, wie wir Gebäudehüllen entwerfen, wie wir sie konstruieren und produzieren.
Um den heutigen Anforderungen an die Gebäudehülle gerecht werden zu können, müssen neue Wege beschritten werden. Neue Technologien bieten einen Ansatz zur Entwicklung neuer Herangehensweisen, neuer Produktionsweisen und neuer Umsetzungsstrategien. Die richtige Technologie für die Verbesserung der Gebäudehülle zu finden, ist eine Herausforderung – AM ist eine mögliche Lösung auf dem Weg.
Der Begriff „AM Envelope" (Additive Manufacturing Envelope) beschreibt den Transfer dieser Technologie in die Gebäudehülle. Die additiven Verfahren stellen einen Baustein dar, der die Weiterentwicklung der Gebäudehülle vom reinen Raumabschluss hin zu einer dynamischen Gebäudehülle unterstützt.

Erste Ansätze zur Anwendung von AM in der Fassadentechnik zeigen sich bei der Betrachtung der relevanten Aspekte wie Materialverbrauch, Montage, aber auch bei der Leistung einzelner Bauteile. Über diese Aspekte wurden erste Bauteile aus einem bestehenden Pfosten-Riegel-System ausgewählt, und mit dem Ziel, AM als Produktionsverfahren zu erproben, optimiert und verbessert.
Verbesserungen konnten hierbei in allen Phasen der Herstellung einer solchen Fassade erzielt werden.
Die additiven Verfahren ermöglichen ein Just-Intime-Management im Produktionsablauf. Lagerhaltung und Vorproduktion großer Produktmargen entfallen. Ebenfalls können Investitionskosten zum Beispiel für den Werkzeugbau eingespart werden, wenn neue oder veränderte Bausteine im System benötigt werden. Mit AM wird werkzuglos gefertigt. Alle notwendigen Informationen werden digital in einen Datensatz implementiert und führen somit zu Bauteilen, die stetig weiterentwickelt und angepasst werden können.
Die werkzeuglose Fertigung ermöglicht neue Geometrien und funktionale Bauteile in kleinen Stückzahlen. Dies eröffnet bei der Herstellung und Montage der Fassadensysteme neue Möglichkeiten. Ausformungen einzelner Teile eines Systembausteins werden nicht mehr von den konventionellen Herstellungsverfahren bestimmt, sondern können mit AM neu interpretiert werden. Die Herangehensweise bei der Umsetzung einer technischen Anforderung wird in Zukunft von der Funktion gelöst, und nicht mehr durch die Herstellbarkeit limitiert. AM eröffnet also bei Herstellung und Montage neue Spielräume für individualisierte Funktionalität und verbesserte Leistung.
Eine verbesserte Leistung kann sich zum Beispiel bei der Optimierung von Halbzeugen zeigen. Leistungsstärkere Komponenten können hierbei zu einer Verbesserung des Endprodukts führen – beispielsweise bei der schnelleren Verklebung von Rahmenprofilen durch selbst stützende Schnapp-Mechanismen. Eine andere

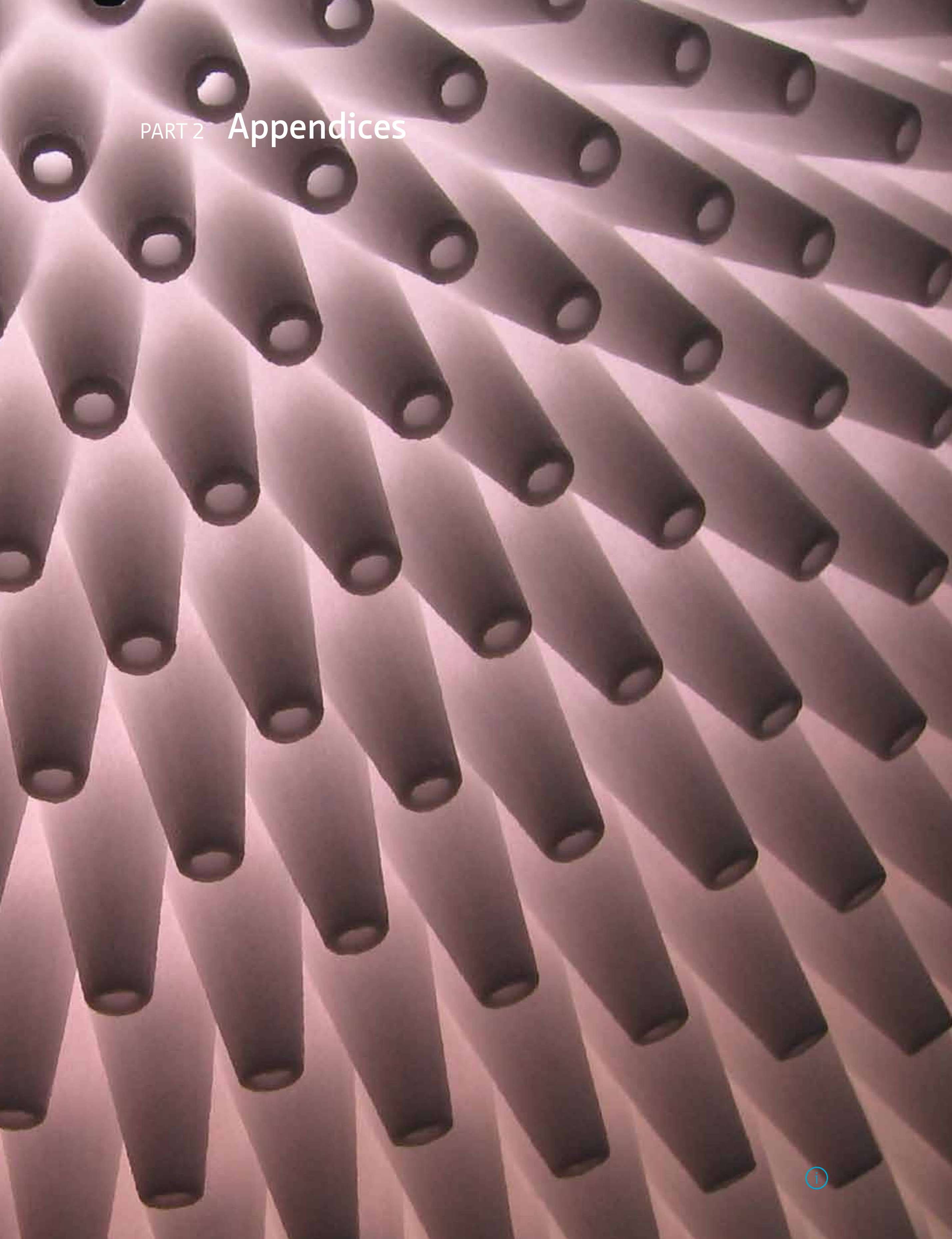
Leistungssteigerung kann bei der Lösung von neuralgischen Problempunkten erfolgen. Werden beispielsweise Verformungen der Tragstruktur ausschließlich an wenigen, aber entscheidenden Punkten gelöst, kann der verbleibende Anteil der Konstruktion weiterhin mit den bekannten Standards abgedeckt werden.

Neben diesen stark produktorientierten Lösungsansätzen für die verbesserte Gebäudehülle vermittelt die Arbeit auch das Hintergrundwissen zu den AM Technologien und zu den verwendeten Materialien.
Das grundsätzliche Prinzip ‚AM' fasziniert unabhängig von einer konkreten Anwendung: das Funktionale Konstruieren stellt das Ingenieurswissen der vergangenen hundert Jahre auf den Kopf.
Eine Sammlung von Anwendungsideen bietet hierzu die Möglichkeit das neue Wissen zu den Technologien mit einem Blick auf unsere (gebaute) Zukunft zu verbinden.

Nie wird AM die etablierten Produktionsabläufe ganz ersetzten, sondern sie immer nur dort ergänzen, wo es sinnvoll ist. AM ist keine Allzweckwaffe, die alle heutigen Probleme in der Fassade lösen kann! Aber AM ist das Werkzeug, welches es schaffen kann ein weiteres Glied in der Produktionskette zu schließen. Mit AM wird es möglich, die heute zunehmend freieren Entwürfe besser, genauer und sicherer umzusetzen. Die Gestaltung ergibt sich dabei aus den Algorithmen der verfügbaren Software.
Und auch bei der Umsetzung dieser Bauaufgaben lässt sich die Herstellung der neuralgischen Systemkomponenten mit den digitalen Werkzeugen schon in der nahen Zukunft ablesen - ein AM-Envelope ist heute in greifbarer Nähe. Trotzdem werden zunächst keine ganzen Gebäude „gedruckt" und es wird noch für eine lange Zeit das menschliche Geschick auf der Baustelle gefordert sein, welches es ermöglicht mit den High-Tech Werkzeugen die Visionen der Planer umzusetzen. Gedruckte Gebäudehüllen sind ein mögliches Ergebnis davon!



PART 2 Appendices



A I Additional information AM

AM history

The actual motivation behind the development of Additive Fabrication – that means the possibility of creating physical parts from virtual data – is shrouded by various myths.

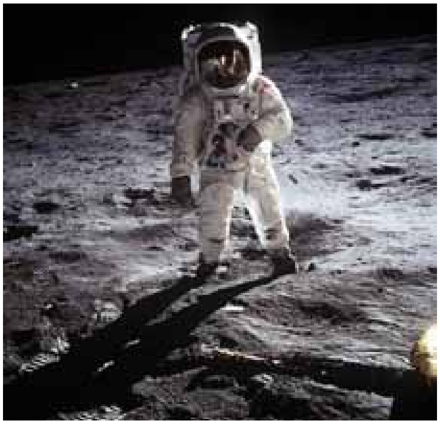


Figure 86

Left: Astronaut Buzz Aldrin, lunar module pilot, walks on the surface of the Moon near the leg of the Lunar Module (LM) "Eagle" during the Apollo 11 extravehicular activity (EVA). Astronaut Neil A. Armstrong, commander, took this photograph with a 70mm lunar surface camera.
Right: Astronaut Eugene A. Cernan, Apollo 17 mission commander, makes a short checkout of the Lunar Roving Vehicle during the early part of the first Apollo 17 extravehicular activity (EVA-1) at the Taurus-Littrow landing site. This view of the "stripped down" Rover is prior to loadup. This photograph was taken by Geologist-Astronaut Harrison H. Schmitt, Lunar Module pilot. The mountain in the right background is the East end of South Massif. Imagery courtesy by NASA.

One states that the fundamental idea to develop additive methods came from NASA. According to unverified sources, NASA tried to give its astronauts digital building plans for spare parts and other items to take on their travels to new planets. Instead of physical parts only digital building plans as well as a 'printer' were to be taken along to save space and weight.[1] [2]

This thought was taken up and interpreted by other inventors. An approach by Prof. Bherokh Khosnevis was aimed at creating housing on the moon with ContourCrafting (see § 2.2.4.1). The goal of the approach is to exploit locally available materials – in this case lunar dust – to generate structures with layering methods. The underlying thought is the same: Digital building plans contain all necessary information about performance and manufacturing strategy, and an AM system materialises the parts with little hardware requirements. Physical parts are generated from 3D data with regional materials and a targeted use of the technology.[3] [4]

Figure 87
ContourCrafting: Printed model of a lunar cupola structure (left); internal structures of cupola with printer head (right). Imagery courtesy by B. Khoshnevis.

Build-up welding and additive methods have also been applied for direct manufacturing of metal parts for the military. The U.S. Army employs so-called 'Mobile Parts Hospitals', which are used to repair defect vehicle parts or to fabricate spare parts with CAD data or reverse engineering directly in the operational area. Repair times for emergency and other vehicles are thus significantly reduced. The mobile workshop is setup in a 20 foot container, and can be shipped to the operational area just like any other gear by air, by sea or by land. Due to the limited space available, only very effective and versatile tools are used on board. This requires that the production data is available as 3D data records (point clouds und scanner files), as well as the possibility to create various shapes with a limited number of tools. In addition to the additive methods, high-speed milling machines are used for this purpose.

[5] [6]

Characteristic tables of AM processes – plastics

The profiles of the individual methods provide a detailed overview of the method, the manufacturers and a link to respective web pages.

Laser Sintering

AM process	(Selective) Laser Sintering	
Abbreviation	LS (SLS)	
Main-Application	Prototyping, Manufacturing of end use parts, Tool making (mounting devices, positioning devices)	
Material	Plastics: Polyamide, PEEK, Alumide Other: Ceramics	
Invented by	DTM, USA	
Year	1992	
Manufacturer	EOS	3D Systems
Building Chamber (mm)	700x380x580	550x550x750
Material	Polyamide, Peek	Polyamide
System	EOSINT P 730	sPro 230
URL	http://www.eos.info/	http://www.dimensionprinting.com
Further information	The process heat required for this method means that the models need to cool before they can be removed from the system. According to EOS, Germany, the duration of the cooling phase equals the duration of the actual sintering process. If some thermoplastics are heated, the structure can change which in turn can influence the material properties of the finished model. Therefore, if used powder is reused, the manufacturers specify the required percentage of new powder to be added to the process. LS is also employed to generate models made from other powders (Alumide) and ceramic casting moulds. For both applications the raw powder is encased in a polymer coating. The sintering process causes the polymer to melt which in turn allows the raw powder to melt. The properties of parts made of Alumide are closer related to those of polyamide parts than those made of aluminium; the results are not metal parts! With ceramics, the results are so-called green shapes (unfinished models) that are cured in a subsequent process. The polymer is burnt out and the porous structures are filled with infiltration material.	

Stereo Lithography Apparatus

AM process	Stereo Lithography Apparatus	
Abbreviation	SLA (sometimes STL)	
Main-Application	Prototyping	
Material	light curing resins (Photopolymers):	
Invented by	3D Systems, USA	Chuck Hull
Year	1987	
Manufacturer	3D Systems	Materialise
Building Chamber (mm)	650x750x550	2100x700x800
Material	Epoxy resins, acrylic resins	Epoxy resins, acrylic resins
System	iPro 9000 SLA Center	Mammoth
URL	http://www.3dsystems.com	http://www.materialise.com/
Further information	Stereolithography was the forerunner to AM. Compared to later developments it still has an advantage in terms of accuracy and resolution. The type of resin used varies greatly; each manufacturer offers optimised material compounds for a particular system. Professional systems are relatively large. Therefore, they are not yet suited for office use. A SLA system requires several peripheral devices such as a special chamber to remove support structures, for example, a pre-heater for the resin cartridges, a quick mount module for a second process chamber, and a post-process curing chamber. Compared to other equipment for plastic part manufacturing, these systems are expensive. The resins used are not long-term UV or humidity resistant. Therefore, their use in the building sector is questionable.	

Fused Deposition Modelling

AM process	Fused Deposition Modelling	
Abbreviation	FDM	
Main-Application	Prototyping, Tool making (mounting devices, positioning devices)	
Material	Plastics: ABS, Nylon, Wax (casting cores)	
Invented by	Stratasys, USA	Scott Crump
Year	1991	
Manufacturer	Stratasys	Dimension
Building Chamber (mm)	914x610x910	254x254x305
Material	ABS, ABSplus	ABS, ABSplus
System	Fortus 900mc	Elite
URL	http://www.stratasys.com	http://www.dimensionprinting.com
Further information	FDM is distributed via various licence holders: Alphacam, Fortus, Hewlett-Packard, Dimension, etc. An extrusion nozzle processes the strings of material at approximately 280°C. Different nozzle diameters are available, and the melting temperature can be accurately controlled on the nozzle. Coloured materials can be used. However; since each material must be placed into the system individually, colour gradients or colour mixes are not possible. FDM can also be used to make melt-out models for casting. In general, FDM can be used with all meltable materials (see chapter 4.2: ‘Direct Glass Fabrication’). FDM systems are suitable for office use and are relatively quiet.	

