Rapid Manufacturing in façade design
Case study to an innovative shading device

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- Design of Construction, Faculty of Architecture,
  Delft University of Technology -
Graduation thesis: Rapid manufacturing in façade design
Master thesis:
Rapid Manufacturing in façade design
Case study to an innovative shading device

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Graduation thesis: Rapid manufacturing in façade design
Preface

This graduation thesis has ‘Rapid manufacturing in façade design’ as a subject. It was performed within the chair ‘Design of construction’, which is a part of the masters’ variant Building Technology at the faculty of Architecture (Delft University of Technology). The project started in April 2009 and was ended in April 2010.

During this graduation thesis, I got the change to learn a lot about product development, building technology and architecture. Although I sometimes found myself completely buried in all this knowledge and it seemed as if there was no easy way out whatsoever, I did, in the end, find the right direction with the help of my mentors and can now safely consider this as one of the most valuable learning experiences I had in my university career. Therefore, I am proud to present to you my master thesis.

This would not have been possible without the help of my mentors that guided me along the way. Thank you: Ulrich, for guiding me through the first part; Marcel, for your enthusiastic support and guidance; Engbert, for sharing your thoughts and your sincere commitment; and Holger, for the critical, detailed and essential comments.

Leonie van Ginkel
Delft, April 2010
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Abstract

Rapid Manufacturing (RM) is a relatively new discipline which offers great potential for designers in every industry. When further developed, this new method of manufacturing, which eliminates tooling and uses additive material processing for fabrication, could have major impact on the way we design, manufacture and sell new products. In several industries, RM is already being developed to contribute to an improvement in technology and for the building industry, it could also be worthwhile to explore the possibilities in the field of façade design. The technical performance within the façade industry could potentially be brought to a higher level by implementing the positive properties that the technique can provide.

A façade has to integrate a lot of functions for it has to deal with thermal, visual, hygienic and acoustic comfort, provide safety and meet the requirements for aesthetics as well. Looking into further depth to the visual comfort of a façade, shading devices play an important role, because they are dealing with the entering of heat and light in the room. The production method determines the appearance and the properties for the detailing of a façade. When RM is used as a production technique, the design will become different than when contemporary production techniques are used. Geometric freedom, material properties and the fact that the design is independent on production eliminates a lot of boundary conditions for the design process.

There will be intermediate steps between the façade produced with current processes, and the fully rapid manufactured facade. During the introduction of the technique, printing shall first be introduced to produce only parts of the façade in a hybrid or a modular approach, applied in the area where the highest profit can be reached, and gradually be scaled up to building size.
Research question

The subject of this master thesis is ‘Rapid manufacturing in façade design’. In this process I researched the fields of facades and rapid manufacturing in order to find the possible impact that the relatively new technique of three-dimensional printing could have on façade design and how the development can be directed.

Predefined objectives of this master thesis:
- Gaining knowledge about rapid manufacturing technologies and applications
- Evaluation of current technologies in façade design
- Development of a (product) design that reflects the possibilities of current and rapid technologies in architecture

Main research question:
*What is the perspective for the introduction of rapid manufacturing in future façade design?*

Sub questions:
1. *What is the state of technique in façade design?*
Different approaches are applied in current façade design and the techniques have developed over history. Current building systems and ways of construction are described to update knowledge about contemporary façade design.

2. *What is the state of technology in rapid manufacturing (RM)?*
The technique of rapid manufacturing is still in development. In some industries, large steps have already been taken in the improvement of techniques in specific applications. By mapping the main advantages and limitations of the process as it is at this point in time, boundary conditions can be developed, describing the outlines for an application in architectural design. Future developments should also be taken into account.

3. *How could RM be used to define new ways of constructing facades?*
The analysis to the state of technology in rapid prototyping and manufacturing on the one hand and current technologies in facade design on the other can be combined in the description of a path for further research and strategies on a method of working.

4. *What is the influence of RM on façade design?*
A case study is developed on an innovative approach for a shading device. The research covers the (sub-) aspects of this system and result in two designs for a facade. One shows an upgrade for a facade using
common production methods in a curtain wall facade. The second design is shows a future perspective by using rapid manufacturing to produce and materialize the facade.
Read me

This report is split in three main parts.

**Part 1, Literature study: ‘Rapid Manufacturing in façade design’**
In this part of the report, an analysis is done to the current state of technique in façade design as well as in rapid manufacturing. This was performed in cooperation with another graduation student J.N. Volkers. As a conclusion, a possible field of implementations is described, using small concept designs to illustrate the solutions.

**Part 2, Implementation: ‘Towards an innovative shading device’**
Part 2 describes a research to a shading device which is inspired by rotating disks. The device and its influence on the working environment is the main topic of this part of the report. It is divided in a section research and a section design of a façade. In the design part, two designs are developed, the first is called ‘Upgrade’ and describes a façade design with contemporary production techniques. In the second proposal, rapid manufacturing is used to develop the detailing and materialization of the façade design.

**Part 3, Evaluation**
The research question is answered in part 3 in overall conclusions, discussion and recommendations for further research.

**Appendices 1 and 2**
The appendices contain additional information about the brainstorm and the design drawings.
Part 1; Literature study: ‘Rapid Manufacturing in façade design’
1. State of technology in façade design

To get a grip on the possibilities which RM offers for façade design, we first have to identify the points of improvement in the facades itself. This chapter briefly describes the history of façade developments and results in a SWOT analysis of the current state of technology.

1.1 Development of the façade typologies

As mankind developed shelter through the ages, from clay huts to modern housing, it constantly developed a surrounding layer to protect itself against the elements. This layer was often called ‘wall’, while it primarily fulfilled the function of carrying the loads and only contained some holes where people could get in or to let the smoke out. In later days people added holes in the wall for light and views to the outside.

The openings in the wall gradually transformed from basic outlets to windows. Holes were covered with first translucent materials, like thin slabs of marble, and then with glass panes. The single glass panes evolved into boxed windows and people began to make opening windows – this can be regarded as a first form of an ‘intelligent’ façade, while the properties of the opening could be adjusted to the circumstances.

Although primitive, those early walls can actually be seen as what we see nowadays as an ‘integral’ façade. Aside the holes for some basic functions, functions as ‘carrying load’, ‘insulation’ and ‘sealing’ were all fulfilled solely by the material of the wall. These could be clay (or later bricks) or a mixture of straw and manure. The last one can be seen as one of the first composite facades. Today’s facades can be typified as ‘segregated facades’, in which functions are at least layered, stacked or solved in a total different building part.
Although the solid wall was the most basic façade typology, it was not the only one. Nomadic tribes already had to deal with a demand for flexibility and lightweight structures. Their tents had to be light and easy to (re-)construct. Where the solid wall was the ‘integral façade’, the nomadic tents are the early examples of a façade where functions are separated – an early predecessor of the modern type post-and-beam façade.

Gradually, the openings got bigger and the glass won surface over the solid wall. Examples of this can be found in the succeeding styles of the Romanesque style, Gothic and Baroque styles. These developments took millennia, while the last century the developments in façade design were fast and rapid. Nowadays, architects seem to prefer to have no walls at all; at least, this is suggested by the erection of a lot of seemingly transparent boxes they call ‘modern architecture’. In contemporary buildings the solid wall is still the main typology in the Netherlands especially in dwellings. But for high-rises and office buildings a new typology developed in the 20th century.

A lot of the modern façades are characterized by a maximized window and the separation of support and covering functions. This brings the development of the solid wall and the previous described tent together in the modern relatively light weight façade where there is a support frame and cladding. A parallel development led to the post-and-beam façade.

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1 Source: (U. Knaack, 2007)
In post-and-beam systems the façade mostly hangs from the floor above and the voids in the structure can be filled with different elements providing different functions. They could provide for example transparency or normal cladding, but also sun shading, ventilation or other climate related functions are often integrated. Here we find a total separation of functions. The post system is limited by the maximum (economical) size of the infill elements. Within these system there is a variety of solutions, like suspended façades where the bearing elements are replaced with tie rods, which makes it possible for designers to get even more transparency in their facades.

A clear division within the typology of the post-and-beam façade can be made if one observes the modularity of one façade element. We can divide the curtain wall typology into ‘stick systems’, ‘component type’ and ‘super component type’\(^2\). The stick system is a modular system with a layer of framing and the infill elements making the actual façade. The component types are integrated façade elements of one storey or more (super-component) which are highly industrialized products – for the building industry this is as far as it goes at the moment for turning buildings into industrial products. Its use is still mainly limited to high-rises.

\(^2\) Source: (J. Renckens, 1996)
The last three decades the energy issues, and especially in the last decade climate issues, played an important role in the development of facades. Single glass panes became double glazing and details got very complicated structures to prevent thermal loss and condensation through cold bridges. Next to double glazing, double facades were developed to further integrate the climate (ventilation) concept of the building into the envelope. Nowadays, more and more functions are integrated in the façade and instead of the old core-oriented approach a number of essential functions are now transferred from the core to the façade.³

The development of the facades tends towards divesting the building itself of all functions apart from that of bearing its own weight and incorporating all other functions in the façade. The question still remains where these developments are really heading. The modern metal-glass façade is a highly developed typology and improving details or glass performances is providing little progress. The trend of function integration reminds us of Mike Davies’ concept for the polyvalent wall. This vision, of a highly functional integrated and adaptive façade might be one direction to head for. Current technologies and materials might offer solutions he did not have.

³ Source: (U. Knaack, 2007)
1.2 Principles of construction

An important part of the façade is the connection between the different elements. Improvements of the last decades focused on sealing and preventing thermal bridges. Where connections between elements might at the moment require three connections and five materials, future technologies and design might enable façade design where these interfaces are more integrated. This part takes a closer look on these principles. This paragraph describes the principles of construction of a modern façade.