3D Printing

AM process	3D Printing		
Abbreviation	3DP		
Main-Application	Prototyping, Manufacturing (artefacts of art pieces), Tool making (casting cores)		
Material	Other: starch, gypsum, casting sand, PMMA		
Invented by	Massachusetts Institute of Technology, USA		
Year	mid 1990's		
Manufacturer	Z-Corporation	3D Systems	Voxeljet
Building Chamber (mm)	254x381x203	550x393x300	4000 x 2000 x 1000
Material	Gypsum	Gypsum	casting sand, PMMA
System	Zprinter 650	sPro 230	VX4000
URL	http://www.zcorp.com	http://www.3dsystems.com	http://www.voxeljet.de
Further information	The infiltration with epoxy resin or instant adhesive can be done by dipping, coating or soaking. Due to the lower density of the materials used, the durability of 3DP models is lower than that of SLA or SLS models, but is comparable to that of brittle plastics. Final stability largely depends on the geometry and property of the individual model. Filigree parts will remain fragile whereas larger, more complex parts are more robust. The colour spectrum corresponds to a 24 bit true colour rendition. However, since a binding agent is used instead of a black colour cartridge, true shades of black cannot be rendered. Different from the actual CMYK palette, all colours are created using the three colours available. Full colour intensity only becomes visible after infiltration. 3DP models are also used as intermediate products for further use in printing block fabrication and moulding technology. Thus, German system manufacturer Voxeljet has established their systems in the field of supplies for casting core manufacturing. The powder material for this process consists of silica sand bonded with an inorganic binder. The results are fragile casting cores that are used to fabricate metal casting moulds. Foundries have recognised the 3DP method as an opportunity to generate geometrically demanding parts directly from CAD data. All of the necessary supply and exhaust lines, lifting and fixing points are directly integrated in the CAD model. Particularly with Voxeljet, industry demands have caused the company to drastically enlarge the process chambers of their systems. Systems with process chambers as large as 4 x 2 x 1 metre have been built to produce casting cores for large ship's engines and body parts! In order to be able to handle such process chamber dimensions, Voxeljet has chosen a combination of the 3D Printing and the Inkjet technologies. On their system 'VX4000', 26,650 serially connected print nozzles deposit a 1.12m wide bed of powder with an inorganic binder. (see chapter 2.4) Voxeljet's systems feature a layer thickness resolution of 0.08 – 0.15 mm. Advanced technological developments allow considering new areas of application, for example in the field of manufacturing replicas. Herewith, deceivingly real replications of works of art can be created. A 3D scanner first collects the precise dimensions of the item, then transforms the data into a print-ready file, and finally creates it based on all necessary information about chromaticity and surface structure. This application can be used by museums and galleries to preserve original works of art, or to make others that are not fit for display, accessible to the public.		

InkJet

AM process	InkJet	
Abbreviation	PolyJet (Objet, Israel) MultiJet (3D Systems, USA)	
Main-Application	Prototyping, Manufacturing Manufacturing of end use parts (design parts), Tool making (mounting devices, positioning devices)	
Material	Plastics: Light-curing, viscous plastics;	
Invented by	PolyJet: Objet Geometries, Israel	
Year	Mid 1990ies	
Manufacturer	Objet	3D Systems
Building Chamber (mm)	500x400x200	550x393x300
Material	Acrylate	Acrylate
System	Connex500	ProJet5000
URL	http://de.objet.info	http://www.3dsystems.com
Further information	Great progress has been made in the area of materials. With the PolyJet technology it is possible to mix numerous gradients of the two original materials directly onto the process platform, using so-called 'digital' materials. Because the material is deposited droplet by droplet, the base materials mix at the predefined ratio when hitting the building platform. Here fore, the digital model of an object contains the information about the mix ratio that is predetermined in percentaged gradation. Thus, different areas of the part can feature different material properties. We know this from handles with hard as well as soft parts, for example, or remote controls with a hard casing but soft buttons. This is of great advantage for realistic prototype production (for example for flexible joints, rubber soles, springs a. o.). Currently, the systems support up to six pre-programmed material mixes made up of two base materials each. Further development depends on improving the software, not the system technology. It is not yet possible to program a 3D model such that different materials are allocated within a part (solid). Manufacturability of digital materials marks a significant step in material and system development, and opens up a development of true seamless graded materials (FGM's) on the basis of an available AM process. Even though it is not yet possible to print the materials in a true gradient, meaning with seamless transition, current technical feasibility already points toward the next step: programming true seamless gradient materials (see chapter 2.4).	

Selective Laser Melting

AM process	Selective		
Abbreviation	SLM		
Main-Application	Rapid Tooling: production parts, Manufacturing: end use parts (aerospace, automotive), Prototyping		
Material	Metal: all kinds of metal powders; metals alloys		
Invented by	MCP. Germany		
Year	2004		
Manufacturer	SLM Solutions GmbH	Renishaw	Realizer GmbH
Building Chamber (mm)	250x250x215	250x250x215	250x250x215
Material	Metal alloys	Metal alloys	Metal alloys
System	SLM 250	SLM 250	SLM 250
URL	http://www.slm-solutions.com	www.renishaw.com	www.realizer.com
Further information	The method was developed by MCP (later MTT Group and SLM Solutions, today Renishaw and SLM Group.). It derives from a research initiative by Fraunhofer Institut, the company Trumpf and the developers Fockele and Schwartz. Following several restructuring efforts within the company (MCP), the later group of companies (MTT), and the separation of the developers, there are three sales channels for the SLM technology today. Research and development is still done in Germany. SLM Solutions GmbH is a direct successor of the original MCP GmbH. There are no requirements in terms of the material powder to be used. The SLM system is an open system that allows the user to test and modify different materials. Since its beginnings the SLM system featured an integrated QM system that generates a detailed protocol with processing parameters for each job. What other system suppliers now advertise as a new development is a long-time established technology with SLM.		

Laser Engineered Net Shaping

AM process	Laser Engineered Net Shaping
Abbreviation	LENS / DMDS
Main-Application	Rapid Tooling: deep-repair applications for engine parts, Rapid Manufacturing: semi-finished parts (aerospace, power plants)
Material	Metal: all kinds of metal powders; metals alloys
Invented by	Sandia National Laboratories, USA
Year	1994 - 1997
Manufacturer	Sandia National Laboratories
Building Chamber (mm)	170 x 220 x 145
Material	Metal alloys
URL	http://www.sandia.gov
Further information	Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration. With main facilities in Albuquerque, N.M., and Livermore, Calif., Sandia has major R&D responsibilities in national security, energy and environmental technologies, and economic competitiveness. Optomec offers ready-to-use systems in various configurations as well as a research system. The latter can be used to test and evaluate different materials.

LaserCusing

AM process	LaserCusing
Main-Application	Rapid Tooling: production parts, Manufacturing: functional parts, Prototyping
Material	Metal: all kinds of metal powders; metals alloys
Invented by	Concept Laser GmbH, Germany
Year	2000
Manufacturer	Concept Laser
Building Chamber (mm)	300x350x300
Material	Metal alloys
System	M3 linear
URL	www.concept-laser.de
Further information	One application for this method is Rapid Tooling; tools can be made with contour conform cooling channels. Examples of such tools are casting inserts for spray tools, cast iron tools, and prototype tools. Another application are finished products made of steel and products for the medical industry. The term 'Cusing' is derived from the first letter of the company name Concept Laser and part of the word fusing.

Electron Beam Melting

AM process	Electron Beam Melting	
Abbreviation	EBM	
Main-Application	Rapid Tooling: production parts, Manufacturing: medical implants (dental, chirurgical), jewellery	
Material	Metal: all kinds of metal powders; metals alloys	
Invented by	Arcam, Sveden	
Year	1997	
Manufacturer	Arcam	
Building Chamber (mm)	200x200x350	300 (diameter) x200 (height)
Material	Metal alloys	Metal alloys
System	A2	A2
URL	http://www.arcam.com	
Further information	Arcam introduced its own development with a particular jet melting method. By using an electron beam instead of a laser, this technology offers advantages in terms of maintenance and energy consumption. In order to increase the processing speed, Arcam developed a 'Multibeam System', which can trace the entire building plan more quickly. Over the past years, Arcam did not work on enlarging the process chamber but rather on fine tuning the technology. Their target market segments are medical applications and jewellery making. These applications do not require large process chambers.	

Direct Metal Laser Sintering

AM process	Direct Metal Laser Sintering
Abbreviation	DMLS
Main-Application	Rapid Tooling: production parts, Manufacturing: medical implants (dental, chirurgical), jewellery
Material	Metal: all kinds of metal powders; metals alloys
Invented by	EOS, Germany
Year	1994 (LS for plastics)
Manufacturer	EOS
Building Chamber (mm)	250x250x215
Material	Metal alloys
System	EOSINT M 270
URL	http://www.eos.info
Further information	EOS developed the first marketable AM system to process metals. It is sold since 1994. In the field of laser sintering, EOS is the global market leader. The development of DMLS was further driven on this background and with the existing machines. Special developments serve niche markets such as the jewellery industry (gold), micro applications in the field of laser sintering or special applications for high-tech plastics (PEEK). EOS only permits their own material mixes to be used on their systems. The warranty policies prohibit testing of new materials or using cheaper industry standard powders.

Electron Beam Free Form Fabrication

AM process	Direct Manufacturing / Electron Beam Free Form Fabrication
Abbreviation	DM / EBF^3
Main-Application	Rapid Tooling: production parts, functional prototypes;
Material	Metal: titanium, stainless steel, nickel and refractory alloys
Invented by	Sciaky, USA
Manufacturer	Sciaky, USA
Building Chamber (mm)	4978x2286x1778 (Moving Gun EB)
Material	Metal alloys
System	VX.4
URL	http://www.sciaky.com
Further information	First invented by NASA engineers, EBF^3 is now turned into DM and is being sold commercially by Sciaky, USA. Advantages of AM: Compared to milled shapes, material cost can be lowered, manufacturing cost and time expenditure for moulding tools are eliminated, small batch sizes down to 1 piece are possible, geometries can be optimised, and hybrid applications with standard methods are sensible.

Direct Laser Additive Manufacturing

AM process	Construction laser additive directe - Direct Laser Additive Manufacturing
Abbreviation	CLAD
Main-Application	Rapid Tooling: production parts, Manufacturing: functional parts
Material	Metal: all kinds of metal powders; metals alloys
Invented by	IREPA-Laser, France
Year	2009
Manufacturer	EasyCLAD Systems
Building Chamber (mm)	1500x800x800
Material	Metal alloys
System	Magic LF6000
URL	http://www.easyclad.com http://www.irepa-laser.com

Direct Metal Deposition

AM process	Direct Metal Deposition	
Abbreviation	DMD	
Main-Application	Rapid Tooling: repair of metal parts; Manufacturing: depositing complex metal alloy powders on massive tool/die components for manufacture and repair in industry applications	
Material	Metal: all kinds of metal powders; metals alloys	
Invented by	POM Group, USA	Dr. Jyoti Mazumder
Year	1996, 2000 (commercial version)	
Manufacturer	POM Group	POM Group
Building Chamber (mm)	673x749x474 (3D axis)	3.2m x 3.665m x 360˚ (robot arm)
Material	Metal alloys	Metal alloys
System	DMD505D	66R
URL	http://www.pomgroup.com/	
Further information	The basic system called "Laser Cladding" was developd at the University of Illinois, later at the University of Michigan by Dr. Jyoti Mazumder. What first started as a 2D machining, later turned into a 3D free form application. DMD was first commercially available in 2000, and still Is distributed by POM. POM was founded in 1998. The Robotic DMD® system offers a work envelope of 1.955m x 2.14m x 330˚ (Model 44R) or 3.2m x 3.665m x 360˚ (Model 66R). Whereby a DMD head is mounted on a 6-axis industrial robotarm. DMD is a direct modification of contract laser welding with AM technologies. In addition to systems that process material powders, there are those working with material in wire form that is supplied to the melting pool automatically.	

Characteristic tables of other AM methods

There are other methods than the AM technologies described in the main part of this dissertation; however, they have no relevance for façade technology. For the sake of completeness they are listed and described here – they complement the overall picture of the diversity of the AM methods. Under consideration of the requirements of adapting the technologies for an application in the façade technology, as described in the main part, they do offer inspiration for further development.

High Viscous Material Ink Jetting

AM process	High Viscous Inkjetting
Abbreviation	
Main-Application	None: aims toward end use parts with multi-materials
Material	plastics: high viscous, UV curing polymers, can be filled with secondary material
Invented by	TNO, Netherlands
Year	2007
Manufacturer	TNO
Building Chamber (mm)	254x381x203
Material	High viscous polymers
System	Beta system
URL	http://www.tno.nl
Further information	The Dutch research institute TNO creates beta systems for path-breaking technologies. These are then brought to marketability with an industry partner to earn back the investment. The process mentioned here, which enables various materials to be printed simultaneously is quite unique. Currently, three print heads are being used. More may be added in the future. Currently, no other developments of this technology exist other than the beta system!

A notable development in the field of inkjet technologies (see PolyJet) was conducted by the group 'Additive Manufacturing' of the department 'High Tech Systems and Materials' at the Dutch research institute TNO. The beta system for High Viscous Ink Jetting makes it possible to create true material gradients.

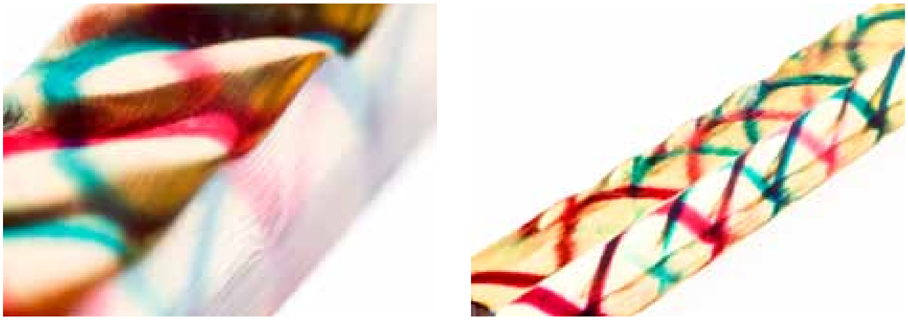


Figure 88
Gradient spiral prototype with fading materials, produced with High Viscous Inkjetting technology by TNO.

Special software is used to save the geometry and material properties of the desired 3D part in a GIFF file (Graphics Interchange File Format). These building plans reflect the material distribution with a point-by-point accuracy. One GIFF file per layer reflects the number and position of each point of every individual layer. Material droplets from the print head are then allocated to each point. Therefore, a certain materiality can be determined for each point of the GIFF file. The system employs three print heads, more can be added. The system then reads the GIFF data and processes the material distribution per layer. The print heads spray or jet between 30,000 and 100,000 material droplets of high viscous plastic onto the building platform. Electric tension is used to direct the individual droplets such that they are a perfect rendition of the building plan. The high resolution makes it possible to generate true gradients: A string of material can be printed in a spiral with a density of 100% on one end and 0% at the other. A transparent carrier material serves as support structure.
The system can also create vertical 'walls' only a few droplets wide – without support material and without the inherent viscosity of the material causing the 'wall' to be instable. This can be achieved because of particular material properties; a material developed by TNO. The carrier material is a polymer paste that can be filled with different powders. The filling can consist of ceramics, plastics or metals; which in turn can be used to vary the material properties of the manufactured parts.
A particularity of this system is that the building platform moves underneath fixed print heads, instead of the print head moving over the platform as is typically the case.[7]

The TNO system is a specialty in the series of developments in Additive Manufacturing because the system technology followed a unique approach. Freedom of form is complemented by freedom of material – programmable gradients open up a variety of new constructive methods, for example for fittings or the manufacturing of gradient materials.[7]

Print-On-Glass

The possibility to capture material distribution via image files and to materialise these images with an according system has lead TNO to develop another method. Print-On-Glass means using a software tool to translate images and graphs into RGB pixels which are transferred onto float glass panes with a 'glass printer'. Coloured glass particles in powder form are distributed by a print head analogue to the image file. The result is a representation of the original file on the glass surface which is then burnt-in in a glass kiln to permanently bond it to the float glass. The final coloured glass panes are made of one monolithic material.[8] The idea of 'Direct Glass Fabrication (DGF)' derived from this concept. With DGF several millimetre thick structures are created instead of building up a thin layer of glass powder onto a glass pane (see § 4.2.2).[8]

Figure 89

Left: Beta system of a glass powder printer at TNO in Eindhoven; the principle was adopted by Saint Gobain Glass and is now commercially used for façade projects.
Right: Application of the glass powder printer for the 'Beeld –en Geluid', Hilversum; all glass panes in the façade are individually coloured with printed glass powder particles.

Digital Light Processing

AM process	Digital Light Processing	
Abbreviation	DLP	
Main-Application	Manufacturing: hearing aids, casting cores for jewelery	
Material	plastics: light curing resins; Epoxy, Acrylic, Wax, Silicones	
Invented by	EnvisionTec, Germany	
Year	2003	
Manufacturer	EnvisionTech	DWS Systems
Building Chamber (mm)	457x304x508	110x110x70
Material	Photopolymer resin	Photopolymer resin
System	Perfactory Xede	DigitalWax 029J
URL	www.envisiontec.com	www.dwssystems.com
Further information	A few hundred dental prostheses can be manufactured with one build job on a DLP system. Individual geometries allow for customized fitting. The 'printed' prostheses are casted in different materials from the DLP-part. Using DLP for the manufacturing of fine-casting cores for jewellery, very accurate detailing can be achieved.	

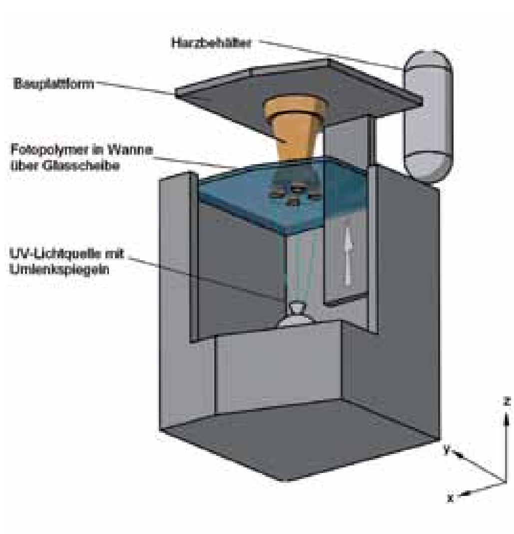


Figure 90
Schematic drawing DLP method

Figure 91
Casting modells for jewellery produced with DLP

With DLP, a fluid resin – so-called photopolymer - is cured by means of exposure. The photopolymerisation process is based on the projection of UV light masks over a mirror matrix across the entire building platform. The building plan of an entire layer is exposed with an 'image' and not, as with laser sintering, traced with a light source. The image is projected onto the surface of the building platform as a bitmap mask. Hereby, the process chamber is filled with fluid photopolymer. Exposed, i.e. unmasked areas are cured. One particularity of DLP is the continuously rising building platform. Firstly, the models are created upside down and secondly, the model grows continuously. This eliminates the stepped surfaces and visible layers typical for other systems; the surfaces are smooth and highly accurate. The resolution is between 15 and 150 µm; which is significantly higher than that of other methods.

Therefore, this method is used to manufacture jewellery (casting moulds) and toys as well as for medical engineering (dental prosthesis, hearing aids). For products used in medical applications, biocompatible materials are used that can be implanted into or worn on the body. To create customised dental prostheses, the DLP models are cast in gold, ceramics and other specialised materials in a subsequent process. One building job can produce several hundred individualised dental prostheses.

Due to the high resolution, the method is well suited to produce filigree cast blanks for jewellery.

Laminated Object Manufacturing

AM process	Laminated Object Manufacturing		
Abbreviation	LOM		
Main-Application	Prototyping		
Material	Material sheets: paper, PVC, Aluminium		
Invented by	Helisys, USA (afterwards: Cubic-Technologies, USA)		
Year	1991		
Manufacturer	Cubic Technologies	Fabrisonic (Solidica)	M-Cor Technologies
Building Chamber (mm)	170 x 220 x 145	110x110x70	277 x 190 x 150
Material	PVC	Aluminium, copper, stainless steel, titanium	Paper sheets
System	SD300	Ultrasonic Consolidation	Matrix 300
URL	http://www.cubic-technologies.com/	http://www.fabrisonic.com http://www.solidica.com	www.mcortechnologies.com
Further information	The LOM was invented in 1991 as an independent development since it is fundamentally different from the other methods. This method no longer plays a role in today's AM industry because the post-processing requirements are too time-intensive and the processing speed too low. The first systems were used for product design because the manufactured prototypes made of paper were easy to post-process (sanding, cutting).		

The LOM technology is an independent method that is significantly different from the other methods in terms of the form of the material and the method with which a model is generated. The building material is supplied as sheets of material that are stacked on top of each other and then glued together. The sheet of material is pulled from a roll across the building table, or laid on it if provided in single sheets. Depending on the material, the individual sheets of material are either heated and glued with a melting drum (Paper, PVC), or wetted and bonded with appropriate glue. The contour of the model is cut with a CO2 laser or a knife blade; the remaining areas are first used as support structure and pre-perforated for later removal. They remain part of the geometry until the process is complete. Upon completion they must be separated and removed; a difficult task in case of filigree or complex geometries.
Since its invention, several companies further developed this method. Therefore, there are LOM systems that work with different materials: 'Ultrasonic Consolidation (UC)' by the company Solidica, USA; hereby aluminium sheets are used as building material. The individual layers of material are bonded by ultrasonic welding, and then cut with a laser. The material properties of the resulting aluminium model match those of aluminium formed with conventional methods.
The method developed by the Israeli company Solidimension replaces the originally used paper with a PVC foil; a reversing blade is used to cut the contours of the geometry.

The newest development by the company M-Cor Technologies turns the method into an economic alternative for schools and universities. Inexpensive Din A4 printer paper us used as building material.

With LOM, the accuracy does not quite match that of other methods. The advantages for the user are the haptic experience and the appearance of the models as well as the low cost of material. If paper is used, the models display wood-like structures and can also be reworked like wood. Usually, the models are used to develop prototype shapes or as a core for a subsequent process. Enclosed geometries pose a problem in terms of removing unused material; therefore the shapes are typically limited to planar parts that might be turned into three-dimensional volumes by folding.

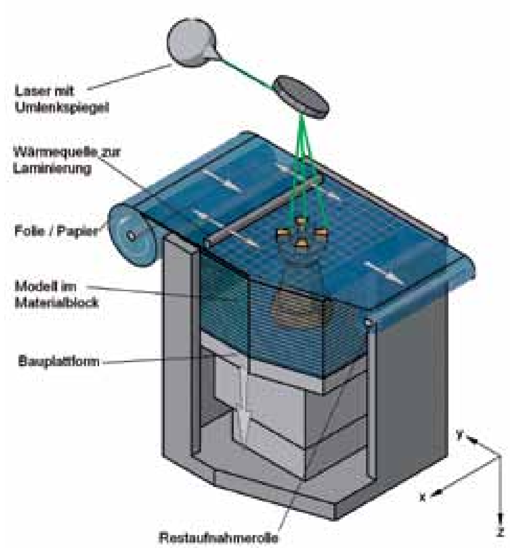


Figure 92
Schematic drawing LOM method

Figure 93
One available product for LOM by Solidimension; using PVC film (bottom, right) for part production.

Contour Crafting

AM process	Contour Crafting
Abbreviation	CC
Main-Application	Manufacturing: shelter and housing
Material	Other: fibre reinforced concrete
Invented by	Behrokh Khoshnevis, University of Southern California (USC), USA
Year	
Manufacturer	USC - Viterbi School
Building Chamber (mm)	6000x6000x6000
Material	Concrete
System	Beta system
URL	http://www.contourcrafting.org/

D-Shape

AM process	D-Shape
Abbreviation	
Main-Application	Manufacturing: big scale sculptures
Material	Other: stone powder, marble powder, sand
Invented by	Enrico Dini, Italy
Year	2009
Manufacturer	Monolite, UK
Building Chamber (mm)	6000x6000x6000
Material	Stone powder
System	Beta system
URL	http://d-shape.com

Fabbing

Introduction

In parallel to 'industrial' or 'professional' AM applications, another branch of the methods has evolved since their invention that is summarised here under the term Do-It-Yourself (DIY). All the methods described hereunder have the goal to offer 'Personal Fabricating'; i.e. the production means should be accessible to all consumers. Consumers of today's mass products are to be made into 'prosumers', to producing consumers. Additive methods are seen as a tool to make the 'prosumers' independent of mass producers. Everybody should have the opportunity to create their own, individual environment. The phrase 'Democratisation of production' encompasses different approaches to achieve this goal: One approach is to provide young adults with intensive training to discuss everyday items and to understand their own consumption behaviour. This is supported by 'FabLabs' worldwide. Here, people relearn to develop and create things themselves, using today's technical possibilities of digital production. AM is one building block that makes it possible to design products, produce them in small quantities and further develop them in user communities.[9]

RepRap

RepRap (derived from 'Self Replicating Rapid Prototyper') is an invention by Dr. Adrian Bowyer and his team of researchers and developers at University of Bath, England. The first RepRap is called Darwin1 because it is the starting point for its own independent multiplication. Darwin1 can be used to print many of the parts required for subsequent systems. The first RepRap was reproduced in April 2008. In order to operate the RepRap, additional mechanic and electronic hardware components must be purchased (metal rods, the building platform, cables and PCB, etc.). All assembly drawings, the necessary data to print the parts and the operating software are available as 'open source' files on the RepRap homepage. One RepRap costs between approximately 400 and 1000 US-Dollar, depending in the desired model and type of delivery (kit or assembled). A map (Google Maps) shows the distribution of the systems via worldwide RepRap locations.

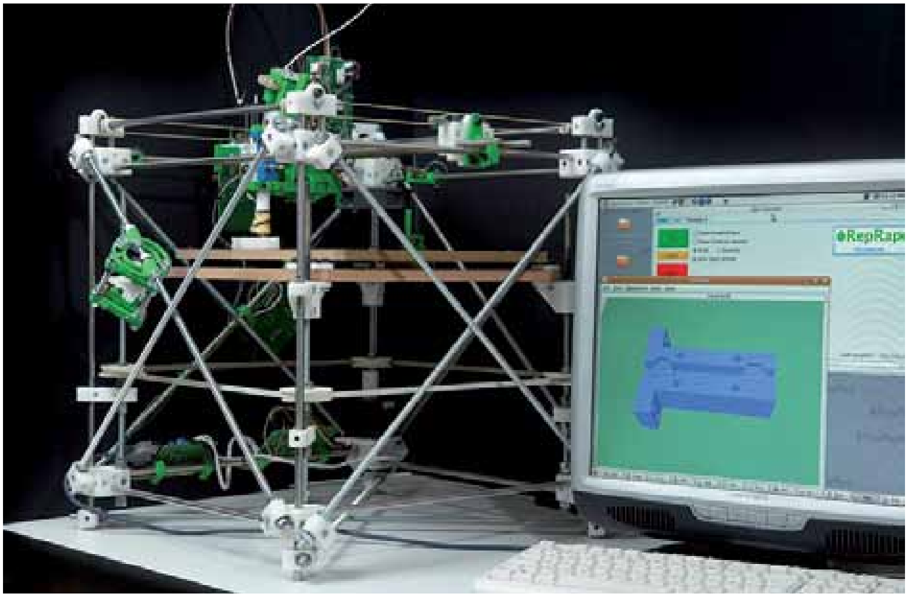


Figure 94
RepRap, Darwin1; Developed at University of Bath, England.

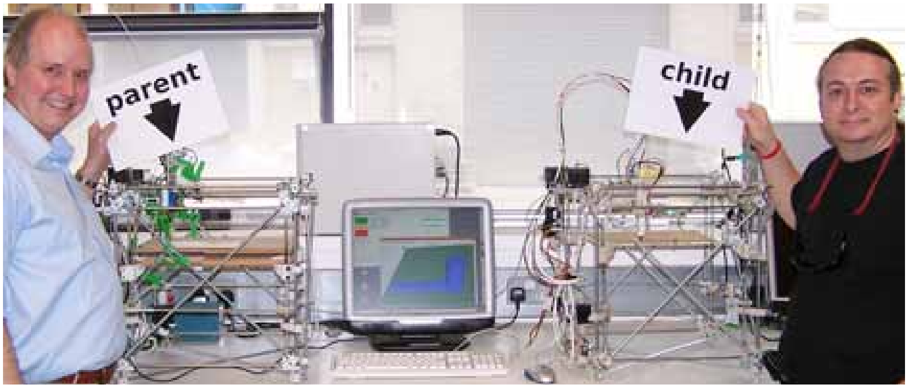


Figure 95
RepRap inventor Adrian Bowyer (left) with first and second generation of RepRap

The system functions like a FDM system: Plastic is melted through an extrusion nozzle onto the building platform. The effect of the temperature lets the layers of strings of plastic bond to each other. The print head is mounted to a mechanic system of rods that can move along the x and y axes. Building up the height of the model is achieved by lowering the work platform.

The material used is polylactic acid (PLA). PLA is a biodegradable polymer created from lactic acid. The lactic acid can be fermented from corn which makes RepRap independent of industrial products.
Adrian Bowyer's slogan is 'wealth without money'. The underlying idea is to break down the interdependency of wealth and production means. If all necessary consumer goods can be produced by the consumers themselves by offering inexpensive manufacturing methods, the market will no longer be determined by a network of production facilities and means. Scientists develop building materials based on starch to eliminate the dependency on materials made of raw oil. Any user owning a small piece of land could generate starch from growing crop on the property, and use this as a renewable material for the RepRap. A positive side effect is the fact that printed items no longer in use are easily compostable. The researchers' goal is to build a machine that can be used for the most diverse applications. In contrast, the professional systems of the AM industry are highly specialised machines that are strongly limited in their range of application.[10]

Fab@Home

Fab@Home is an invention by Prof. Dr. Hod Lipson at Cornell University in Ithaca, NY, USA. A list of materials and a construction and user manual can be downloaded from the internet. And therewith an inexpensive kit. Alternatively, commercial vendors offer customised kits and pre-assembled systems for approximately 3000 US-Dollar. The basic idea is similar to that of RepRap.
The system also functions like a FDM system: Fluid or pasty material is squeezed through an extrusion nozzle (in this case a disposable plastic syringe or similar). The nozzle is mounted to a mechanic system of rods that can move along the x and y axes. Building up the height of the model is achieved by lowering the work platform.
Any type of sprayable material such as silicone, acrylic, epoxy resin, clay, modelling clay, gypsum as well as chocolate, spread cheese and icing can be used.