A building façade is a technical challenge while it combines a lot of functions. Figures 7 and 8 give an impression of the variety of functions and influences a façade engineer has to take into account. The façade can be described as the ‘adaptive interface’ between the user (-space) and the outside world. A façade should adapt its properties to the changing environments, inside or outside, to what the use wishes. This adaptivity can be very basic – eg. Opening a window, or simple venetian blinds for sun shading – or very technically sophisticated – eg. By using integrated mechanisms or smart materials. Either way, the façade brings together a lot of different functions, which are often performed by a lot of different components.

To start with, the contemporary metal-glass façade is taken as an example. Three main areas of construction can be defined within the façade:

---

4 Source: (Feldtkeller, 1989)
- Primary structure (shell of building) forming the main load bearing structure of the building.
- Secondary structure, which is the load bearing structure for the façade and is a connection element.
- Infill elements

The infill elements could be standard façade panels for opaque parts of the façade, glazing for light and view, but could also contain multiple layered functions like sun shading inside the glass cavity.

Figure 9 – layering of the façade and affections by external loads

All façade elements have to carry their own dead load and external loads that act upon them. The different types of loads which affect the façade⁵:
- Dead load of the façade elements
- Weight of snow
- Wind load
- Live loads – e.g. fall protection
- Stress loads – e.g. caused by deflection of components.

The loads can be transferred to the main structure of the building in several ways. They can either hang or stand on the structure, but for almost all systems there is a differentiation in primary structure, secondary structure and infill elements and between these levels of construction there are interfaces which need to be able to deal with tolerances. More on detailing and tolerances will be described in chapter 1.3.

To get a grip on what facades could look like in the future we should describe them in a more general way. Looking at the product architecture of the metal glass façade, two main areas can be defined: the system, which is basically a grid of posts and beams, and the infill elements. A large part of the façade systems currently used is systemized, which means that specific parts are factory proved and standardized. This

⁵ Source: (U. Knaack, 2007)
productizing of the façade is driven by the ever increasing demands and complexity of the façade detail.

Above we spoke about the different systems as in stick systems, component systems and super-component systems. This is mainly a difference in production method, it defines where elements are put together (on the site or in the factory). The other way to look at this topic is to make a difference in ‘integrality’ and ‘modularity’. This division is also a matter of scale. The ‘super component’ – eg. A façade element which spans two floors – can be considered integral because all functions are integrated in the panel, but it can also be considered as a modular element on a building scale.

The organization of functional elements, the product architecture, might be one way to change and improve façade design. A fully modular façade could offer economical and sustainable solutions for manufacturers to easily upgrade or re-use façade elements, but it will require a whole new set of solutions for the interfaces between the different components. On the other hand, a fully integral façade might offer a solution for optimized use of materials and integrated functions.
1.3 Detailing, Tolerances & Interfaces

In the field of detailing, tolerances and interfaces, façade technology has gotten really complex throughout the last decades. As already described in paragraphs 1.1 and 1.2 the façade developments were driven by new use of materials, the urge for transparency, integration of building functions and in the last years more and more important: energy performance.

The fact that a façade has to combine a wide range of functions makes the detailing quite complex. The composition of parts is for a part done in factories, where the circumstances can be controlled. On the building site, still a lot of actions have to be done to construct the building. On the site, structural elements with large tolerances have to be combined with the relatively high-tech façade components with small tolerances. Consisting of different materials and with different tolerances this needs careful thought throughout the phases of design and manufacturing. This paragraph gives some examples of details, tolerances and interfaces to highlight this complexity.

While there are a lot of factors influencing the façade, there are a lot of different functions to be fulfilled by ‘one’ object. The façade is under influence from external factors, including noise, wind, rain, heat and cold, as well as internal factors including air humidity, heat and cold and for example a falling person.

These factors culminate in several functions like: ‘rain protecting’ or ‘water tightness’. These functions can be fulfilled by components of the façade which are either stacked or layered in respect to each other.

Figure 10 – The complexity of façade detailing: upper left, Crown Hall Chicago, relative simple detailing; The other images show how modern façades are build up with all functional aspects integrated.
Between the elements a variety of possible 'interfaces' are placed to connect them. Think of rubbers, glue, nuts and bolts. These interfaces make the fabrication of the façade elaborative and complex to design while everything has to fit to each other during manufacturing.

Next to the internal interfaces the connection of the façade to the main construction is a point of concern. The façade elements are made of different materials with different on-metal and different deviations in size.

The interface between the construction and the façade should cope with these differences. Façade elements itself can have deviations in size up to several millimetres; an 'in situ' concrete construction can have deviations up to centimetres.

The images above show examples of these interfaces, making it possible to mount the façade with its tolerances in x-, y- and z-direction. Overall “Detailing is reduced to systematic combination of the appropriate individual components to perform the required functions against a background of growing overall building complexity”

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6 Source: (U. Knaack, 2007)
1.4 Conclusions

The façade developed from pre-historic clay shelters, to the classical architecture with massive walls and openings, to the light weight structures with the façade as a curtain wall. Overall, this can be regarded as a separation of functions of the former wall.

Modern buildings consist of numerous complex interlinked technical solutions for the load bearing structure, technical equipment and the façade. Especially the façade itself is subject of increased complexity, while the modern building envelope plays a key role in the performance of the building when it comes to aspects as energy saving and economics.

Façade details have developed into technological complex structures which provide thermal separation, water drainage, ventilation, sun shading, and so on. Critical design issues are often concentrated on the connection between the façade components, and on the connection between the façade element and the building structure. All these interfaces are complicated while they have to be air and water tight, as well as insulating, opening, maintainable, replaceable, durable, etc.

Although changes in façade design were large and rapid when technological developments drove the façade development in the direction of the curtain wall facades, the improvements made in the last decades are mostly done in the field of details optimization and improved insulation values. For instance, the improvements in the U-values of glass are technologically advanced, but relatively small.

The ‘product sophistication’ graph in figure 13 shows the development of a product as a cycle with rapid change at the start followed by a phase of improvement. The modern façade, the curtain wall, is built for about 50 years and developments that are done nowadays can be considered as optimization. A new discovery means a new phase of rapid change, where fast improvements can be made. In this graduation project, the purpose is to find out whether rapid manufacturing could be this new discovery for façade design.

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7 Source: (T. Klein, 2009)
2. State of technology in Rapid Manufacturing

The technology of rapid manufacturing is in a phase of large developments. In this chapter, the technique is looked at in more depth to provide a basic understanding of the properties, possibilities and developments.

2.1 Introduction to Rapid Manufacturing

There is a variety of definitions used by people to describe rapid manufacturing (RM). The term is also often interchanged by its apparent synonyms: rapid prototyping (RP) and rapid tooling (RT).

Rapid prototyping is a term which is used in many ways to describe techniques which enable designers to make prototypes in a fast way. The purpose is mainly to make test and show models for design development purposes. Rapid tooling describes a similar set of methods for producing tools to make the components of prototypes or actual products.\(^8\)

Noorani gives the following definition for RP: “Rapid prototyping takes information from a three dimensional (3D) computer-aided design (CAD) database and produces a solid model (prototype) of the design.”\(^9\) While RP is primarily used for design and show models, RM opens up a new world of opportunities. New and improved techniques make it possible to process different materials like metals, polymers, ceramics or even graded components. This makes it possible to manufacture actual ‘end’ components and products for all kinds of industries.

Although different by definition and purpose, RT, RP and RM have a basis in the same techniques and are all controlled by computers. This requires the use of computer aided design (CAD) and therefore requires the designers to be skilled in the necessary technologies to produce the right digital files for rapid processes.

To narrow down to a set of technologies which have to be researched for this master thesis project, the following definition is used for rapid manufacturing:

“Rapid manufacturing is defined as ‘the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components’.”\(^10\)

RM technologies have some clear benefits, which can be summarized by:

---

\(^8\) Source: (N. Hopkinson, 2006)
\(^9\) Source: (R. Noorani, 2006)
\(^10\) Source: (N. Hopkinson, 2006)
**Geometric freedom**

The freedom in design is unbounded. All mind twisting geometries made with CAD software can be produced. The main difficulty in comparison to conventional techniques is now not to produce the actual product but to design it with the software.

**Materials**

Different materials can be used, with properties that can be compared to the common properties of the processed material. The development in RM provides the possibility to print multiple materials in one process and it is also possible to control the meso- and micro-structure of the printed material, in this way properties of the material can be optimized.

**Elimination of tooling**

The CAD file is directly processed into a solid-state material in the right shape; tooling is in theory not necessary for the production. This is resulting in a saving of time and money and creates the possibility to produce parts with design parameters, which were not possible otherwise.

**Mass customization**

Products can be designed by and for individual consumers, in this way it is expected that the consumer needs can be satisfied more precisely.

### 2.2 Processes

Fabrication processes, manual or automated, can be classified as either subtractive, additive or formative, depending on the way they operate on their raw material.

In a **subtractive** process, material is carved away from a solid block, until the desired shape is reached. Examples are milling, turning, sawing or grinding.

An **additive** process successively adds material into place to build up the desired object. Processes which are used are stereolithography, selective laser sintering and fused deposition on-metal.

The last typology is the formative process, where mechanical forces are applied to material to form the desired shape. For instance this is done by bending, forging and plastic injection molding.

The rapid prototyping process uses layered manufacturing and is therefore a part of the additive processes. With additive fabrication, the machine reads in data from a CAD drawing and lays down successive layers of liquid, powder, or sheet material. In this way the model is build up from a series of cross sections. The layers, which correspond to the virtual cross section from the CAD model, are joined together or fused automatically to create the final shape.

Rapid manufacturing systems can be classified according to the state of the raw material they use, in one of the following categories; liquid-based systems, powder-based systems and solid-based systems. These categories will each be discussed separately with their corresponding processes.
2.2.1 Liquid-based systems

These systems start with the build material, photosensitive polymers, in liquid state. The liquid is converted into a solid state through a curing process. Liquid-based technologies were the first processes in the development of Rapid Prototyping and have some distinct properties. This process is very accurate, but the material properties are poor compared with other processes.

Stereolithography (SLA)
This process can be seen as the basic technique for rapid manufacturing, other systems are derived from this system. It is based on parts that are built from a photo curable liquid resin that solidifies when exposed to a laser beam. The product is built layer-by-layer, controlled by an elevation mechanism that lowers at the completion of each layer. Exposure to the UV laser light cures, or, solidifies the pattern traced on the resin and adheres it to the layer below. The laser is driven by a CAD file. After one layer has been traced, the platform is lowered, typically by 100 µm, to allow the liquid polymer to be swept over the part to begin the next layer.
In some areas where overhangs are created, a support structure is automatically generated by the machine’s software. This needs to be removed once the final part is made.
Once the product is finished, the parts are removed from the machine and the platform, the supports are removed and post curing is performed to solidify the part completely. The post curing is required because some liquid regions can remain in each layer, due to the finite size of the laser beam.

2.2.2 Powder-based systems
This system uses powder in granular form as a base material and notwithstanding that powder is considered a solid, this process forms a special category. It is possible to use a wide range of materials like polymers, metals and ceramics. Furthermore, it is possible to produce functionally graded materials.
Selective Laser Sintering (SLS)

The powdered raw material is sintered or melted by a laser that selectively scans the surface of the powder bed to create a two-dimensional solid shape. A fresh layer of powder, typically 100 µm, is added to the top of the bed when the elevation is lowered after the completion of the preceding layer. A two-dimensional solid shape can again be created by the laser, automatically bonding it to the layer below. The unfused powder acts as support material, which should be removed after completion of the product.

The powder bed is preheated during the selective laser sintering process, to bring the temperature of the powder to a few degrees below sintering temperature. This prevents thermal gradients to occur between sintered and non-sintered material and reduces the required energy of the laser.

Polymers with a high crystalline structure are used, notably nylons, because they lead to good contact between particles and result in parts with relatively good mechanical properties.

2.2.3 Solid-based systems

Solid-based systems start with the build material in a solid state. This solid form may include the material in the form of a wire, a roll, laminates, or pallets. The systems have already been commercialized for some time, but improvements are still made.
Fused Deposition Modeling (FDM)

Material is added layer by layer through a temperature controlled head. The head deposits the material in place, where each layer bonds to the previous layer and solidifies.

The materials that can be used are mostly thermoplastics, but also wax or metal can be used.

Semi-liquid material is extruded in layers of typically 100 µm.

This process does, most of the time, not need any post curing. Because the material cools very quickly into a solid, overhangs can be created without support structure.

Figure 16 Fused Deposition Modeling (FDM)
2.3 Materials

The essential properties of fabricated models are caused by the material chosen to work with and the process that is used to shape the model; properties like the shape, dimensions and durability are all directly related to this. Fabricated materials can be divided in three main categories; polymers, metals and ceramics. The fourth category is composites, which can be described as any combination of materials of the three main categories. RM is able to process materials from each of these categories, an overview will be given in this section.

2.3.1 Polymers

In Rapid Prototyping polymers are mainly used because of their low electrical and thermal conductivity and high strength-to-weight ratio. Another advantage of polymers is that they can be processed at lower temperatures.

There are three categories of polymers; thermosets, thermoplastics and elastomers (figure 17) which can be used for different purposes because of their specific properties.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Polymers</th>
<th>Thermosets</th>
<th>Thermoplastics</th>
<th>Elastomers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonding</td>
<td>Cross-linked</td>
<td>Linear or branched</td>
<td>5% cross-linked</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>High (more brittle)</td>
<td>Average</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Example</td>
<td>Phenolics, animo resins, acrylates, epoxies</td>
<td>Nylon, polyethylene, polystyrene, polypropylene</td>
<td>Synthetic rubber, silicone, neoprene, RTV rubber</td>
<td></td>
</tr>
</tbody>
</table>

Figure 17 Categories in polymers and specific properties

Polymers can be processed using different techniques:
- Stereolithography can process thermoplastic and thermosetting polymers and in general acrylates and epoxies.
- Polymers are used in the form of thermoplastics, such as polyamide (nylon) and polycarbonate. The powders are heated by a laser to a temperature just below the melting point of the material. The temperature is high enough to sinter or bond the individual powder particles together and afterwards the post processing is used to increase the density of the part.
- The polymers that are used in fused deposition molding are polycarbonate, ABS, polymethyl, methacrylate thermoplastic, wax and elastomers.
2.3.2 Metals

The main properties of metals are their resistance to high temperatures, the good combination of strength and toughness and ease in machinability. Other physical properties are good electrical and thermal conductivity and good ductility. In many applications, metal alloys are used to improve the physical properties. Alloys are composed of two or more elements, in which at least one is a metallic element. Two general categories:

Ferrous metal alloys are based on iron, where steel and cast iron are most common. The alloying element that is most often used is carbon. Other alloying elements are chromium, manganese, nickel and molybdenum.

Nonferrous metal alloys include all other metallic elements and their alloys. The base metals include on-metal, nickel, copper, gold, magnesium, silver, tin, zinc and titanium. Super alloys are produced for high-temperature performance, where nickel and cobalt are used as a base metal.

From selective laser sintering, different ways to process metals have been derived using powder as a base material.

- The first process is ‘Álumide’, which uses a CO2 laser. This laser is not capable to sinter the metal particles together, it can only heat the metal powders to half their melting point. A thermoplastic binder is used to coat the metal particles and the binder of the powder is sintered together to form green, fragile parts.

- Direct Metal Laser Sintering (DMLS) consolidates metal powder to nearly full density. This process does not require liquid infiltration and the surface finish of the materials is very good. The metals that used are steel, bronze and nickel.

- Direct metal deposition is a process that injects metal powders into a melted pool on a substrate surface as the laser scans the shape of each layer of the part. This method of powder fusion results in improved material properties, due to the uniform grain structure.

2.3.3 Ceramics

Ceramics are compounds that contain metallic (or semi-metallic) and on-metallic elements.

Metallic elements (cation): Al, Mg, Si, Zr.

Nonmetallic elements (anion): oxygen, nitrogen, carbon, boron.

The general properties are the very high strength, brittleness and high melting points. Ceramic materials have low electrical and thermal conductivity, reasonably low density and high hardness. Because of these properties, the common use is in rapid tooling.
2.3.4 Composites

Composites are non-homogeneous mixtures of the three main types of manufactured materials in order to improve the properties of the host matrix. The lower modulus matrix adds greater elasticity and strain-to-failure to the composite. The reinforcing phase can improve the fracture toughness of the matrix. Properties are the high strength-to-weight and stiffness-to-weight ratio.

2.3.5 Functionally graded materials

“Functionally graded materials (FGM’s) are a form of composite where the properties change gradually with position.”

![Figure 18 Typologies in Functionally Graded Materials (FGM)](image)

There are three types that can be distinguished. The first type is a composite, where materials are homogeneously mixed to enhance the specific properties of the main material. Second type enhances the surface properties of an object, the most common examples are coatings. Last are the FGM’s that have a gradually graded composition between different elements. The properties are engineered over the structure to fulfil various requirements.

The research is connected to the production methods using the technique of laser sintering or laser fusion of powders.

The STL file format, used in common RP technologies, cannot be used to contain information about the gradients. Therefore a research is done to new formats that can provide a link between the computer and the RP machine.

At TNO in The Netherlands, such a system is being developed to fulfil this vision, it is called Innerspace™.

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11 Source: (Hopkinson, 2006)
12 Source: (TNO, 2010)
This CAD-program can define materials in a 3 dimensional product and translate this to data suitable for a RP machine. The machine itself is also developed at TNO and has three printer heads that can print different UV curable materials selectively next to each other on a moveable table. The accuracy and speed is still in development.
2.4 Design methods

Rapid prototyping is fabricating a model from three-dimensional data in a CAD file. This process involves the following steps in order to make physical prototypes:

1. Create a CAD model of the design
The CAD model should completely consist of solids, which can be defined as a volume completely bounded by surfaces: each surface edge must be coincident with one, and only one, other surface edge. In this model, the complete geometry of the object is shown and also the inner and outer side of the space of the geometry is defined. A wide range of programs can be used to build this model. Examples are AutoCAD, Pro/Engineer, CATIA, Solid Works and Rhinoceros.

2. Convert the CAD model to STL file format
The next step is the conversion to a STL (Standard Triangulation Language) file format. This STL file originated from 3D systems, which developed this file format to support the first rapid prototyping process, Stereolithography.

In the file a 3-dimensional surface geometry is represented. The surface is tessellated into a series of small triangles, also referred to as facets. Each facet is described by a perpendicular direction and three points representing the vertices, corners, of the triangle. The tolerance defines the accuracy of the model, which can be adjusted to the desired values.

3. Slice the STL file into 2D cross-sectional layers
The information from the STL file is electronically sectioned into layers of predetermined thickness. The more complex the file is, the more triangles are required. The file will become bigger according to the difficulty of the file. The STL file is now a format the Rapid prototyping computer recognizes.

4. Making the prototype
The machine receives the information from the STL format from the RP computer and runs the process until completion. The model is built one layer at the time from the base material with the specific process. Little human intervention is needed.
5. Post processing

The post processing consists of three steps; cleaning, post curing and finishing. Depending on the process that is used for the rapid prototyping, a combination of post processes is used. The removal and cleaning refers to taking the prototype out of the machine and remove the excess material and/or support material.

The post curing process is only necessary for the Stereolithography process and for Selective Laser Sintering. This is because the laser scans each layer along the boundary and only hatches the lines. This can result in side portions of the layers, which have not completely solidified. The post curing process uses UV radiation to improve the mechanical properties of the prototype. The finishing is done as a final step. The model is cleaned and for example sanded for the visual of the outer surface.
2.5 Applications

The possibilities of rapid manufacturing with its different processes and materials cause the applications to vary widely. This chapter gives a short overview of the range of possibilities and developments of RM.

The technique provides the possibility to design products on a micro scale. Models in the size of a red blood cell have been printed with large accuracy in the shape of a bull as well as a model of the Venus of Milo on a human hair (Figure 20).

The customized sports shoe design (Figure 21), adapted to the specific properties of an individual foot, is playing up to a mass customization possibility that the technique offers. Each product will be the exact optimal solution for the client.