The system can be equipped with a second extrusion nozzle so that two materials can be printed simultaneously.
The resolution and surface structure depends on several factors: Property and consistency of the material, spraying speed, heat supply at the nozzle, and speed of the aggregate movement.
Fab@Home is well suited for experimental work in DIY or educational facilities. The advantages over industrial systems are 'open source' data processing, low initial investment, material diversity and low material cost.[11] The cost for a Fab@Home lies between 1900€ for a kit and 2800€ for a ready-to-use printer.

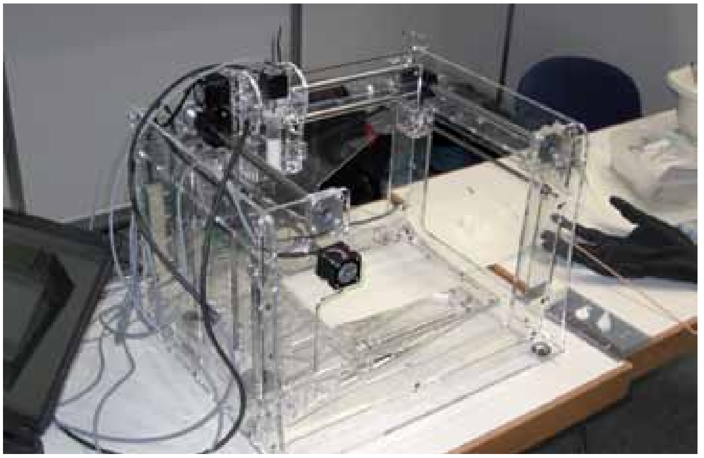
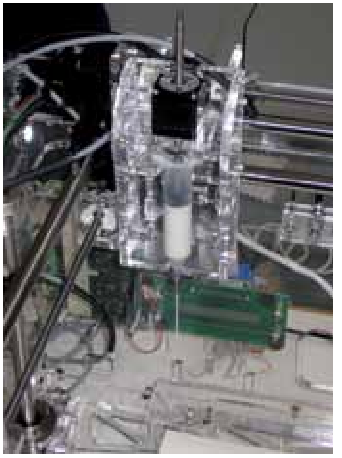
 

Figure 96
Fab@Home (left); extrusion nozzle (right) with medical syringe as the nozzle device.

Summary 'fabbing'

The DIY applications described here do not primarily focus on the development of the AM technologies; but rather show the inventive spirit of the 21st century. This spirit is closely linked to the current technologies and therefore leads to Additive Manufacturing.
There are many different kinds of DIY-kits and different fabber systems available. To name just a few more, there is the MakerBot's 'Thing-O-Matic', there is the 'fabster' by FIT GmbH, there is the 'RapMan' and the '3Dtouch' by Bits from Bytes, the 'Fabber' by Napster and many more.
All of them offer much scope for do-it-yourselfers and tinkerers. In combination with other DIY tools, a system can be enhanced with self-fabricated hardware parts. Again, the underlying principle is that of the FDM method.
All kinds of materials are being processed with fabbers: spread cheese, silicone, chocolate, dough, wax, human tissue cells, wood polymer, sugar and many more.

The individual kits are also targeted toward very different user groups: RepRap, MakerBot and others gear toward pupils and students who enjoy putting together a machine. Therefore, these systems are often found in technical classes at schools or universities with a background in engineering. Other vendors focus on the do-it-yourselfer at home, who finds fabbers to be an enhancement to other manufacturing methods for building models and realise inventions. Typically, these fabbers are ready to use and work with the plug-and-play principle. Inexpensive 3D modelling software leads in the direction of product development; however, usually more as a means to an

end rather than in the sense of using the possibilities in designing with AM.
It is notable that a few years after fabbers began to spread, commercial manufacturers from the professional AM market segment complement their portfolio with low-cost 3D printers. One motivation certainly is customer loyalty and the attempt to spread knowledge about these technologies.
Fabbers are definitely no competition for professional AM systems, but they do represent a growing market.

Sources related to the technologies:

The information about the methods described in chapter 2 and 6 A are gathered from the following sources: [11] [12] [13] [14] [15] [16] [17] [18] [19] [20]. The internet pages stated also point toward further information by the system manufacturers (see appendix A II / Weblinks). The descriptions were enhanced by personal conversations between the author and technology users and developers in meetings, at conferences and trade shows.

AM file format

One important factor when developing new applications for AM technologies is the file format used to edit, render and reproduce 3D geometries. The STL format developed during the eighties by 3D-Systems is no longer accepted by all suppliers and users since it is too limiting. In addition to the STL format there are more than twenty independent developments, each with their own advantages and disadvantages, but none of them is generally accepted.
Since 2010, a group of participants from system manufacturing, software development, science, AM associations as well as user groups work together on developing a universal data format. The work title is 'Additive Manufacturing File Format (AMF)'; and the development is conducted under the patronage of the American Society for Testing and Materials ASTM. The goal is to develop a format that is supported and accepted by all users. It should stand against the multitude of insufficient alternatives currently available, and offer technical advantages over the no longer adequate STL format. One such advantage is compatibility between the different digital tools. Currently, complications often occur when exchanging files between input and output devices such as scanners, graphic cards and modelling software.

Another issue of the STL format is a limited possibility to store additional information in the file. In the early days of AM it was sufficient to define the surface properties by specifying edge definition and orientation; however, today's improved system technology demands that we can also determine information such as colour, material, texture, support structure, and orientation within the process chamber, amongst others. The requirements are mostly driven by developments in the fields of multi-material printing, multi-colour printing, and creating gradient materials.
The AMF file format should allow an easy exchange between all 3D input tools and AM output devices. Similar to the PDF format that offers problem-free exchange of digital documents in computer applications. The ASTM development should be openly available, not be subject to any copyright, compatible with any available system, and upgradeable for future enhancements. The involvement of all key companies and key persons from the AM industry shall preserve the 'open source' approach.[21]
Another factor is that as the files grow in complexity they grow in size, too. But there are technical limits in terms of generating, storing, sending and using large data files for production. The STL format does not aid in reducing the file size. By using 'dumb' vectors to describe geometries, all edges of a body, for example, are represented by two, ideally identical vectors of different triangles. The results are unnecessarily large files and risks of error. Improving the part tessellation (the degree of approximation

of 3D planned geometries and the resolution of the AM output device) through better vectorisation and triangulation can help.[22]

Currently, 3D geometries are only described and defined via their edges and surfaces. It was therefore sufficient to specify the edge vectors and surface orientation of a volume. This is true for those programs called 'surface modellers' as well as for those that work with so-called 'solid modellers'. Using parameters for 'filling materials' to create a shape is not (yet) included, but is the key factor for gradients within a part. The goal is to define a body via voxels (Volumetric Pixels). Existing methods circumvent such voxel programming by representing the volume in bitmap files; however, this mandates a non-universal computer language.

CAD software

Besides technical limitations, the use of AM is also limited by the currently available software to create the necessary CAD data sets.
Even professional software hits a barrier concerning the development of functional constructing for AM. Most programs are designed to represent and generate surface areas. Even though some of these programs do have the capability to process additional information they are not designed to handle grid structures, material gradients or other quantity-intensive shapes. Usually, such designs result in drastically slower processing speeds, infinitely large files and often failure of the software application. Similarly to the AM hardware, which is coined by its evolution from the early prototyping systems, the software is also coined by previous applications, and not by the requirements of production with AM. Fundamentally new developments are required for AM and AM system technology to achieve easier handling of the 3D data. Data transfer to and from utility programs must be guaranteed, and the development of specialised software for design, simulation and manufacturing of AM parts must be pushed on.

It still takes expert knowledge to develop products in virtual space. The design process will only undergo a comprehensive change when user friendly and easy to learn software tools are available for such complex AM developments.

Technical drawings T-Connector

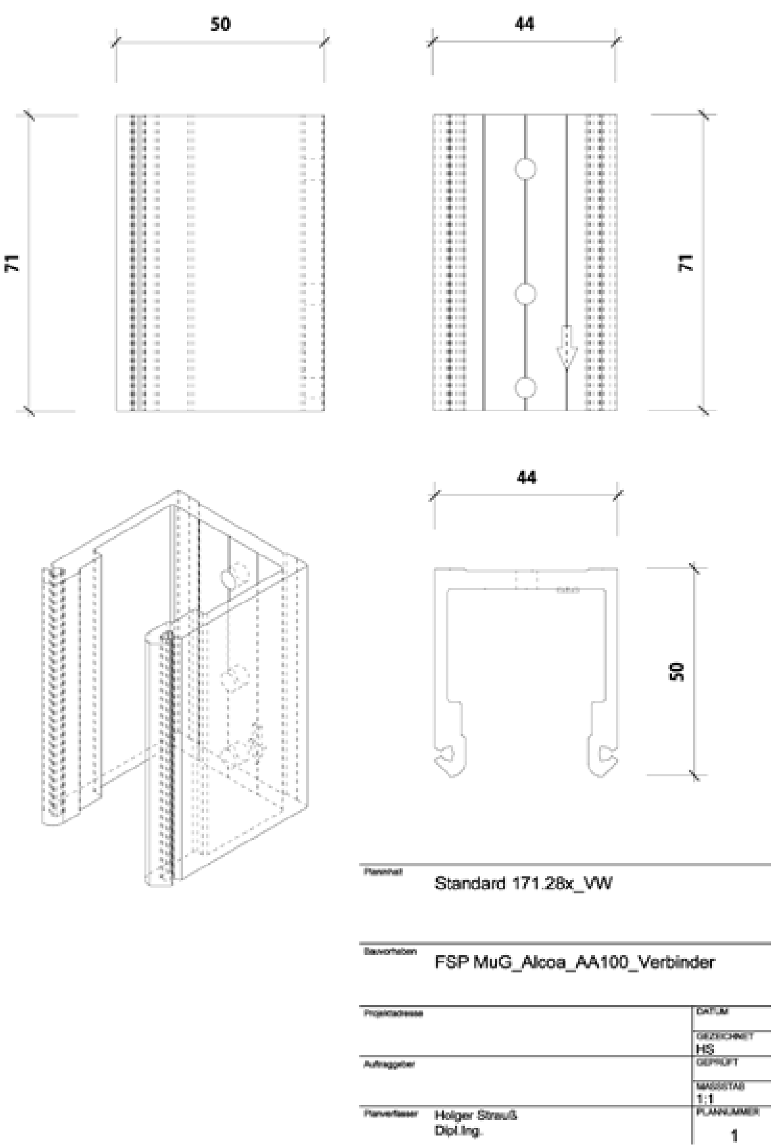


Figure 97

Technical drawing of the standard T-connector for a stick system; used as digital background for optimisation.

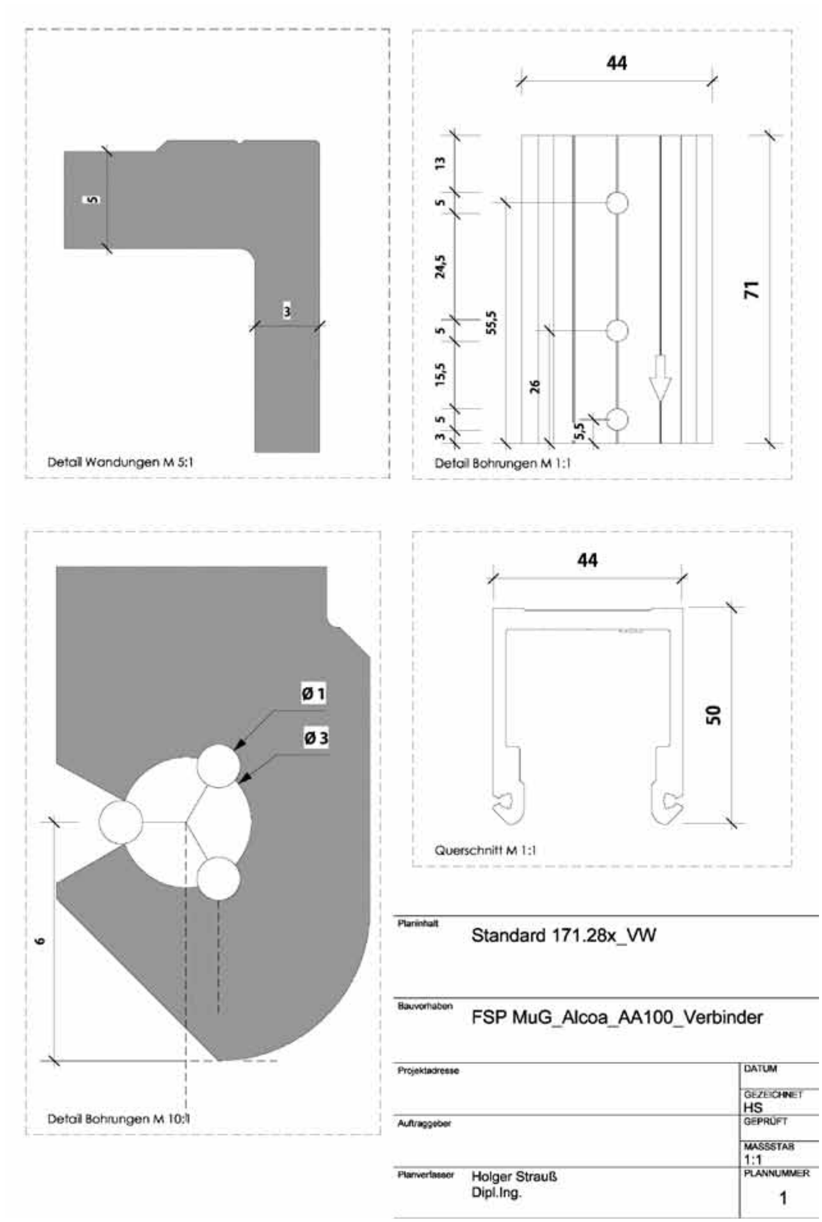


Figure 98

Technical drawing of the standard T-connector for a stick system; details and dimensions for the optimisation process. All screw channels and technical features were re-constructed in the advanced connector.