On a larger scale, the Monolite technique has been created, which is able to print a monolithic sandstone structure with a printer in a freeform design (Figure 22). The technique, developed by dr. Ing. Enrico Dini, uses as a main material sand, dust or gravel, from the direct environment, which is mixed with an inorganic binder to reach properties exceeding Portland cement. The process used is Stereolithography, with a printer able to print layers of 10-200mm.

Possibilities: From micro to macro design
Because of the basic intent of the processes, designs can be made with turning parts integrated and from one material, printed in one time. A graded structure, with colours or different materials can be manufactured from the process and because of the range of materials; it is possible to print rigid as well as flexible products with varying properties.

2.5.1 Engineering

In engineering, the technique is developed especially in the application of metal printers, constructing prototyping parts or optimized parts for manufacturing. The techniques are used in aerospace and mechanical engineering.

In the U.S. army, Rapid Manufacturing techniques are used in Iraq to produce replacement parts on demand on location. In this way the logistic burden is reduced during operations. The ‘mobile parts hospital’ is able to print plastics, rubbers, metals and ceramics and prepared to produce parts from a variety of machine and metallic elements for military vehicles, to generator sets.
2.5.2 Rapid Tooling (RT)

Rapid Tooling is an application of Rapid Prototyping which is often used. There are two ways to use Rapid Tooling, either direct or indirect:

Direct tooling; Selective Laser Sintering or Stereolithography is used to produce products with specific applications and material requirements for moulding and casting.

Indirect tooling; the model that is produced by RM is transferred into another material, using the actual product as a pattern or a mould. This is done because the material properties of products produced with RM are mostly not up to the high level which is required and because the process is not suitable to produce for series production. The mould can be produced from different materials, like silicone rubber.

For mass production purposes, moulds are produced with conformal cooling channels that make it possible to reduce the internal stresses within the mould (figure 36). Next to the original advantage that moulds could be produced much faster, the conformal cooling channels actually increase the quality of the moulds because they provide 40% faster cycles than is possible with conventional technologies.
2.5.3 Medical

In the medical field, the technique of Rapid Prototyping has been adopted in a wide variety of applications. In dental care, artificial teeth are printed as an exact fit for the patient. First the jaw is scanned, in order to produce a three dimensional computer model that forms the input for the RP process. For other parts of the human body the same technique is used, based on the possibility RP gives for mass customization. Research is done to the production of a jaw bone made from polymers with bone grow stimulating tissue printed on top. In this way, the bone tissue will grow back and the prototype will disappear gradually over time.

Another application in the medical field is in the hearing industry. For hearing-aid apparatus the technique is able to produce an exact fit for each individual ear. This stimulates the performance of the product, because of the exact connection.

2.5.4 Design

Artists have seen the development of a new computer-controlled technique as a possibility to create shapes
that were unable to be produced with the existing techniques.

The bone chair for example, created by Joris Laarman, is inspired on the bone structure in nature. Material is only added where it is needed in order to increase the strength. The design has been made with an optimization computer program, but has not been printed.

Light designers make special shapes to play with the light falling through the geometry and the properties of material. This is for example the case with the AI light designed by Assa Ashuach, the light is spread fluently adapting to the circumstances in the room and is able to react on light and sound. The movement is created by anticipating on material properties that are flexible in one direction and stiff in the other. The shoes designed by United Nude are first made as a prototype made from cardboard, scanned in to produce a computer model and than processed by a RP machine to create the actual shoe.

2.5.5 Architecture

In architecture the technique of Rapid Prototyping is used in different applications and with different intentions.
- Blob/hyperbody design

A relatively new vision on architectural design is Blob design or hyperbody design. In the process, CAD software is used to produce the difficult shapes of the geometry and the components, while the actual production is done with conventional techniques. The illusion of a freeform is approached as close as possible. The design done in this way is asking for a method to produce the actual shapes without compromises done because of the current state of technology.

Figure 42 Iweb pavilion Kas Oosterhuis

Figure 43 Interior Blob Pavilion Studio Jurgen Bey

Figure 44 Blob Paviljoen Studio Jurgen Bey

- Display models

Another application is also the most common one in architecture at this moment; a CAD model is produced to visualize the design and with the RP technique, a display model is produced to communicate with the client. The machines used have commercialized very fast, because the properties do not have to be of a very high quality.

The prize of the printers will be in the close future under a 1000 euro’s, available for a wide market. Already it is possible to create models with different colours and close details.
Macro design

Contour crafting was developed at the University of Southern California. It is a technique by which large scale parts can be fabricated layer by layer. It pours and shapes a clay-like material, producing the designed shape. An extrusion nozzle pours the material and two trowels create a smooth finishing. It combines techniques from the field of robotics with rapid prototyping technologies and is the first step in rapid mass customized cheap housing projects.

A concept which is almost the same as the contour crafting is used with the Monolite structure, developed by Enrico Dini. This process uses gravel or sand, whatever is available on the site, and combines this with an inorganic binder to produce freeform structures. The printer is able to produce inner structures as well in one line, like stairs and partition walls. At this moment it is possible to produce products of 2 meters in height, but this will increase during the development.
Graduation thesis: Rapid manufacturing in façade design

Figure 48 Contour crafting

Figure 50 Contour crafting process

Figure 49 Monolite construction
2.6 Conclusions

The analysis of Rapid Manufacturing shows a wide range of applications in several very different industries. This gives rise to the question how rapid manufacturing can find its implementation in future façade design. Looking at the literature, a SWOT analysis can be made, where the strong and weak opportunities and threats are mapped in one table to give an overview of the values of the technique for façade design.

SWOT analysis of the current state of technology in Rapid Manufacturing for a use in façade design

<table>
<thead>
<tr>
<th>Strong</th>
<th>Testing of unique products/certification</th>
<th>Geometric freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Costs per piece</td>
<td>Printing ceramics</td>
</tr>
<tr>
<td></td>
<td>Production time</td>
<td>Printing polymers</td>
</tr>
<tr>
<td></td>
<td>Mass production</td>
<td>File to factory</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No tooling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No inventory/labour costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sustainability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Freeform design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum waste</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass customization</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weak</th>
<th>Properties of materials/anisotropy</th>
<th>Metal printing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>Glass printing</td>
</tr>
<tr>
<td></td>
<td>Finishing</td>
<td>Graded materials/Micro structures</td>
</tr>
<tr>
<td></td>
<td>Limited size/Macro scale</td>
<td>Printing composites</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hybrid structures</td>
</tr>
</tbody>
</table>

Looking at the opportunities, a clear advantage of the technique is the large geometric freedom in design and the decrease of mistakes during construction because of the process from file to factory. The range of materials is still developing, with ceramics and polymers as current possibilities with good material properties and the metals, which have an ever increasing performance. The glass printing is still at the starting point of its development, with only opaque glass produced up until now produced at the University of Washington’s Solheim Rapid Manufacturing Laboratory in a process called Vitraglyphic. Prof. Mark Ganter created an open 3D printing forum [Open3DP] to make the technology accessible for everyone. To stimulate a fast improvement he publishes in this forum the recipes for the glass powder he uses in his laboratory.

13 Source: (open3dp.me.washington.edu, 2010)
As weak threats, there are the properties of materials, caused by the process of layered manufacturing. This results in anisotropy within the material; the properties will be better in horizontal direction than in the vertical printing direction.

The limited sizes that are commercially available are very limited. There are some processes which have been scaled up to a size of a dashboard (Volvo, Materialize), or entire building structure\textsuperscript{14} (Contour crafting, California). Especially the processes used for building construction have not been optimized yet. Each building is approached as a unique project, with a very tight budget, therefore the development of new techniques are mostly adopted from other industries. The building industry prefers to wait for others to develop techniques for them.

A strong threat is the costs per piece. This will obviously be reduced by the commercialisation of the techniques. The machines will drop their prices and be available for a wide range of applications. The material will follow with the opening of the technique for the free market. The Reprap is a printer which costs 350 Euros and is able to reproduce and upgrade itself\textsuperscript{15}.

Because this technique is now in a phase of strong development, the assumption can be made that in 20 or maybe 50 years from now, the possibilities of the technique will be changed. This development can partly be foreseen through the current research that is done and the market situation. A strong focus for this graduation project on the current state of technology is therefore not enough. It is more rational to already anticipate on the development and maybe in this way stimulate technology ever further. The SWOT analysis that we can make for the near future situation will be as follows.

SWOT analysis of the near future state of technology in Rapid Manufacturing for a use in façade design

\textsuperscript{14} Source: (www.contourcrafting.org, 2010)
\textsuperscript{15} Source: (reprap.org, 2010)
<table>
<thead>
<tr>
<th>Strong</th>
<th>Mass production</th>
<th>Geometric freedom</th>
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<tr>
<td></td>
<td>Printing ceramics</td>
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<td></td>
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<td></td>
<td>Sustainability</td>
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<th>Weak</th>
<th>Testing of unique products/certification</th>
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<tr>
<td></td>
<td>Production time</td>
<td>Accuracy</td>
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<td></td>
<td></td>
<td>Costs per piece</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Threats</th>
<th>Opportunities</th>
</tr>
</thead>
</table>
3. Range of possibilities

3.1 Introduction

In this chapter, a field for the possible implementations of Rapid Manufacturing in façade design is set out, building on the literature study in the preceding chapters and the brainstorm session.

The possibility to introduce rapid manufacturing is in a wide range of applications, but these are limited by the specific properties of the materials and techniques in comparison to the current processes that are available. The difficulty is to separate the useful from the useless implementations.

Additive manufacturing builds up a product layer by layer and has therefore in fact all the geometric possibilities that other techniques can provide and even a lot more, because it is possible to create internal structures and different scales can be easily handled, because of the computer generated products. On the other hand, the comparison should always be made to current ‘contemporary’ techniques, whether they are faster, more optimized or better suited for the circumstances. Per project can be decided if the extra features that rapid manufacturing can provide, add up to extra costs, etc. It is difficult to assign specific rules for rapid manufacturing and make a comparison when it is useful or useless to apply; this should be done per project and will differ over time while the technique develops.

The main advantages of printing applied in the building industry can especially be found in:
- Unique or series production/elements
- Small tolerances
- Combination of techniques and materials
- Small scale; material design on nano-scale
- Large scale; endless printing
- Internal structures and function integration
- To limit the amount of parts and producers

The position that is taken by printing directly from the 3D file can vary widely between applications and scales. A careful deliberation should be made in relation to the other existing techniques to produce a product. While printing has some extensive advantages in comparison to other techniques, it also has some disadvantages which should be taken into account. Where is it useful to introduce printing and what are the consequences for the design; where is extra value created compared to a ‘normal’ production technique and/or how does it use the main benefits of RM?
3.2 The RM’ed building

3.2.1 Scale and production

The implementations can be on a very big level (building size) to very small components, like a door handle or even screw size.

![Component scale](image)

Figure 51 Component scale

Current rapid prototyping machines are able to print with a maximum at about 30 x 30 x 30 centimetres, because of the size of the machines and the factories.

If the market develops a request for products on a larger scale, the producers will anticipate and try to solve the difficulties that are coherent to the up-scaling of a process. In the building industry, already some experiments have been done with the production of printed structures at a building size. Contour Crafting is experimenting with concrete printing in America and in Italy an initiative resulted in a printed Monolite structure with gravel as a base material. The development in scale for printed objects will take years, which means for the application path of RP in the building industry that probably first parts of components can be printed, before the actual façade elements are ready for production.

A future vision, though, is the possibility to create an entire building in one go. No additional handlings, except for an on-site printer which is able to print everything, from the main structure to the window frame and interior finishes. The share of building mistakes would decrease, which is a problem in the building industry. In current building projects, about 30% of the investment costs are caused by mistakes during construction. A print file can be checked easily and mistakes can be foreseen and diminished.

3.2.2 Function integration

When we think about future buildings, the free formed shapes are popping up in every architect’s brain. The geometric freedom is able to step away from the mass production of façade component types to make a project feasible, because for RM it does not matter if each component is the same or totally different. Nowadays all the free formed structures have had a lot of compromises for structural reasons, but also for
production reasons.

Façade components would not need to be assembled anymore; the manual labour is decreased by the printing process which means a decrease in investment costs for mistakes at the building site. All the functional elements can already be integrated in the printed component in one continuous process.

![Image of integral wall](image)

Figure 52 The integral wall: Material has the required composition differing over the cross section.

The entire structure is acting as a fool proof element, where over the section each function is provided at the exact correct spot and the desired materials are used.

![Image of function arrangement](image)

Figure 53 Function arrangement

The façade operates as a barrier between inside and outside and therefore needs to adjust itself continuously to the current situation. The preferences of the user are also of great importance. In modern office buildings, more and more installations are integrated in the building skin; a de-central instead of a central approach. The complicated structures can be easily printed instead of installed on site, where the chance of mistakes and broken parts can be avoided.
The building skin could be build up from a continuous graded material, which has only the properties that are needed at the place where they are needed by influencing the density and composition of the material. The section is optimized for its purpose considering f.e. structure and climate aspects.

Figure 54 Integral façade

The possibility to create internal structures makes it possible to add these functions to the desired place in the cross section. Not only the density of the material can be changed, but also other parameters that shape the façade. For example overhangs can be created and the section of the material. By influencing these, different properties can be designed to be placed where necessary, with the expression that is wanted by the designer, leaving the design totally free from material properties.

Figure 55 Material design on nano-scale
Part 2; Implementation: ‘Towards an innovative shading device’
4 Concept

4.1 Introduction

The conclusions from the preceding part of this report are giving a direction for the following research and design part. The goal is to see how rapid manufacturing could influence the architectural design by rethinking current systems.

In this part, the treatment of daylight is taken as a research topic. At first, the properties of daylight are analysed and an approach is described. The subcategories are examined in more detail and conclusions are drawn.

The design for a façade is made from these conclusions. This is done in two ways. First the common techniques are used to design a façade system. In the second design, one more step is taken in a futuristic approach for rapid manufacturing. The extra value of printing this system will be evaluated and the research question is answered in the final conclusions. To give a perspective on the development of the technique a time path is made to show what steps are in between the current way of building and the introduction of the integral printed façade.

4.2 Considering daylight

‘No space, architecturally, is a space unless it has natural light.’ Louis Kahn

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16 Source: (www.schoon-licht.nl, 2010)
The development of facades from pre-historic clay shells to the current mostly light weight structures with the façade as a curtain wall, turned the building skin into an adaptive interface between the user (space) and the outside world. The target to perceive a total state of transparency in the façade resulted in large glass filled surfaces, where it is the role of the envelope to control over levels of connection and separation to the outdoors for the comfort of occupants for privacy, security, and control of indoor conditions.

Light enables us to see architecture and is able to make architecture. Daylight has some distinct, beneficial properties, which are important for a good indoor environment. It has, for example, a very high quality in comparison to artificial lighting, because it contains the entire light spectrum with a very high intensity. Another property is that it is a dynamic light source, it changes continuously over day and year and the light of the sun is essential for the human metabolism as well. The influence on the efficiency of people in a working environment is substantial in the way that it helps them to concentrate and perform better when enough daylight is available.

And also not of the least importance; it is for free. In utility buildings, approximately 22% of the total energy consumption is used for lighting\textsuperscript{17}. This amount could easily be diminished with the current state of technique.

For an indoor environment, it is not about the quantity of daylight entering the room, but about the condition of incoming daylight: the quality. Especially in office buildings, working behind a computer screen is a known fact. The inconvenient reflection, also called glare, on the screen or too strong contrasts within a room causes people to adjust their working environment by clinging papers to the windows and turning on the artificial lighting. An approach only focussing on the quantity of incoming daylight therefore does not work. But amongst other aspects, attention should be paid to colour rendering, differences in brightness and glare.

The art project Flow 5.0 by Studio Roosegaarde\textsuperscript{18} shows a totally different approach concerning

\textsuperscript{17} Source: (E. Melet, 2006)

\textsuperscript{18} Winner of the Dutch Design Award, best autonomous spatial design (2007-2009)
translucency and transparency than we are used to. Hundreds of fans were placed in the city hall of The Hague, with as a main goal for the visitor to create an illusive landscape of transparencies and winds. The ventilators are reacting on the movement of the passenger who walks along the 10 meter long wall, causing it to change from translucent to transparent by the actuation of the fans.

Figure 59 Flow 5.0 by Studio Roosegaarde

This combination of a tempering of light incidence while a clear view is maintained is taken as an inspiration for the design of a façade shading device. In this case, the device can either stand still or be turned on, while the light and heat incidence remain the same; the view drastically increases over the two states.

Figure 60 Light incidence disk standstill

Figure 61 Light incidence disk rotating

19 Source: (www.studioroosegaarde.net, 2010)
5 Research

5.1 Light

5.1.1 What is light?

Light is electromagnetic radiation, with those frequencies that it’s able to be seen by the human eye, in general including ultra-violet light and infrared light. Light can be described by its properties. The four basic properties are intensity, wavelength of frequency, polarization and phase.

If the atoms are heated enough or end up in an excited state, the outer electrons get to a higher, also excited, energy level. When an electron returns to a lower energy level, the released energy will be emitted as a photon. This amount of energy determines the frequency and the wavelength and therefore the colour of the light.

![Image of Electromagnetic spectrum](image)

**Figure 62 Electromagnetic spectrum**

Sunlight is the total spectrum of the electromagnetic radiation emitted by the sun. Before sunlight reaches the earth, it will be filtered through the atmosphere. Solar radiation is only present when the sun is above the horizon.

Direct sunlight has a luminous efficacy of about 93 lumens per watt of radiant flux. This includes the visible spectrum, infrared and ultra-violet light.

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5.1.2 The importance of daylight

The world is concerned about global warming, carbon emissions and sustainable design, whereby the planned use of natural light in non-residential buildings has become a very important strategy to reduce the energy consumption by minimizing lighting, heating and cooling loads.

Daylight is acknowledged to be very important for people. In architecture it is not only used for art, but also because of the scientific studies about the dependency of people on natural light. Since the era of Enlightenment, architects began to see the importance and started to interweave daylight-design as a part of architecture\textsuperscript{22}. Nowadays, the façade is often as transparent as possible allowing daylight inside the working space and reference to and view of the outside world. But there is also a counter side to the light of the sun; overheating and glare form serious threats for the working environment. Light controlling systems protect people from inconvenient light and artificial lighting is added.

The unique properties of the light of the sun can not easily be replaced by artificial lighting. Daylight has the complete light spectrum with high intensity, which artificial light cannot copy. In the light schemes of artificial light you will notice missing wavelengths. Test results prove that people need the complete light spectrum for mental and health reasons. Artificial light is very monotone, daylight changes over the day because of the rotation of the earth and the differing weather conditions; changing angles and intensity. The human metabolism requires sunlight, because the blue part of the spectrum slows down the bodies’ production of Melatonin, the hormone responsible for day and night rhythm. The morning light therefore carries relatively much blue light, while in the late afternoon the light turns red activating the hormone production again. When there is too little light, the human body will interpret this as being night, so the body keeps on releasing melatonin and the person will feel sleepy. This can even cause depression or sleep

\textsuperscript{21} Source: (perswww.kuleuven.be, 2010)
\textsuperscript{22} Source: (N. Baker, 2002)
disorders.

Inside an office room in the Netherlands there are certain requirements when it comes to lighting. All working places need to have a certain glass surface. This is defined in the Dutch Building Decree, NEN 2057. For unobstructed non-residential buildings, this legislation requires 0,03 m² glass surface for each m² user’s area, unless the room will be used more than two hours; then the requirement will be 0,05m² glass/m² user’s area. The glass window will provide occupants of view and will improve their health. In some exceptional cases, it is not possible to make a window in the room, because it will give a conflict to other requirements of the Building Decree.