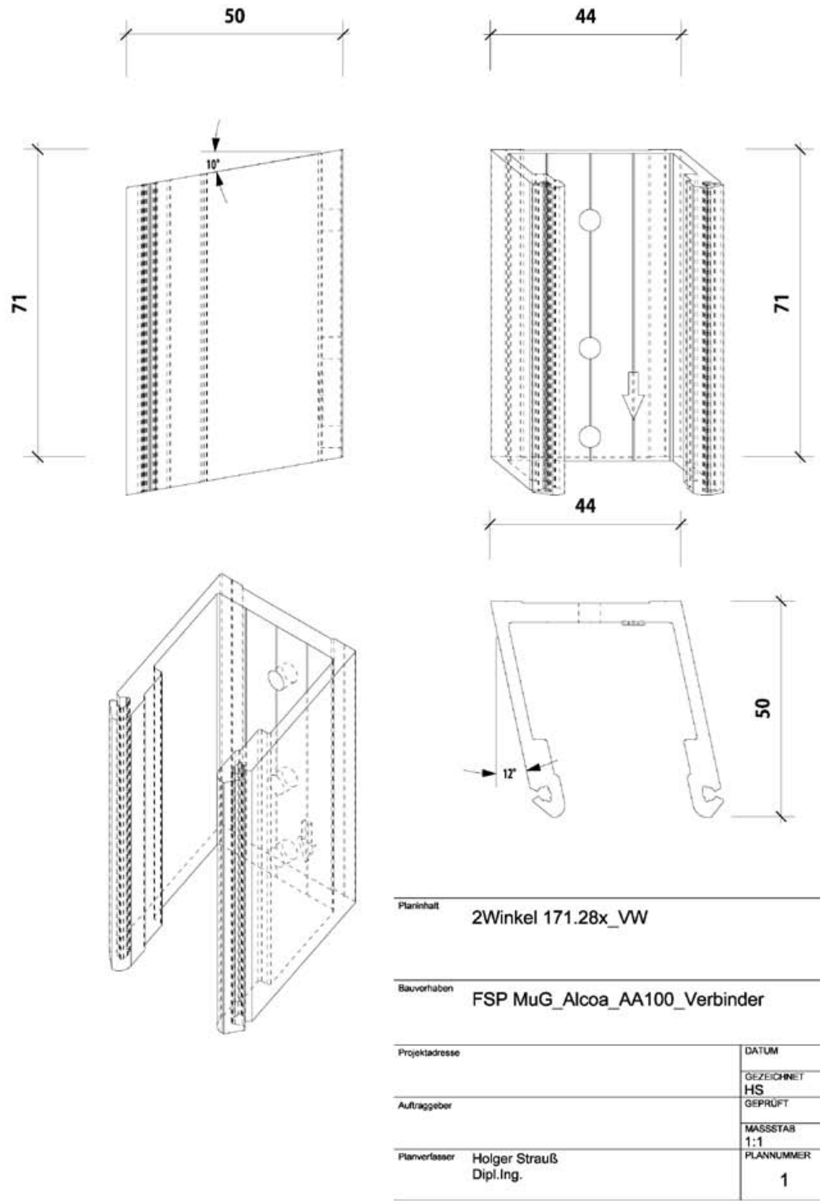


Figure 99

The first adjustment was the implementation of two different angles; this would allow for deformation in the façade.

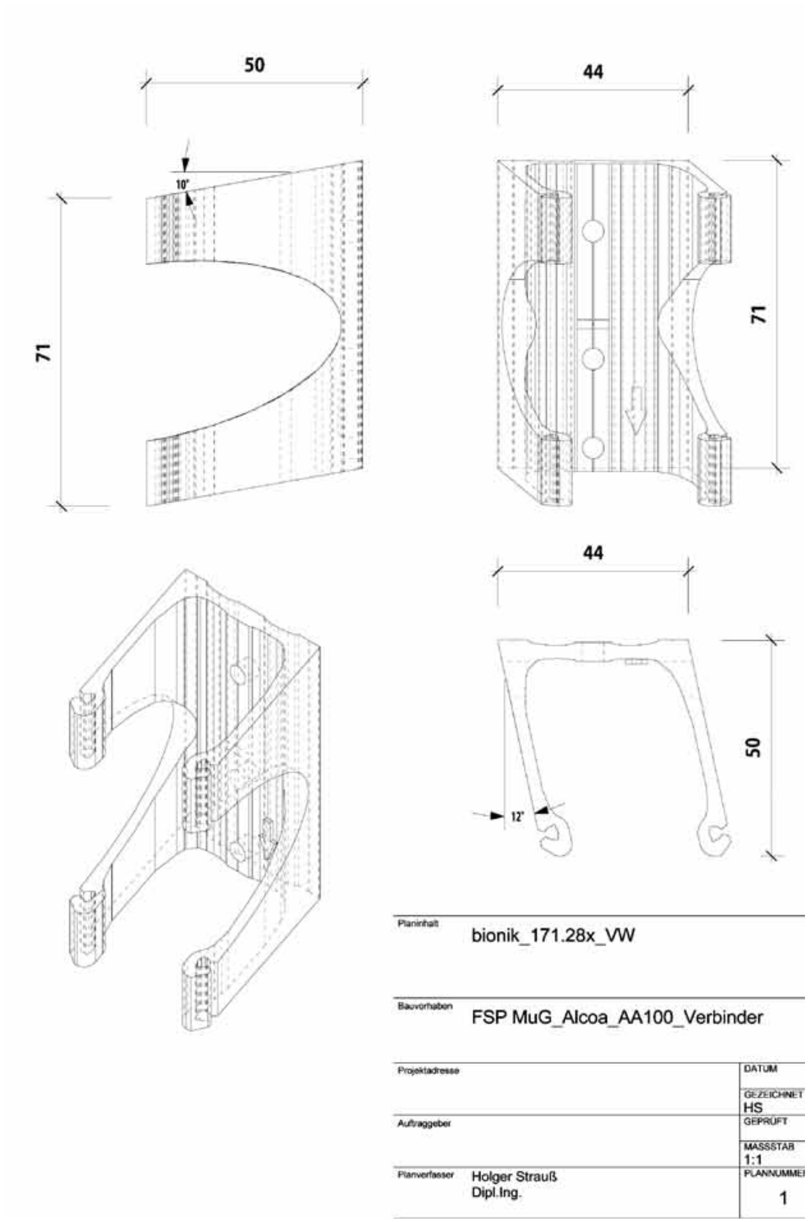


Figure 100

Optimised part as result of the optimisation for AM; in this part material was digitally 'cut off', where it is structurally not needed.

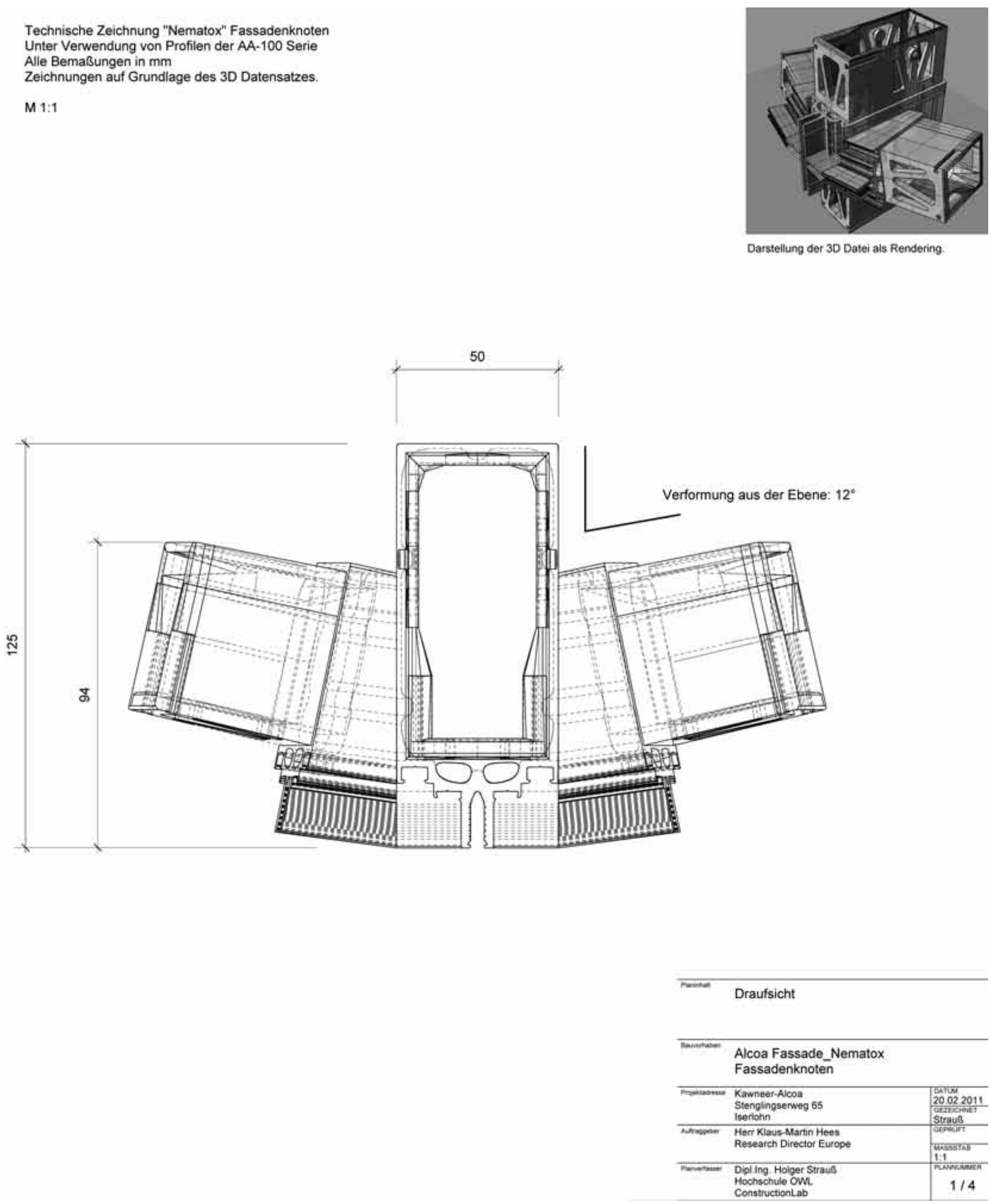


Figure 101

Technical drawing with real dimensions of the Nematox II; top view.

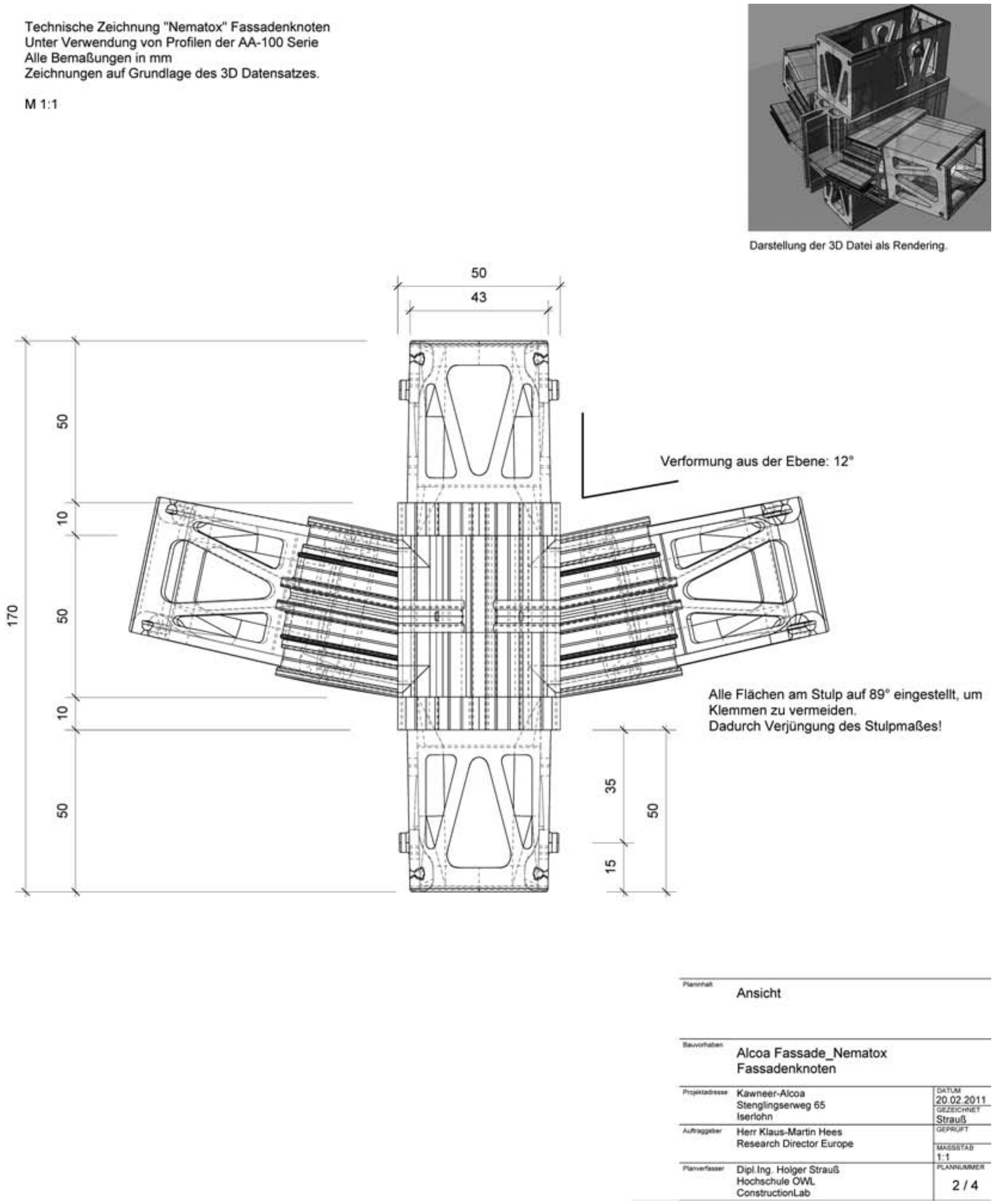


Figure 102

Technical drawing with real dimensions of the Nematox II; front view.

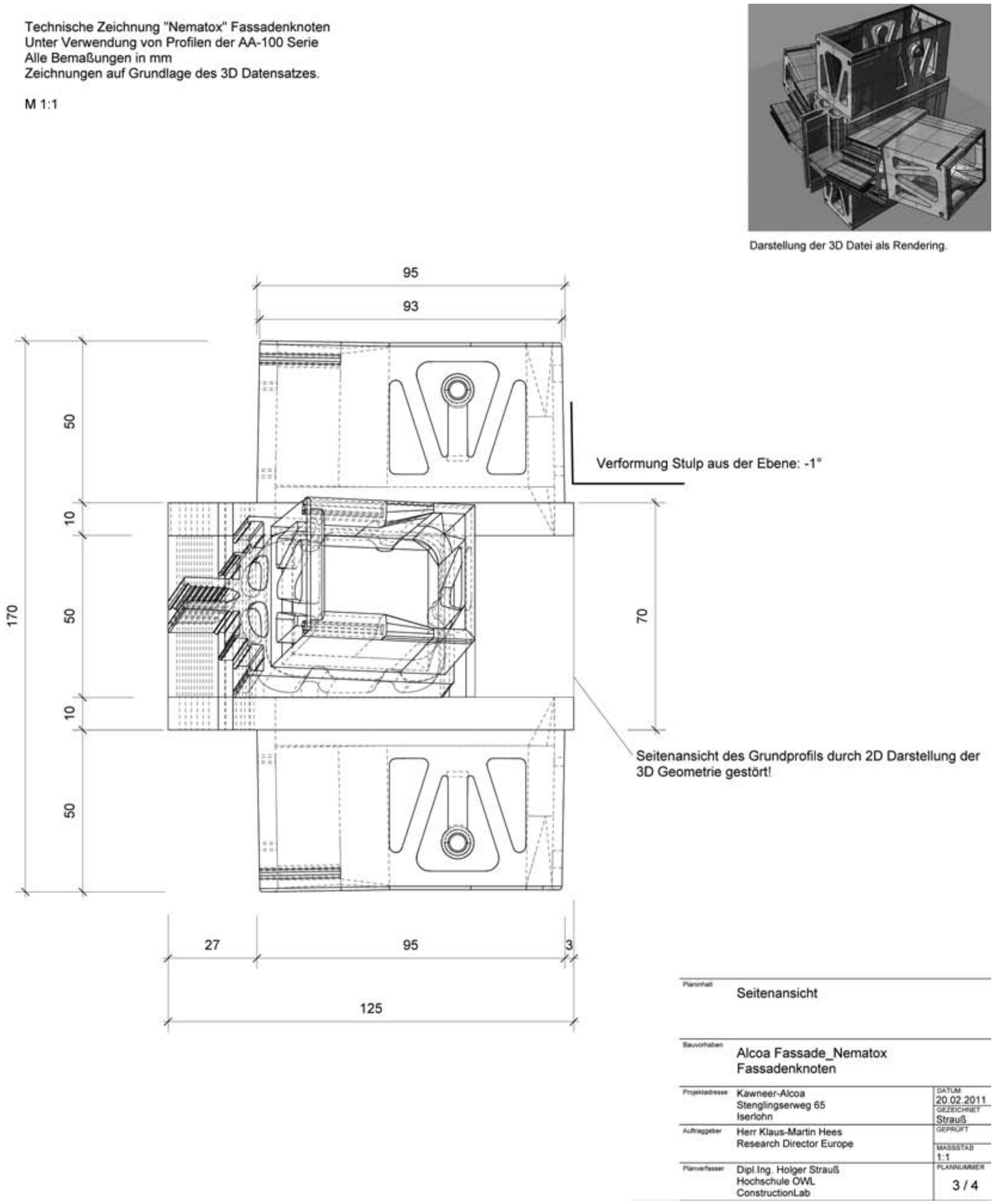


Figure 103

Technical drawing with real dimensions of the Nematox II; side view.