Another requirement of the Dutch Building Decree is the luminance in the offices. In general this required luminance is 500 Lux on each working space. Some very detailed work requires 1000lux. Most perfect will be when the sun provides this amount of Lux, but unfortunately in practice this is not often the case. Therefore additional artificial light is needed.

The role of sun shading in an adaptive façade is to be able to react on different thermal requirements during the year. The complete different angles of the sun and weather conditions in the summer and the winter require a system that can be optimized for the occurring situation. Where the energy gain of the sun is preferred to enter the room in the winter; in summer it is better shut out to prevent overheating. Sun protection could be in the connection to the urban environment (protection by neighbouring buildings) as well as in passive or active shading devices on the building itself.

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23 Source: (M. Hegger, 2008)
5.1.3 Properties of daylight

The human eye can only perceive wavelengths of daylight in the range of 380-780nm without auxiliary equipment. The radiation lengths silicate glass permits are in the range of 315-3000nm. Only parts of this range of light falling on the glass surface are transmitted; another part will be reflected and the last part will be absorbed.

Figure 66 Specular, scattered and diffuse reflection

There are three different types of reflection: specular reflection, diffuse reflection and scattered reflection. Specular reflection is the reflection of the radiation in the same angle. Diffuse reflection is the reflection of the radiation in all angles (diffuse). And scattered reflection is when both types of reflection happen simultaneously. The quantity of reflected light can be expressed in the light reflection factor $R_l$. For comparison:
- exterior light reflection of single glass: 8%
- exterior light reflection of insulated glass: 14%
- exterior light reflection of glass with Low-E coating: 11-12%

A part of the incident light will be absorbed by the material. Light will then be transferred into heat. Each material has its own absorption coefficient. The amount of absorbed light is determined by the colour, the structure and the density of the material.

Important for view and sight is the transmission of light through a glass pane. The transmission is influenced by the refractive index of light. Refraction of light is the change in direction of ray of light due to change in its speed. The quantity of transmitted light can be expressed in the light transmission factor $T_t$. For comparison:
- $T_t$ value of single glass: 89%
- $T_t$ value of insulated glass: 82%
- $T_t$ value of glass with Low-E coating: 74%

Source: (J. Renckens, 1996)
5.1.4 Measuring light

There is a difference between daylight and sunlight, which should be separated in use. Sunlight can be defined as the light flux (the measure of the quantity of light) supplied by direct solar radiation. Daylight, on the other hand, is the light flux jointly delivered by direct and diffuse solar radiation. This is used for the available quantity of natural light. In a room, the quantity of daylight is dependent on the how the light is guided into a space. The daylight cannot be influenced, but the lighting of a space by daylighting can be determined by the design of a building.

A light source is defined by its luminous flux, which is the measure of the perceived power of light, adjusted to the sensitivity of the human eye for different wavelengths of light and is measured in lumen. The human eye can only see light in the visible spectrum and has different sensitivities to light of different wavelengths within the spectrum. The eye is most sensitive to greenish-yellow light at 555 nm. Light with the same radiant intensity at other wavelengths therefore has a lower luminous intensity.

The luminous intensity (cd) is used to define the power emitted by a light source in a particular direction per unit solid angle and is also adjusted for the different wavelengths. The luminous flux on a surface is measured in the illuminance (lux).

The brightness that is experienced by the human eye is measured in the luminance to characterise the emission or reflection from flat, diffuse surfaces. It defines the intensity per unit area of light travelling in a given direction.

![Figure 67 Defining light](image)

1. Luminous flux (lumen)
2. Luminous intensity (cd)
3. Illuminance (Lux)
4. Luminance (cd/m²)

For daylight, a daylight factor is used to define the relation between the density of light on any surface and the intensity of light measured in the free field on a horizontal surface with a cloudy sky (CIE sky). In office rooms, a daylight factor of at least 3 to 5% is needed at 1.5m distance from the façade.

5.1.5 Comfort

The luminance necessary for a specific function differs. For a school, 300 Lux is required, while this is 500 Lux for an office space. For a museum, the requirements are more difficult and change over the collection, because the art pieces should not be damaged in any way and in the same time, the view should be optimal. Whether a situation is comfortable for the eye depends on the amount of luminance and on the contrasts.
within the room. Depending on the adaptation level, the eye adapts its sensitivity so that a limited range of luminance is perceived (perhaps 1:100). In the graph below, the luminances lying below the lower bound are perceived as black shadows and, on the other hand, luminances lying above the upper level appear as glaring. These are no sharp boundaries, but are experienced gradually.

![Graph showing the range of luminance adaptation](image)

**Figure 68 Effect of visual adaptation**

Within the direct visual field, the contrasts in luminance may not exceed 1:10, as a rule of thumb, while in a wider range 1:30 is the maximum. This means that a computer in front of a window is in fact always a problem, because the large differences in luminance lead to excessive fatiguing and loss of perception.

![Image of classrooms](image)

**Figure 69 South oriented class room**

**Figure 70 North oriented class room**

In the example in figure 69 and 70, two classrooms are shown with the luminance indicated in number over the picture. The first picture shows a classroom at the south side of the building, in the second the room is at the north side. The contrast differences make the southern room very difficult to work in, while on the north side diffuse light incidence diminishes the contrasts within the room, but additional artificial lighting is required.

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26 Source: (N. Baker, 2002)
27 Source: (E. Melet, 2006)
5.2 Light incidence

Developing the concept, the assumption was done that the total amount of incoming light would stay the same for rotating and non-rotating elements. When there is no rotation, the contrast between where the light can fall through freely and where the disk hinders this incidence, is quite large. When the disk is rotating, there is no contrast; the penetrating light gives an even surface for the eye. The assumption is that the intensity is the average of the intensities in standstill.

In this section, this assumption is checked by using hand calculations and a Lux meter to measure the quantities of light incidence.

![Figure 71 Light incidence 50% closed disk, off](image1)

![Figure 72 Light incidence 50% closed disk, on](image2)

![Figure 73 Light incidence 95% closed disk, off](image3)

![Figure 74 Light incidence 95% closed disk, on](image4)

5.2.1 Hand calculation

The LTA value is a property that describes the amount of light that is falling through an element. It can be calculated as follows:

\[
LTA = \frac{\text{Passing amount of light}}{\text{Total amount of light}}
\]
Figure 75 Light flow through a glazing unit with in-between shading device

(a) Off  (b) On

Figure 76 Example disk, 50% closed surface

For a 50% closed disk (figure 76), there are two conditions: off and on (standstill and rotating).

As a factor for the reflection is taken: \( r_1=r_2=r_3=0.1 \)

As a factor for the absorption is taken: \( a_1=a_2=a_3=0.1 \)

<table>
<thead>
<tr>
<th></th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( d_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed</td>
<td>1</td>
<td>0.8</td>
<td>0.64</td>
<td>0.51</td>
</tr>
<tr>
<td>Open</td>
<td>1</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Average LTA = 0.26

On:

<table>
<thead>
<tr>
<th></th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( d_4 )</th>
</tr>
</thead>
</table>

LTA = 0.26

In the hand calculation, the LTA value is 0.26 for both situations.

5.2.2 Lux meter

The measuring compilation includes a Lux-sensor attached to a Lux-meter, a completely closed black box with exception of the size of a disk and a transformer to drive the motor attached to the window that is able to carry the disk. The Lux-sensor is placed parallel (vertical) to the façade to assure that only the direct light is measured. The diffuse reflection of the surfaces in the box does, in this way, not interfere with the results.
One measurement is done following three steps: 1. Reference situation, there is no disk in the compilation; 2. the disk is placed in the compilation; 3. the disk is placed and driven at a speed of 250 Hz. A second test is performed directly after the first following the same process. The entire test (1 and 2 combined) is considered valid if the intensity of measurement 1. (reference situation) does not deviate more than 10% between the first and second test result\textsuperscript{28}. If the measurement is valid, the average of the two measurements is taken as a starting point and is normalized over all the measurements to make them comparable.

The firmament can be considered a CIE overcast sky which is a cloudy sky where the luminance division is not dependent on the orientation\textsuperscript{29}.

1. Without disk
2. With disk, no rotation
3. With disk, rotating at 250 Hz

For a disk with 50% closed surface and a disk with 95% closed surface, the following results were found from the measurements:

Figure 78 Light incidence; (1) 50% closed disk, (2) 95% closed disk

The measurement shows that in case of standstill and in case of rotation, the light incidence is the same.

\textsuperscript{28} Verbal agreement H. Hellinga (2010)
\textsuperscript{29} Source: (E. Melet, 2006)
This procedure was followed for a range of measurements for varying purposes. The results of these measurements are added in the relevant sections.
5.3 Heat incidence

The shading device is implemented between glass sheets. In this case, the heat incidence into a room is caused by the heat that is transmitted directly through the device and another part is the heat that is absorbed by the device and radiated to the glass sheets. Radiation and convection transport the heat into the room.

An in-between shading device (Figure 61c) blocks a part of the heat that is travelling with the daylight into the room. While the device can be turned on or off, the amount of heat incidence by the sun is not changing. Even when the device is turned on, creating a clear view outside, the heat is still blocked.

![Diagram of shading devices](image)

Figure 79 Working principles of shading devices

The ZTA value of glass indicates the sun entry factor of the façade. This value is calculated as follows:

\[
ZTA = \frac{\text{Passing radiation} + \text{dissipated heat by radiation} + \text{dissipated heat by convection}}{\text{Total amount of incident solar power}}
\]

To draw a comparison, a double glazing unit has a ZTA value of approximately 0.7 and an outside shading device has a ZTA of 0.1. An in-between shading device will have a ZTA value of approximately 0.3.\(^{30}\)

\(^{30}\) Source: (van der Linden, 2005)
5.4 Perception

5.4.1 Movement

A movement can be defined as a change of location and time. Each movement can be described as either a translation or a rotation or as a combination of the two (figures 80 and 81).

![Translation](image1)

![Rotation](image2)

Figure 80 Translation Figure 81 Rotation

A movement can be divided in a uniform or a non-uniform motion. In the first situation, the speed of the movement does not change over time or direction. There can be different kinds of uniform movement; the movement can be a uniform consistent movement, a uniform acceleration, or a uniform circular movement. A non-uniform movement accelerates its speed, the acceleration is not constant. A rotating movement starts with an acceleration from standstill and than stabilizes in a uniform motion. This situation costs less energy than a non-uniform movement and is therefore more economic than a side wards translation.

5.4.2 Relation open/close

When using disks as a facilitator of sun introduction into a room, it is important to know the maximum rate of closed surface. The main interest is to preserve the quality to see through. The objects behind the disk should be clearly visible in order to be able to serve as a transparent sun shading device. The disk with 98% closed surface is not transparent enough, because the objects behind the disk cannot be recognised. With 95% closed surface over the disk, on the other hand, the objects outside can be recognised. A 50% closed surface gives a totally clear vision on the environment outside.
Two disks with the same percentage of openness, in this case 95%, are compared. The first disk has only one opening; the second disk has its opened surface spread over four openings. Measuring the intensity of the light intensity behind the disks, the conclusion can be drawn that the amount of openings is not important for the light flux (figure 86).

Figure 82 98% closed surface divided over 1 opening

Figure 83 95% closed surface over 1 opening

Figure 84 95% closed surface divided over 4 openings

Figure 85 50% closed surface divided over 4 openings

Figure 86 Measurements comparing light incidence (1) 95% closed disk, 1 opening; (2) 95% closed disk, 4 openings; and (3) 50% closed disk, 4 openings
5.4.3 Frequency

![Figure 87 Low frequency](image)

![Figure 88 High frequency](image)

The human eye is able to process 24 images per second. This is something that can be experienced when looking at car wheels during acceleration; they appear to spin backwards instead of forward at first, because the brains are processing the images they receive faster than the actual movement.

The frequency in which the disks are rotating has an influence on the perception of the human eye. This can be compared to the refresh rate of a computer screen or a television screen. Early television screens had a refresh rate of 50 Hz, which means that the screen refreshes 50 times per second. Nowadays, it is possible to buy modern CRT screens that are flicker-free which are able to produce up to 100 Hz.

For a computer display, the size of the screen also has an influence on the perception. A 15” display can be comfortable with a rate of 60-72 Hz, while a 17” display needs a 85 Hz refresh rate in order to be comfortable. Again 100 Hz gives a very good quality and is comfortable for the eyes, but there are even LCD monitors which operate around 200 Hz.

The power of the motors, the transformer and the weight, width and materialization of the disks are factors that determine the speed and therefore the perception of the device. The faster the rotation, the less the brain can detect any movement at all, which results in a steady image.

5.4.4 Pattern

In the first tests, symmetrical divisions from the centre with linear wings have been used to determine the transparency rates. The pattern could also be arranged in a different way, creating a different façade appearance. The level of transparency over the cross section determines a pattern in the transparency even if it rotates. The disk will show darker and lighter rings over the section where the transparency changes when it is in motion.
There is a large freedom in the design of the disks; some experiments are shown in the figures 89 and 90. The chess pattern is changing from high to low transparency and shows three rings where the density is higher. The dots show a gradient from completely transparent to a higher density. Combining the two approaches, a symmetrical division with changing transparencies, result in designs as shown in figures 91 and 92, where the wings are composed in a non-linear way. When in motion, the disks show a gradient over the cross section, which changes gradually from less to more transparency.

5.4.5 Colour

The perception of an architectural space is mainly done by light reflecting from surfaces. It is therefore an architectural task to design texture, reflectance and colour as properties of a room. The colour of the disks also has an impact on the perception and the view outside. The picture shows an example of subtractive colour mixing, which is the result when different pigments are mixed. The primary subtractive colours are red, yellow and blue, from which all other colours are derived. In the picture can be seen that each individual colour has a different influence on the perception of the behind laying surroundings.
Black and white both have their own specific properties that can be used for the design. White reflects the light that falls on its surface for a large part. In Mediterranean countries, the houses are often painted in light colours to keep the heat out for the largest part. For a sun shading device it would also be an advantage if it could reflect the heat outside.

Contrast is defined as the difference in brightness. What happens for example to the colour of the middle square in the picture above? Because the eye takes a reference image, the grey square seems to become darker from left to right.

With the disks something comparable is happening. The black disks appear to brighten up the colours of the environment, while the white disks seem to make the colours lighter. The brain processes the image with the reference colour of the disk and relates the other colours to this. This is why, the behind laying colours seem brighter to the human eye as if it were stronger colours, because of the interaction of the hues of disk and environment.
The colours seem brighter, but the light that is entering the room is the same as with a white disk as can be seen in the graphs (figures 99 and 100).

Influence of colour

Figure 99 Measurements comparing light incidence (1) 50% closed disk, white; (2) 50% closed disk, black
Figure 100 Measurements comparing light incidence (1) 95% closed disk, white; (2) 95% closed disk, black
5.5 Scale

The scale of the shading device is not defined by technical impossibilities, because if we look at examples of rotating devices we can find a scale range from a micro fan to the Ferris wheel in London. If we consider the building scale, we can find some restrictions. In an office building, for example, it is necessary to have an acoustic and fire barrier between floors to provide a good working environment. A disk for this building typology would therefore probably not exceed about 3 meters.

The smallest motor that can be produced defines the minimal size that can be used nowadays. The disk should be transparent enough to guarantee sufficient view.

Another restriction is the depth of the motor. The bigger the power, the bigger the depth of the motor. The detailing of the façade package will therefore change with the depth of the drive. Where a small motor can be integrated in a double glass unit, a large motor should probably be designed to be placed in between a double skin façade.

Figure 101 Sepa micro fans
Dimensions: 10x10x2 mm

Figure 102 The London Eye Ferris Wheel
Diameter: 120,000 mm

31 Source: (www.sepa-europe.com, 2010)
32 Source: (www.londoneye.com, 2010)
5.6 Conclusions

From the research to the sub-aspects of using rotating disks as a shading device, the conclusions show a wide range within solutions, that represents the freedom for design. The implementation of the devices can be adapted within certain boundaries to the creativity of the architect.

The conclusions from the aspects are shortly described here.

*Light and heat incidence*
- The heat and light incidence in the room remains the same in standstill or rotation, while the view increases over the two states.

*Transparency*
- 98% Closed surface does not provide enough transparency to see through, 95% does.
- The number of openings does not have an influence on the light penetration or view when the disk is in motion.
- A 50% closed disk gives a very clear view.

*Pattern*
- A non-symmetrical division of the infill of a disk results in rings with more and less transparency when the disk is in motion.
- This effect can also be reached more gradually by using wings with a varying section other than linear.

*Colour*
- A white or reflective surface outside is able to reflect heat.
- A dark colour of the disk make the colours of the environment appear stronger in comparison to a white disk, because the brain processes the image using the colour of the disk as a reference.

*Scale*
- The building design and function is defining restrictions for the scale of the disks.
- The size of the drives too defines the detailing of the façade, whether it can be implemented in a double glazing unit or should be incorporated in a double façade.
6 Design

6.1 Design intention

The design intention is to research possibilities to implement the concept of rotating disks in a façade as light adapting elements to improve the office climate. The disks have a major influence on the architecture to be built up from or with a circle mesh. The application is able to vary widely from additional element to architectural tool.

![Figure 103 Technical solution as additional elements](image1)

![Figure 104 Technical solution as an architectural tool](image2)

The consideration to make technique superior or inferior in the architectural design process, determines the overall performance of a building regarding energy use, comfort parameters and architecture. The integration of technical solutions should be leading in the façade design from the early start of the project.

Architectural firms over the world use circular meshes to design their facades and distinguish their design from others. To interweave the shading devices in an architectural design for facades, these projects are taken as a source of inspiration.

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33 J. Nouvel, Institute du Monde Arabe, Paris
Graduation thesis: Rapid manufacturing in façade design

Figure 105 Circular mesh

Figure 106 BIG Architects, Peoples Building Shanghai

Figure 107 Façade mesh

Figure 108 Foster, World expo, Shanghai

Figure 109 BIG Architects, Tivoli retail shop, Copenhagen

Figure 110 BIG Architects, Tivoli retail shop, interior, Copenhagen
It is possible to apply the shading devices in a random project even for existing buildings. The devices can be incorporated in between a double glazing unit and function as a shading device. The design in size and layout is done according to the preference of the architect, users and/or function of the building. This can be regarded as an update for each building which has a big impact on the building design and performance.

When Rapid Manufacturing is considered as a production technique, the implementation of this shading concept in a façade could lead to a different design, because of changing variables. The advantages that RM brings cause a different view into the production and integration in a façade design. A futuristic RM-inspired approach explores the impact of technical developments on design, with a focus on the drive of the components; combining maximum flexibility with minimal power to drive the elements. The use of RM for the production of a façade panel with an integrated shading device anticipates on a certain development of the technique because of the problems that should be solved. In a time path, the development towards the fully printed integral façade is shown.
6.2 Upgrade

In this section, one variant is developed as an architectural design for a contemporary façade that uses the rotating elements as a shading device.

Figure 111 Façade design 'Upgrade', interior view, standstill

Figure 112 Façade design 'Upgrade', interior view, rotating
6.2.1 Context

The design for a façade proposed in this section is made for a building with an office function. The literature study showed that the modern way to build facades is by using a curtain wall system. This system is also taken as a starting point for the design in this section, where contemporary methods are used for production.

The name of this variant is ‘Upgrade’ because it is possible to apply the design even for buildings that are already built. The shading device can be used as an additional element in the design; in fact in any building. The design can be integrated as an addition to a glass façade or window with elements placed in between two glass sheets and sealed like a normal double glass unit.

The proposed façade design uses a climate design with a central controlled air inlet. The air is preheated when entering the room. The outlet is done via the light armatures. For additional heating, a convector unit is placed in the floor slab close to the façade. Ventilation with fresh air can be done by opening parts of the façade.