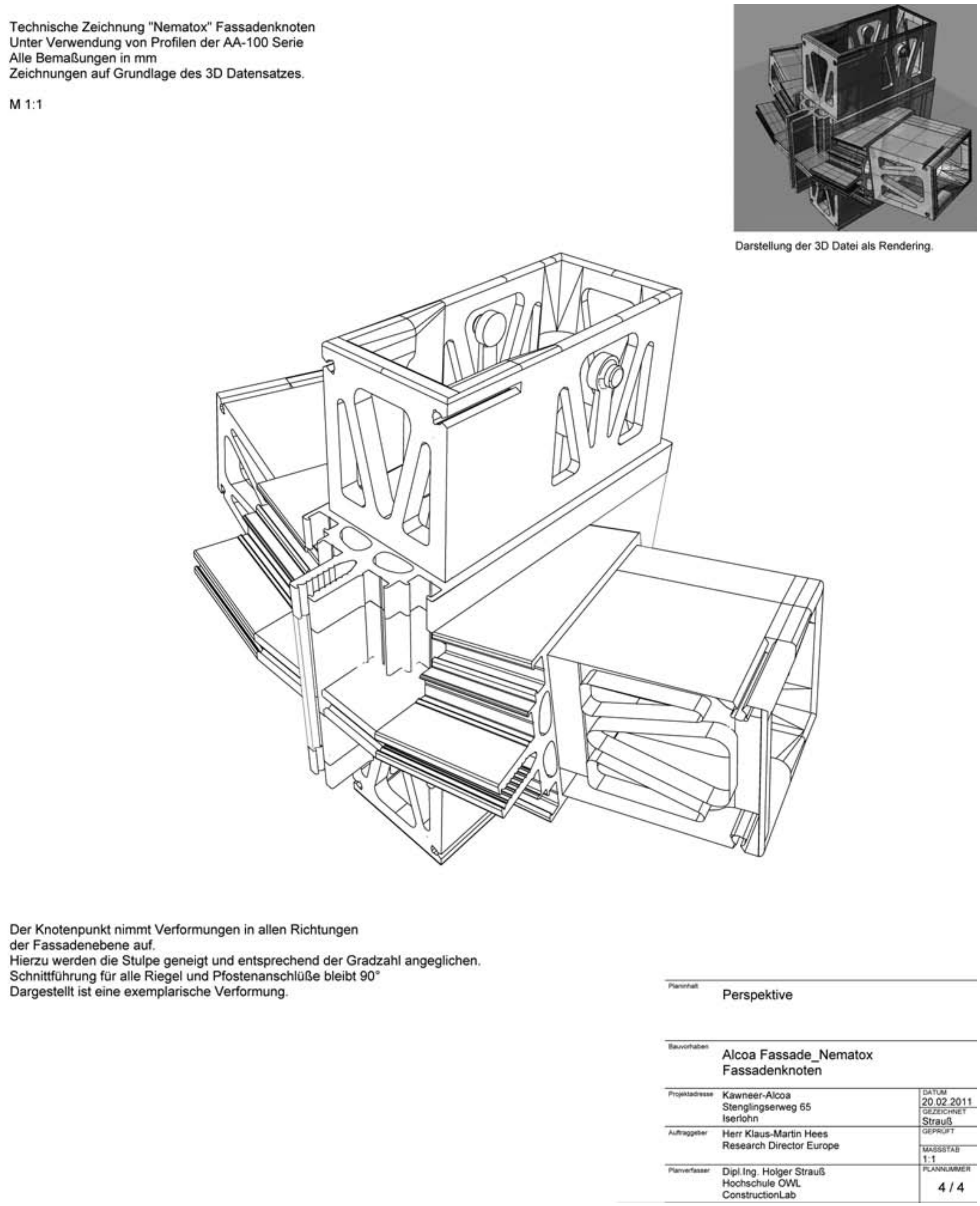


Figure 104

Technical drawing with real dimensions of the Nematox II; isometric view.

SWOT Analyses: AM in the façade industry

A SWOT analysis collects 'Strengths', 'Weaknesses', 'Opportunities' and 'Threats' closely connected to a particular project, a company or business venture. It is a way to find and specify factors that are favourable or unfavourable to achieve the objectives of the project or enterprise. At first, it is only a collection of aspects and factors. In a second step, the results can be used to draw conclusions and / or develop strategies.

SWOT analysis gives an overview of individual aspects in a field of investigation. In this case the charts show strong and weak aspects of different main topics ('Aims') concerning the use of AM for Kawneer. The original aim of SWOT to compare internal and external of a certain topic was changed in the given charts to a ranking of weak and strong aspects because AM is not yet applied by Kawneer.

The five SWOT charts are followed by an interpretation of the resulting aspects to provide a resume of the charts. (see [23] [24] and [Wikipedia])

SWOT 1: AM for façade system provider

Aim: to become AM producer in the own company.

	Strong	Weak
Opportunities	- be the early adopter - gain AM knowledge - develop AM strategies - engineering to company needs - branding for the company with AM	- adjust DMF process to company needs - control of processes/innovation - new materials for façades
Threats	- certification - cost per piece - initial investment high - liabilities for DMF parts not clear - fit AM into existing façade systems	- risk of failure of technology - risk of failure in marketing - limited size of parts - accuracy / finishing - time consuming production - time consuming designing - no long-term experience yet

SWOT 2: AM for One-Off Solutions

Aim: apply AM to show its potential in a 'Abu Dhabi Façade'.

	Strong	Weak
Opportunities	- show possibilities - 'AM inside' branding - test-drive AM parts - push the limits - amortize first system fast - adjust AM strategies	- start a demand in the market - acquire new customers - train contractors
Threats	- time consuming production - designing and scripting complicated - limitations for whole façade unknown	- cost per Node - post processing unclear - tolerances in the façade - movements in the façade

SWOT 3: freeform for aluminum façades

Aim: show if freeform design is the choice for existing post-and-beam systems.

	Strong	Weak
Opportunities	- start from far developed system - need for change in the market - improvement in Stick- façades low - new discovery desperately needed - 'file-to-factory' possible in façade industry - optimized part geometries for minimized material consumption	- marketing success - fool proof solutions - less waste in production
Threats	- limitations from stick-system - limitations from glazing - design limitations - need for specific architectural design	- market request low - material limitations

SWOT 4: metal for freeform façade solutions

Aim: application of alternative materials for an enhanced façade system.

	Strong	Weak
Opportunities	- well known properties - same material as standard profiles - strong	- easy to post-process - aluminium available (for most stick-systems)
Threats	- heat conductivity - need for thermal break - expensive to 'print' - more complicated to 'print' - heavy - limited in material performance - not gradable	- deformation - limited size in AM - repeatability not clear

SWOT 5: DMF as method of choice for the presented parts

Aim: evaluation of printed parts.

	Strong	Weak
Opportunities	- 'real' material - strong enough - impression of 'real' part in mock-up - same material as for standard profiles	- post processing possible - properties like existing standard parts
Threats	- price per part / mock-up - production more complicated than 'printing' plastic parts	- production time - low expertise in metal-design

Resume

To optimise the results of the SWOT analysis and to make use of the Strengths and Weaknesses shown, it is necessary to find suitable ways / strategies that can be followed. To do so, there are combinations of the S, W, O and T, that will give some hints about the results from the listing of the aspects.

S-O combination

To be an early adopter has opportunities as well as downsides. For marketing purposes, it is certainly right to:

- invest into AM research;
- try to adopt AM for production.

The combination of some of the found opportunities offers benefits:

- by using AM early, the company can get thorough insight into the feasibility of projects in advance;
- by training their staff early on, Kawneer could become known as an expert consultancy and/or gain leadership in the façade market.

S–T combination

Which Threats can be counteracted by which Strengths? By using which Strength can we ease/relief possible Threats?

- Developing an expertise in AM for façade applications offers the opportunity to create new markets/market shares.
- This transfer can only be realised by knowing the full capability of AM technology. For example, by demonstrating potential customers that 3D controlled façade nodes make the simulation, control and mounting of individual façades viable.
- New marketing strategies can derive from DMF parts (the 'Abu Dhabi Node').

W–O combination

How can Weakness be transferred into Strengths for single aspects of the analysis?

- Being an early adopter can, for example, the company can be the first to establish hitherto non-existing certificates in the market. Therefore the experience and expertise will grow. The company can get ahead of the competition.
- Only if the technology is used extensively, will the price per piece drop. The more investigation is put into new applications, the faster the investment will pay of.
- Limitations within the (extensively) developed stick system may lead to new impacts for the system itself, maybe to a re-interpretation of the post-beam façade.

W–T combination

What is the weakest point, how can it be addressed?

- Investing into future innovation is always a risk. The chance to participate in the return of investment is high if the 'product' succeeds.
- Liabilities / certificates are inevitable. By 'test-driving' first parts, the company becomes the pioneer in AM for façades.

Spread the idea - ideation with AM

The response to the technology was tested in different workshop situations with different groups of participants such as students, researchers as well as architects and planners.
To be able to judge how architects perceive the AM technology for their own field of expertise, two meetings were organised during the research project. Both were conducted at renowned architectural offices in the Netherlands and Germany. To limit the topic to the scope of the workshops, it was based on ideation. The AM technologies were introduced and guided workshops were conducted. The results are a colourful mix of intuitive ideas – some very abstract, some closer to reality. But considering the short amount of time invested to develop these sketches (approximately half a day) it is obvious that brainstorming with likeminded people leads to an amazing potential for invention.[26]

The setup of the workshop was the same for both events in order to be able to compare the two different groups of engineers and designers, and compile a critical resume for the façade industry/Kawneer. The topic for both meetings was 'SKIN and NATURE' to stimulate the ideation process and find a connection to the building envelope.

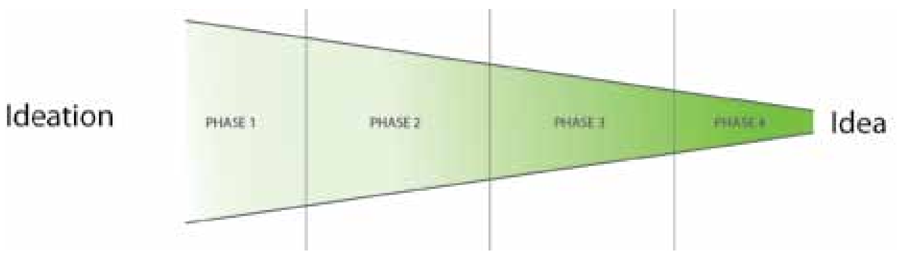


Figure 105
Different phases of the ideation process.

Phase 1 / Briefing

In the beginning of the ideation process, manifold impressions and associations from different areas are collected: Lectures and information exchange build the background of the continuing imagination process. To think outside-the-box and to collect input for the ideation is necessary during this phase.

Phase 2 / Associative brainstorming

For both topics - 'Skin and Nature' - all appearing terms are collected in a freely associative manner. There is no need to link these terms directly to architecture or façade technology. The variety of ideas and combinations will actually benefit from neglecting the 'main topics' and will become broader. The more the participants open up their minds to associative thinking, the more combinations will appear in the following steps.

Phase 3 / Initial ideas

Combinations from both fields are selected from the terms collected in phase 2. Depending on the available time, two to five pairs are possible as a starting idea. These pairs then form the basis for further ideation. A first assessment of the rough idea is possible (indicate size, define group of materials,...).

Phase 4 / Evolution

The ideas from phase three are presented, explained and discussed by the group. The most promising ideas are followed up on. Combinations of initial ideas into one new idea are possible. After the second presentation to the group the teams will further develop the strongest result into a more complex vision.

[25]

Regarding 'AM Envelope', you can find those kind of visions in § 4.2, as they were generated in the same manner in various gatherings.

UN Studio, Amsterdam; held on April 29th, 2010

Participants:
UN Studio: Astrid Piber, Abhijit Kapade, Christian Veddeler, Cynthia Markhoff, Ger Gijzen, Hisa Matsunaga, Joerg Lonkwitz, Jordan Trachtenberg, Juergen Heinzel, Juliane Maier, Luis Etchegorry, Miklos Deri, Mo Lai
Kawneer-Alcoa: Jeroen Scheepmaker, Klaus-Martin Hees, Michel van den Berg
TU Delft / Hochschule OWL: Ulrich Knaack, Holger Strauss

A general first result was the identification of a broad range of application opportunities. The technology was not yet recognised in the field of architecture. The resulting ideas stimulated the responsible office partner to work out life-size applications for some of the concepts. However, the limitations caused by a lack of certified materials and certifications for building applications will inhibit the use in 'real' architecture. One option to trigger the process could be to realise interior design items that derive from the workshop results. Everyone was open to test-drive AM technologies.
The focus of the brainstorming sessions was restricted to façade solutions alone but covered a brought range of 'architecture'. Therefore the results were not directly connected to Kawneer façade systems, but demonstrate that AM could become a general branding aspect and opens up new ways of reinterpreting existing solutions.

Behnisch Architekten, Stuttgart; held on May 4th, 2010

Participants:
Behnisch architects: David Cook, Martin Haas, Maria Kohl, Stefan Rappold, Isabel von Schmude, Patrick Certain, Frank Kimpel, Dominik Heni, Lisa Dengler, Stefanie Platsch, Samuel Schmidt, Christian Zwick, Christian Goldbach, Matthias Ryntowt, Theresa Kessler
TU Delft / Hochschule OWL: Ulrich Knaack, Marcel Bilow

At Behnisch Architekten, a renowned architectural office in Stuttgart, the response was similar to the one stated above. The consensus here was that the technology was only known for the production of display models in design competitions. Applications from Rapid Manufacturing and mass customisation (see § 4.3) were new to the participants who found the idea very interesting. The fact that AM can be part of an everyday production chain, for example in the medical field, was perceived positively; with the result that the participants discussed future application in an architectural context. Right now, Behnisch Architekten has no application possibility for AM; however they are keen on following its evolution.

Figure 106
Imagination workshop at UN Studio, Amsterdam, May 2010.

The strongest limitation is seen in the price of the technology and of the parts. Opportunities for the application of AM are seen in the field of freeform steel constructions or individualised fittings for architectural solutions.

At the end of the workshop the use of multi-material parts was considered and discussed related to their implementation into electronics and sensors for an enhanced living environment (for example living for elderly people).

Standardization

No quality standards or norms have yet been established for AM products. In order to be able to compare the products to one another and to conventionally manufactured mass products, traceable and comprehensible criteria must be established in the AM industry. The quality of the manufactured parts, the quality standards for the methods and materials available as well as quality control of the individual methods are key factors for the development into an universally accepted manufacturing method.[16]
But just as work groups of ASTM (American Society for Testing and Materials) are dealing with various aspects of the AM technologies, there are efforts to define and establish exactly such test procedures and quality management (QM).[27]
System manufacturers have also acknowledged the importance of establishing a QM system. Thus, since 2010 there are visible efforts by the manufacturers to integrate quality control in their systems. ConceptLaser, for example, has established a QM system in its LaserCusing equipment: A protocol is generated for each produced layer which can be allocated to the built part and manufacturing process, and possibly each exposure cycle during the building process. This allows tracing the heat intensity at the melting point of the laser, and thus conclusions about material properties and the quality of the sintered part. EOS developed a QM system with protocols and test volumes that allows the user to retrace process parameters and document material properties. The protocols are generated for each manufactured part and serve as an assurance for the end user that the system was properly calibrated and serviced, and that the process parameters of two different process cycles were identical.[28]

Regulation and standardisation of the methods will play a key role when applying AM to façade or building technology: When dealing with façade components, it is not only important to ensure proper performance and design, but even more so to ensure human safety. Standardisation and regulations are mandatory to avoid having to receive individual approval for each and every application.

Inspiration from bio-mimicry

One common argument for the use of AM technologies is the possibility to generate free-formed parts without the need for tools. And such free-form designs are usually associated to shapes in nature – thus, the step to implement or transfer bionic principles is apparent. 'Digital availability of bionic principles' makes it easier for engineers and planners to create resource-friendly constructions; skeletal structures, honeycomb structures or even organic structures can be digitally planned, controlled and optimised. What needed to be illustrated, tested and manually translated into technical drawings when Frei Otto and Antoni Gaudi were trying to find shapes for load-bearing structures 'optimised according to the laws of nature', is made easier and accessible to all by the availability of digital tools today.

Considering global warming and the ongoing discussion about sustainability, the building industry and therefore planners and architects must also think of how to handle resources in an environmentally friendly manner. Additive methods open up one possibility to save material. Separately from the debate about primary energy, building constructions should be accordingly optimised. This is true for structural building parts of skeletal load-bearing systems as well as for 'massive' constructions. Optimisation modelled after nature can avoid unnecessary material consumption or possibly reduce material waste through increased performance of existing systems, which would lead to a reduction in overall material use.

Constructive lightweight building is the most obvious application offering the potential for material savings. It is already used in parts of architecture (and interior design). Generative methods could stimulate a more extensive transfer of the lightweight principles to hitherto untouched building components and constructions. Optimising building parts analogue to nature inevitably leads to geometries that can usually not be realised with conventional tools or for which conventional methods are not optimally suited. Methods based on layering are one possibility to overcome this. They allow manufacturing constructions without cut waste; already optimising material consumption during production.

As part of the 'green' discussion, one of the engineers' tasks is to rethink and optimise existing constructions with suitable digital tools. Starting points hereby are shape optimisation (for example with 'CAO: Computer Aided Optimisation', according to Mattheck [29]), topology optimisation (for example with 'SKO: Soft Kill Option', according to Mattheck [29]), but also simulation and iteration of the modified parts with software applications (Finite Element Analysis, realisation in CAD).

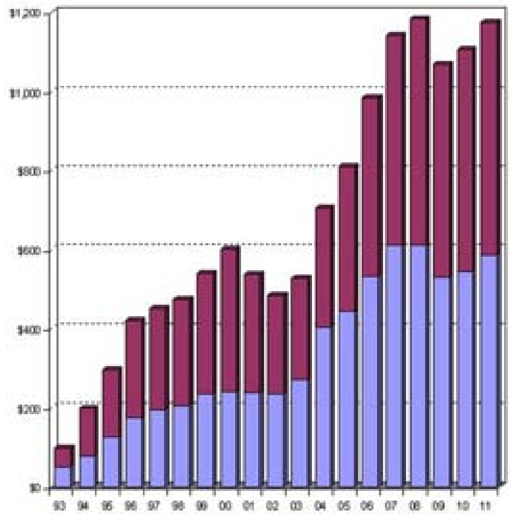
Transferred to the requirements of a façade, the buzz word bionics alone can bring about many new ideas for improved application: Shading, light directing, load transfer, layering, etc. are only a few aspects that can be changed with AM motivated bionics (see § 4.2).

New markets from AM

Spreading new technologies must be tied to the large market developments. To evaluate the potential of a new technology we need to assess its influence on the market: Does the technology already exist in the market or will it remain a specialised niche product? Can the technology spread out; can it open up new markets? 'Conventional' markets and industries have noticeably become aware of the additive methods: if not as a production method, at least as an "emerging technology".[33] The market watches out for and evaluates such 'new technologies' in order to be able to estimate their potential. This means that indications about regional and global trends toward changing production methods can be gathered. Such scenarios can also help in deriving the development of additive fabrication. It must be noted that over the past few years the '3D Printing' technology – conversational term for AM technologies – has appeared on the scene in many configurations; a fact that supports the desire and visions proposed in this work. This allows the conclusion that this technology offers great potential; a fact that is noticed even outside of the sworn in AM community of users and suppliers.

The overall development of '3D printing' (without specification) or specific applications (for example in the medical or aeronautics industries) are looked at or explicitly stated, but the technology was never yet associated with the building technology. However, any professional market analysis predicts great potential for AM (Gartner, 2011; Wohlers, 2012; IBISWorld, 2012).

"The demand for products and services from additive-manufacturing (AM) technology has been strong over its 22-year history. The compound annual growth rate (CAGR) of revenues produced by all products and services over this period is 26.4%. The CAGR slowed to 3.3% over the past three years, with 2009 being the slowest in many years, by far. The chart shows the rate of growth/decline since 1993. The bars for 2010 and 2011 are forecasts.
Unit sales remain relatively strong due to the impact from very low-cost machines. The 3D printer market segment grew by nearly 18% in unit sales, yet the segment experienced a sharp decline in revenues—the first time ever since tracking this market segment.
The additive-manufacturing industry has tremendous untapped potential, especially when considering the opportunity in custom and short-run production. Producing parts for end use products is more challenging than models and prototypes, so this application will take time to develop. It is expected to drive revenues from AM products and services to impressive levels in the future."[30]



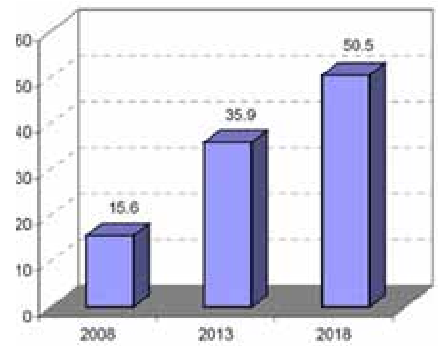


Figure 107
AM market development and growth rates; source: Wohlers Associates; report 2010. "The previous chart gives estimated revenues (in millions of dollars) for additive manufacturing products and services worldwide. The lower portion of the bars indicates products, while the upper portion indocates services. The bars for 2010 and 2011 are forecasts."

Figure 108
Expected Growth of Additive Manufacturing for Part Production Applications; source: Wohlers Associates; report 2009.

Another market analysis by IBISWorld conducted in 2012 also lists Rapid (AM) technologies under the Top 10 of the "emerging technologies". By means of this Top 10 list, the analysts of IBISWorld try to identify trends that promise large growth and thus newly developing or – conversely – decreasing markets. The IBISWorld surveys exclusively represent the US American market; however, they do reflect approximately 700 important industry sectors.
"Rapid technological advances, falling costs and a greater need for new medical devices have led to the growing presence of 3D printing [...]. The 3D Printer Manufacturing industry's revenue has grown an average of 8.8% per year since 2002, with 20.3% growth expected in 2012 alone. As the cost of producing these high-tech machines decreases and printer technology is refined, they will be used for an increasing number of applications, such as aerospace-related part manufacturing. With the rapid pace of innovation already present in the industry, double-digit annualized growth (14.0%) is projected to continue into the next five years."[31]

Noteworthy is a generally positive development in the market segment 'Additive Manufacturing', and a good prognosis for business opportunities, enhancements of existing productions and adaptation for new areas (for example the façade). Based on a market study, the development for the AM market can be summarised such that companies working with AM estimate that in the next five years production of AM products will represent as much as 36% of the business activities. The ten year prognosis

lies at more than 50% – compared to a mere 16% in the year 2008.[30]
Various sources consider the development of the AM technologies positively (Gartner, 2011; Wohlers, 2012; IBISWorld, 2012), and a detailed review shows continuous growth. In order to estimate the development of the different AM methods related to façades and building construction, aspects of a possible business model with AM were considered in addition to those with concrete building practical applications. The results can be illustrated in a developmental 'AM roadmap', which visualises subsequent steps and technological changes, and puts them into chronological order. To do this, already formulated ideas and possible applications were allocated to different 'branches' of the AM technologies. Thus, the roadmap shows the progress of a possible development in terms of technological sophistication and the contextual interdependency of different ideas. Again, this procedure shows that applying AM to façades requires a large number of intermediate steps. Besides these main paths, the roadmap also shows various side roads and common way points.[24]

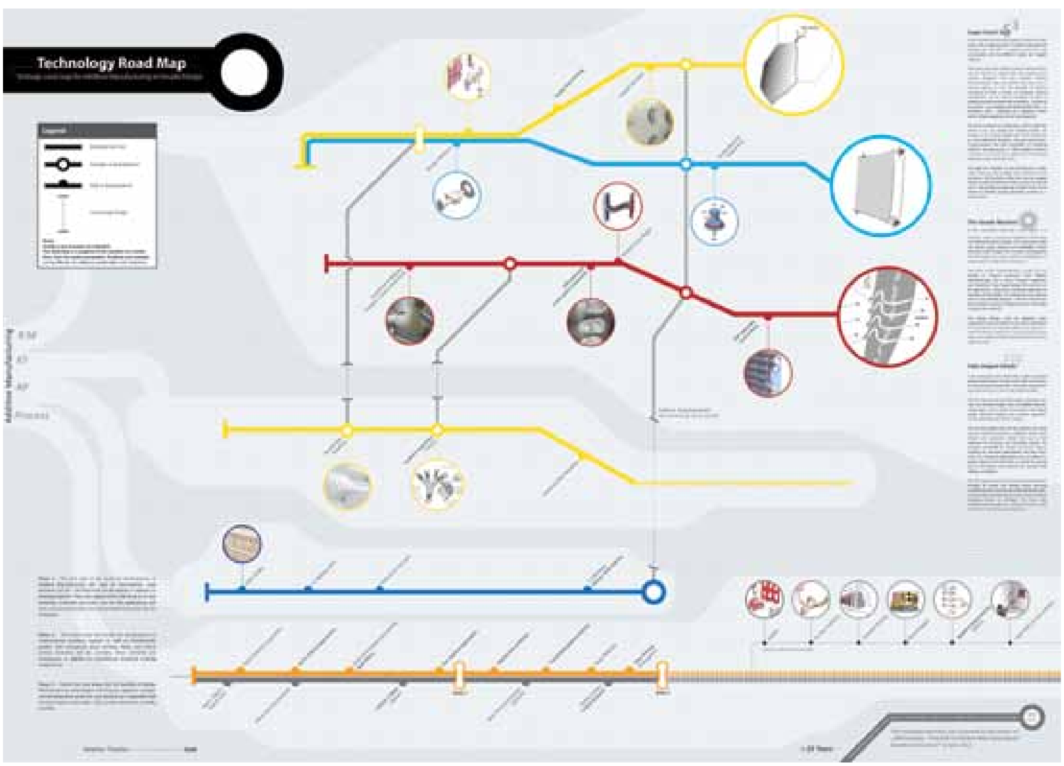


Figure 109
AM roadmap (revised by the author according to Volkers, 2010)

At the end of the roadmap [24] are three concepts related to applying AM to façade technology:

- the Fully integral Façade (FiF);
- the Façade Machine (FM);
- the Super Smart Skin (S³).

These points on the path to a dynamic building envelope illustrate three differently motivated façade developments based on current experience and requirements (see § 3.1) and the current state of technology of AM (see § 2.2). Independent of production reality and contrary to the research results shown in chapter 3 these visions identify possible areas of development. They are examples of imaginative visions whereby 'FiF' (see § 4.2.1 / Fully integral Façade) probably comes closest to an AM building envelope in terms of consequently reinterpreting the building envelope.

To create the roadmap, the first step was to consider the prospect of an industrial application of AM technologies and its transferability to economic use.
Here for, companies must estimate and assess the potential for their own business. The decision of whether or not AM can or should be integrated into the production chain is influenced by external and existing internal circumstances. In order to dare make a realistic estimation whether AM can play an important role in the façade industry, such entrepreneurial deliberations must be considered – the development must be finalised with a proof of economical feasibility. An invention can only mature to a true innovation if it reaches marketability – and this is also valid for generative methods in the façade technology.

External factors to consider are:

- key trends (technology trends, regulatory trends, societal & cultural trends, socioeconomics);
- market forces (market segments, needs & demands, market issues, switching costs, revenue activities);
- macro economic forces (global market condition, capital markets, commodities & other resources, economic infrastructure);
- industry forces (supplier & other value chain actors, stakeholders, competitors, new entrants, substitute products & services).

Internal factors to consider are:

- customer segments;
- value propositions;
- channels;
- customer relationships;
- revenue streams;
- key resources;
- key activities;
- key partnerships;
- cost structure.

[32]

As mentioned before, AM can positively impact the façade industry. But cost efficiency and current existing technological barriers are still used as the main decisive criteria; hindering a 'fair' assessment of its true potential. However, AM opens up many advantages for future business models. The appropriate question to ask is how and in which area AM technologies can benefit the business model. Currently, the bare costs of AM might be higher than those of conventional manufacturing techniques. But if a company can offer better 'value', customers might be willing to pay the premium. Besides savings related to stock keeping and labour, for example, the sum of all aspects might result in overall saving.[24]

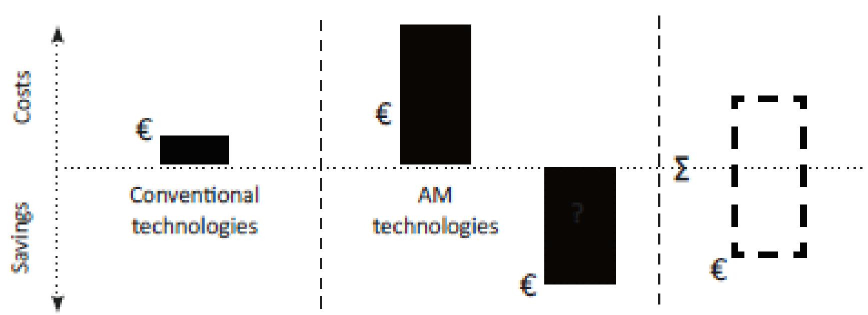


Figure 110
Cost comparison: conventional technologies and AM (Volkers, 2010).

The cost savings shown in figure 110 can have different causes: On one hand, they can be a result of the cost structure of the product, on the other; they can result from additional sales revenues. Besides pure cost calculations it is important to consider the factor 'time to market'. With AM, sophisticated components can be produced and distributed in a shorter time period. If the cost savings for a particular product are large enough they could justify the higher cost for the use of AM technologies.

And there is the possibility to generate added value beyond the production process: The number of parts needed for a multi-part product, for example, can be reduced by generating an appropriate functional construction. In turn, this leads to significantly shorter assembly times for semi-finished products and final assembly of ready-to-use parts. Such modifications of the component structure impact other production criteria as well. Stock keeping, replenishment logistics, assembly, weight and maintenance can be optimised and thus improve the overall cost of the production process. However, the critical factor for all such changes is that the awareness and acceptance of developers and manufacturers must change to allow for a realistic prognosis about the use of additive methods.[24]

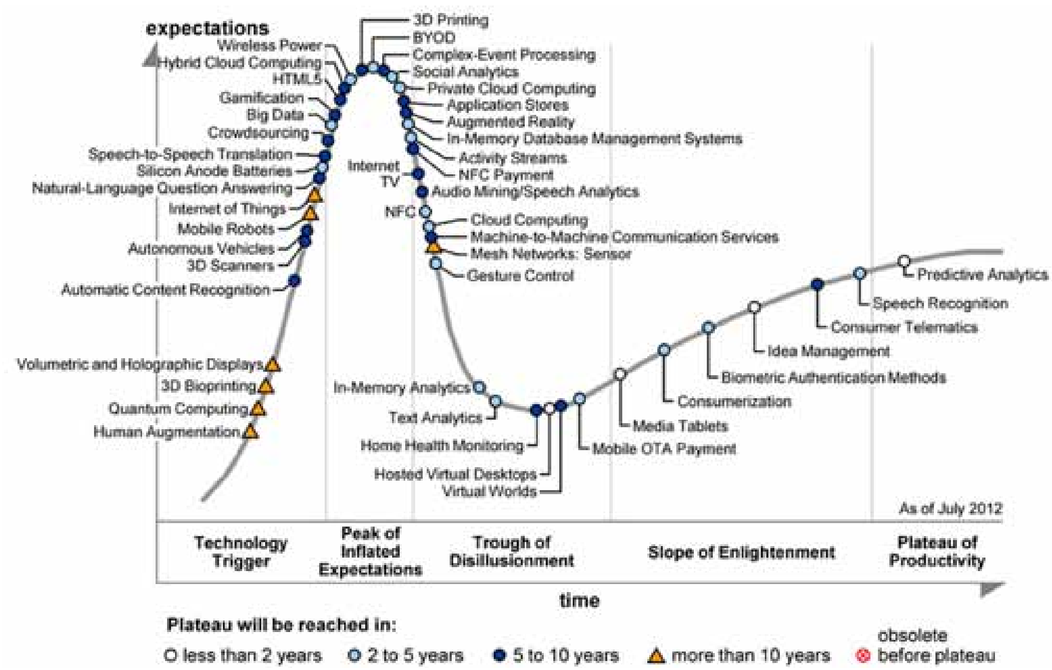


Figure 111
Gartner Hype Cycle 2012, source: Gartner.com.

Besides the approaches described above to integrate AM into corporate structures, the 'Hype Cycle' developed by Gartner in 1995 can be employed as another decision aid.[8] For several years now, '3D printing' can be found in the 'Hype Cycle' for "emerging technologies"; the fact that it is listed means that it is considered a notable technology.[33]

In their research on the development of trends and innovative technologies in Information Technology (IT) they realised that they shared a common pattern. To illustrate the technologies in the "Hype Cycle" the positioning of the technologies is described based on product maturity and average market development. These two factors are plotted onto one timeline, allowing a division of the technological development into different stages:

- innovation trigger;
- peak of inflated expectations;
- trough of disillusionment, slope of enlightenment;
- plateau of productivity.

Generally, when introducing a new product to the market, an initial euphoric start is followed by a phase of disillusionment. During this phase, a (possibly) overrated product meets the real market world with true requirements and the necessity to sustain its position. Only if it emerges from this trough, the product re-enters a phase of regeneration, followed by productivity or realistic market development. At this stage, the product is accepted and valued by a larger circle of users.
Today, many companies base their decisions on the 'Hype Cycle'. In the meantime they reflect more than a decade of dedicated knowledge, and are available for different market segments and are updated annually. The decision aid gives an indication of whether a company should use a new technology, new process chains, applications or ideas, and if so, when. Thereby it addresses scenarios that can be based on interior as well as exterior motivation.[34]

The conservative building market is slow in recognising and accepting such changes. Relating to the development of façade technologies, the past decades reflect a phase of increasing specialisation: Fundamental innovation (meaning new concepts that change fundamental principles) is not apparent. The result is that established building products become more specialised, detailed and thus complicated. The beginning of the 20th century saw a 'rapid change' of façade constructions within a few years; true innovation took place – in the form of the curtain wall, i.e. the first true separation of building structure and building envelope.

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8 The information was taken from: www.gartner.com: "Gartner, Inc. is the world's leading information technology research and advisory company. We deliver the technology-related insight necessary for our clients to make the right decisions, every day. Founded in 1979, Gartner is headquartered in Stamford, Connecticut, U.S.A., and has 5,000 associates, including 1,280 research analysts and consultants, and clients in 85 countries"

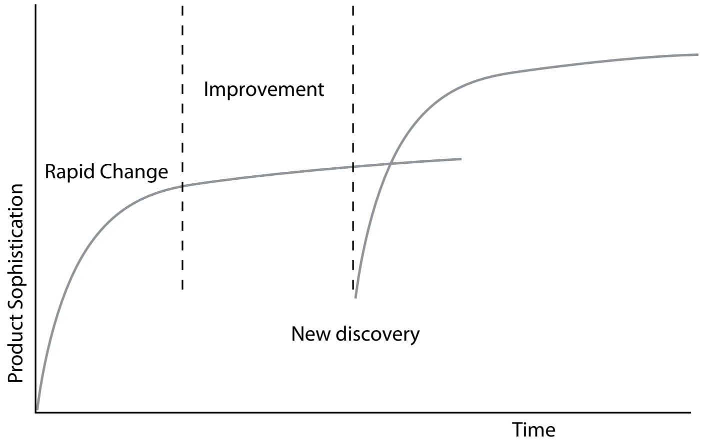

Figure 112
Product sophistication: by Tillmann Klein. In: 'Integrated Façade Components' presentation, Spring 2009, Delft University of Technology.

Figure 113
Faguswerk by Walter Gropius,1920. The first curtain wall façade in Germany.

Since this innovation, the basic principles were continuously further developed ('Phase of Improvement'). Again, external factors were the main drivers, such as the oil crisis during the Seventies: Topics still important today such as energy savings, heat insulation and energy demand were formulated based on this crisis. The façade technology responds to such triggers by continuing the development of existing systems: Single glazing becomes double glazing, then triple glazing – while the effect is not linear but exponential. Therefore, improvements achieved by the changes of the past few years can only be measured using third decimal places. A fundamentally different approach is nowhere in sight. AM could therefore represent a technology that is part of the digital revolution - bringing about a new discovery that will replace current standards.[23]

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Weblinks

General information:

- Terry Wohlers is an insider in AM related to the industry and business markets: http://www.wohlersassociates.com/
- Homepage of the Ennex Corp. about 'fabbers': http://www.ennex.com/~fabbers/
- Castle Island's Worldwide Guide to Rapid Prototyping: http://www.additive3d.com/
- RT e-Journal: web-journal of the Technical University RWTH Aachen: http://www.rtejournal.de/
- Z Punkt - the foresight company: German consultancy for future related questions: http://www.z-punkt.de/

Manufacturer of AM systems:

- Objet: Company site about the PolyJet™ method: http://de.objet.info/
- Optomec: Company site about the LENS and M3D methods: http://www.optomec.com/site/index
- Concept Laser: Company site about the LaserCusing method: http://www.concept-laser.de/
- 3D Systems: Company site about the SLA method and various DIY applications: http://www.3dsystems.com
- Arcam: Company site about the EBM method: http://www.arcam.com
- EOS: Company site about the SLS and DMLS methods: http://www.eos.de/
- SLM Solutions: Company site about the SLM method: http://www.slm-solutions.com/
- ContourCrafting, a technology to 'print' houses: http://www.contourcrafting.org/

AM service providers:

- 1zu1 Prototypen: A service homepage for RP and AM http://www.1zu1prototypen.com/index.htm
- FKM: A service homepage for RP and AM: http://www.fkm-sintertechnik.de/index_de
- E-machine shop: A service homepage for RP and AM: http://www.emachineshop.com/index.htm
- RTC: A service homepage for RP and AM: http://www.rtc-germany.com/index.html
- 4D Concepts: A service homepage for RP and AM: http://www.4dconcepts.de

- Fabtory: A service homepage for RP and AM:
  http://www.fabtory.de/
- Rapid Objects: A service homepage for RM:
  http://rapidobject.com/
- Freedom of Creation: A service provider for jewellery and design objects:
  http://www.freedomofcreation.com
- Materialise: A service homepage for RM:
  http://www.materialise.com

Research and development / teaching:

- TNO NL, the Dutch pendant of Fraunhofer-Gesellschaft:
  http://www.tno.nl/content.cfm?context=thema&content=prop_case&laag1=892&laag2=906&laag3=83&item_id=1445
- Fabaroni, a homemade 3D printer, project of MIT:
  http://fab.cba.mit.edu/classes/MIT/863.07/11.05/fabaroni/
- Centre for Bits and Atoms: Prototype laboratory at MIT:
  http://cba.mit.edu/
- RepRap: Research project at University of Bath:
  http://reprap.org/wiki/Main_Page
- RM Platform: European collaboration on Rapid Manufacturing:
  http://www.rm-platform.com/
- Fraunhofer IFAM: Project pages on RP applications:
  http://www.ifam.fhg.de/index.php?seite=/2801/rapid-product-development/
- Fraunhofer-Allianz Generative-Fertigung: Alliance of research institutions for AM:
  http://www.rapidprototyping.fhg.de
- Loughborough University: Additive Manufacturing Research Group:
  http://www.lboro.ac.uk/research/amrg/
- Loughborough University: 3D Concrete Printing: an innovative construction process:
  http://www.buildfreeform.com/index.php

Trade fairs:

- Euromold, Frankfurt a.M., Germany, one of the most important trade shows for AM:
  http://www.euromold.com
- RapidTech, Erfurt, Germany, trade show and conference on AM:
  http://www.rapidtech.de
- Hannover Messe, an important trade show around innovation and manufacturing technologies:
  http://www.hannovermesse.de

Glossary

Abbreviation / Term	Description / Explanation
3DP	3D Printing; AM process
ABS	Acrylnitril-Butadien-Styrol-Copolymerisat; plastic compound
AM	Additive Manufacturing; general term for additive processes / layered production
ASTM	American Society for Testing and Materials
BIM	Building Integrated Modeling
Blob	Architectural design without orthogonal elements or joining (example: Kunsthaus Graz)
CAAD	Computer Aided Architectural Design
CAD	Computer Aided Design
CAD-CAM	Computer Aided Design-Computer Aided Manufacturing; transition from computer aided design and planning to computer aided realization of such designs
CAM	Computer Aided Manufacturing
CATIA	Computer Aided Three-Dimensional Interactive Application; software for 3D modeling of complex structures; originated from aerospace applications
CC	Contour Crafting; AM process
CLAD	Construction laser additive directe; DMF-development from France; AM process
CNC	Computer Numeric Control
DGF	Direct Glass Fabrication; direct manufacturing of building components in glass (invented by Façade Research Group, TU Delft)
DLP	Digital Light Processing; AM process
DM	Direct Manufacturing; general term for additive processes / layered production
DMDS	Directed Metal Deposition System; DMF-AM process
DMF	Direct Metal Fabrication; direct manufacturing of parts in metal
DMLS	Direct Metal Laser Sintering; DMF-AM process
DIY	Do-it-yourself
EBF^3	Electron Beam Free Form Fabrication; DMF-AM process
EBM	Electron Beam Melting; DMF-AM process
FDM	Fused Deposit Modeling; AM process
FEA	Finite Element Analysis
FEM	Finite Elemente Methode (German) » Finite Element Analysis
FFF	Free Form Fabrication; general term for additive processes / layered production
FGM	Functionally Graded Materials; allows for merging of different materials and properties within one produced part
GIS	Geographic Information System
IGES	Initial Graphics Exchange Specification; Industry file-standard for exchanging CAD files
LENS	Laser Engineered Net Shaping; DMF-AM process

Liquid Architecture	general term for digitally planned architectural designs, using the freedom of form from the applied CAD software (see: M. Eekhout: Tubular Structures in Architecture; 2011)
LMD	Laser Metal Deposition; general term for DMF-AM processes
LS	Laser Sintering; AM process » SLS
M3D	Maskless Mesoscale Materials Composition; Aerosol Jetting System, AM process
MC	Mass Customization; individualized mass production; approach in product design: from 'mass production' and 'individual customization'; paradoxon, but feasible with new technologies!
NURBS	Non-Uniform Rational B-Splines; multiple shaped line, defined from the computer for the representation of 3D-surfaces; originally invented the design of ship hulls, car bodies and aerospace exterior surfaces
ODM	On Demand Manufacturing
PF	Personal Fabber, Personal Fabricator » 3D-Desktop-Printer for the consumer market
PIM	Plastic Injection Molding; Injection-molding process for thermosets
RM	Rapid Manufacturing; evolutionary step from Rapid Prototyping (RP); describes the manufacturing of end use parts with AM
RP	Rapid Prototyping; original application of AM technologies for the manufacturing of prototypes in product development
SFF	Solid Freeform Fabrication; general term for additive processes / layered production
SLA	Stereolithography; AM process
SLA	Stereolithography Apparatus; if used for AM system
SLM	Selective Laser Melting; DMF-AM process
SLS	Selective Laser Sintering; AM process » LS
STL	Standard Triangulation Language; AM file-format, originates from „**ST**ereo**L**ithography term"
Tissue Enginee-ring	Technology that is used to generate tissue from human cells for the application in case of destroyed or harmed tissue after accidents or body impact
VDI	Verein Deutscher Ingenieure; German Society for Standardization
Voxel	from Volumetric Pixel; merging of terms Pixel (definition of reference-point in digital image) and volume definition of solids; aims toward the possibility of defining any point within 3D-modelled solids; would then allow for defining material disposition within solids of 3D model

Index of figures and tables

I would like to thank all the image providers for their support of my work. They are mentioned in this index. All other illustrations were created for this thesis by the author or were provided by members of the Façade Research Group / TU Delft.
Especially some of the imagination-illustrations in § 4.2 were created in workshops and seminars together with students, guests and members of the Façade Research Group / TU Delft.
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Curriculum Vitae

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1974 Born in Wuppertal, Germany

1996 - 1999 Vocational training as cabinet maker / joiner

2001 Certified as log home builder, Canada

2001 - 2003 Degrees from further education:
Master cabinet maker,
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2003 - 2009 Freelance teacher: specialised in hands-on vocational training for journey men in carpentry.
2005 - 2008 Studies of architecture at the University of Applied Sciences - Hochschule Ostwestfalen-Lippe, Detmold, Germany.
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Since 2008 Project leader 'Research and Development' at Hochschule Ostwestfalen-Lippe.
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