![Figure 113 Climate concept office](image)

6.2.2 Façade design

From the research done to the shading devices, a contrast was found between the disks when they are rotating and when they are standing still. A radial organized variant, with 50% transparency over the surface provides the biggest contrast between rotating and standing still.
When standing still, the pattern caused by the light incidence is very specific, while when in rotation; the surface becomes totally clear, providing a clear view outside. The shading device acts as an ornament for the light introduction into the space. This can be seen in figures 128 and 129 from the research above.

Measurements show that the pattern does not interfere with the amount of light that is penetrating the disk, as it is the same for the linear pattern as for this radial organized variant (Figure 131).

34 ‘Dubbel en dwars’-house, Berger Barnett Architecten
Figure 117 Measurements comparing light incidence (1) 50% closed disk, linear; (2) 50% closed disk, radial

Figure 118 Façade view
6.2.3 Materialization

The façade uses double glazing units. In these units, the disks are integrated in between the glazing. The motor is attached to a glass panel and carries the disk that is glued to its surface. The motor and its wiring would look messy if it is kept in sight. Therefore there are two foils on both sides glued to the glass that cover the technical equipment necessary for the drive of the devices.

![Double Glazing Unit Diagram](image)

Figure 119 Exploded view double glazing unit; layers from left to right (1) glass, (2) foil, (3) disk, (4) motor, (5) foil, (6) glass

The double glazing panels are prepared in a factory, where the devices and the foils are placed in between the glass sheets. After this is done, the glass unit can be sealed. The wiring is lead to a central point, where the wiring comes out of the unit through the layer of silicon. At this point, the wiring can be transported to a point in the office where power and a switch is attached. This can for example be done via the posts.
6.3 Rapid manufacturing

By stepping aside the current techniques that are used and try to involve a new technique, which is not yet fully developed, totally new inspirations come to mind. A free choice in materials and large freedom in geometry will cause the façade to become different than a contemporary design would be.

Figure 120 Façade design ‘RM’, interior view, not rotating

Figure 121 Façade design ‘RM’, interior view, rotating
6.3.1 Reinventing the wheel

The contemporary drive that is used in the design with motors could be reconsidered here. Magnetism is a more sustainable way to drive the shading devices and by activating the outer ring instead of the central axis, the device would have a total freedom in design.

![Peugeot concept bicycle](image)

Figure 122 Peugeot concept bicycle

The wheel had for ages and ages the same principle with the drive from the central axis. But this year the designers of Peugeot launched a concept bicycle where the back wheel is totally spoke less, creating a freedom in design which was not possible before.

![Magnetic train (Transrapid)](image)

Figure 123 Magnetic train (Transrapid)  
![Exploded view Transrapid](image)

Figure 124 Exploded view Transrapid

The Transrapid train is a magnetic driven train which can catch very high speeds. The drive used for this method is called a linear induction motor (LIM) and is based, just like an electromotor, on a changing magnetic field. A LIM consist of a row of electromagnets. The object that should be driven, in this case the train (or the disk), carries magnets with a permanent polarity. By driving the magnets along the trail in a way that they change polarity at the correct moment can drive a vehicle on a magnetic wave.
If we consider the LIM as a solution for the drive, the moving parts can be totally unconnected from each other. This means that there is no wear because of the rotation and using RM, it is possible to print a fool-proof element that does not need to be maintained.

6.3.2 Façade design

The concept bicycle with a spokeless back wheel is an inspiration for the design of the printed façade. The technique provides total freedom in design, where solutions like different driving mechanisms can be easily implemented. The principle of the magnetic driven Transrapid train can be used to deduct the main principle of the linear motor for the drive of the shading device. By activating the outer ring instead of the middle axis, the design for the disks can be totally free for an overall façade design.

For the lighting in a building, it is considered more valuable to have interesting daylight incidence into a room than just as much as possible. When the disks are in motion, the experience is totally different than when standing still.

The change from a central drive to a perimeter drive gives a range of design possibilities.
For this design, only one variant has been developed into further detail. As a basic principle, the freedom in design, caused by the perimeter drive, and the light incidence is taken.

![Figure 127 Light incidence in forest](image1)

Jean Nouvel also played with this principle of light incidence in a room in his design for the Louvre in Abu Dhabi.

![Figure 128 Interior render, Louvre, Abu Dhabi, Jean Nouvel](image2)

The size of the windows does not have to be repeatable over the façade, because the design can be independent of the production when RM is used.
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Figure 129 Façade view

Figure 130 Rotating device (using motor drive)
6.3.3 Materialization

The shading device is integrated in an integral façade design. The rotation that is needed to activate the device requires internal structures. Because RM is able to produce internal structures, the disk can be implemented in between two glass sheets that protect it from outer influences and wind.

In the detailing there is some tolerance between the disk and the outer ring, to make the rotation possible. Once power is added to the device, a magnetic field occurs and the disk is ‘floating’ inside the casing. During rotation, the parts will not be in contact with each other so no wear occurs because of friction.

If we look in general at the material design for the realization of the functions in a building skin, we find that the cold bridges should be solved by an insulating material, the transparency by a glass material while the load bearing function of a façade requires a metal material and the conducting trail can also be printed from a metal. The insulation can be printed from glass fibre.

Glass and metal have a material behaviour that could be compatible for printing at the same temperatures in one process. Metals have a crystalline structure, which cause it to melt above the temperature $T_f$ and become a liquid. When this happens, the volume increase stops. Because glass does not have a crystalline structure, it does not have a melting temperature, but it continuously softens under temperature rise and
its volume will increase until the same amount of a liquid crystalline structure in melted state above $T_e$.

![Graph showing volume and temperature relationship with Tg and Te](image)

Figure 132 Glass; ratio of volume and temperature

While metal printing has already developed quite far, with very high qualities as a result, glass printing is more in the start of its development. There are already examples of glass printing available. One technique is developed by TNO for the Institute of sound and vision in Hilversum. In the printing process, coloured glass powder is applied on the glass panes, which is then heated in an oven until the glass powder melts together with the pane. Using this technique, not only the durability becomes better, the colours more intense, but also the perception of the façade is intensified.

![Dutch Institute for Vision and Sound, Hilversum](image)

Figure 133 Dutch Institute for Vision and Sound, Hilversum

Another way of printing glass is developed at the University of Washington’s Solheim Rapid Manufacturing Laboratory and is called Vitraglyphic. The projects are printed using a 3D printer where powder is bonded by a liquid binder material. This technique is still in development, trying to work on the level of transparency and dealing with the enormous shrinkage during the baking process. The responsible

35 Source: (Lohmeyer, 1979)
professor Mark Ganter created an open 3D printing forum to make the technique accessible for everyone in order to speed up the development.

Figure 134 Vytraglyphic glass printing
6.4 Time path

RM has production properties that can enable the development of façade design with a large freedom, because of, amongst others, internal structures, function integration and the use of materials. But the development of the technique cannot be completely foreseen. To produce a fully integral façade with RM some developments are necessary that cannot be expected on a short notice.

The façade design for a shading device shows that materials should be combined into one graded material. The functions insulating, load bearing, conducting and transparency are solved with a design using fibre glass material, metal and glass.

Before it is possible to print a fully integral façade as is suggested in the case study design for a shading device, there will be some steps in between. The printing of an integral façade requires printing on a large scale in combination with a very high detail level, which is at this moment not yet possible. The development could take probably about 50 more years and in the mean time, the technique can be used as a part of the solution for façade building.

6.4.1 Hybrid process

It is interesting to look into further depth to the actual extra value that is created by using RM and what

\[36\] Paragraphs where the design descriptions can be found
parts could be better produced with a different technique in a hybrid production process. In the case study design, the advantages of RM are very useful to create moving parts with small tolerances and internal structures. The drive is another part that can be integrated in the structure. The combination of metal and glass is an extra value because of the combination of the solid metal part of the disk and the glass that protects the shading. The insulating part can be questioned, because of the cheap and numerous existing production techniques.

A combination of techniques is considered in the following two variants.

![Figure 136 Variant 1. Using provisions in the design to add insulation afterwards to the façade.](image)

![Figure 137 Variant 2. Combining the integrated shading device with a sandwich panel.](image)

A façade design could require the use of rapid manufacturing for specific applications. It can in this case be advantageous to produce the entire façade using only one production process. The possibility to produce with several production techniques and combine RM with another process (or other processes) is also thinkable.

### 6.4.2 Integral vs. modular

Karl Ulrich describes his vision on product development in the article Product Architecture using two main approaches; integral and modular. In these approaches, the arrangement of functional elements differs as can be described using the example of the design for a tea cup.

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37 Source: (Ulrich, 1995)
In the case study, the integral approach was used to produce a façade completely from RM, with the shading device and other functions integrated.

The shading device can also be considered to have only the property of shading, while the load bearing and insulating is done in a separate layer.

In the integral approach, RM solves all the functions in the façade, while in a modular approach RM is only used for a specific part of the façade.

### 6.4.3 Printed building

The RM façade should be printed on site and connected to the main structure. RM is able to handle very small tolerances. If only the façade would be printed, the connection to the main structure should still use the tolerances for in situ concrete, which are centimetres.

To gain full profit from the small tolerances, the entire building, including main structure, façade and finishing, could be designed and produced with RM at once.

38 Source: (Heesbeen, 2010)
Figure 141 Printing façade and building structure
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Part 3; Evaluation
7 Evaluation

7.1 Conclusions

What is the perspective for the introduction of rapid manufacturing in future façade design?

The goal of this master thesis was to find an answer to the above stated question by investigating the separate subjects into depth and perform a case study to a functionally integral façade produced with rapid manufacturing. This case study was done to the integration of an innovative moving shading device in the façade that influences the quality of the incoming daylight. The results of both parts can be interpreted to find an answer to the research question.

Theory
From the literature study can be concluded that facades have evolved over history towards the modern curtain walls. The detailing of the curtain walls has become very complicated with the optimization over the last 50 years. From the field of product development can be found that during product sophistication, there is a phase of rapid change at the start, which levels out to a phase of improvements, where the façade design of the curtain wall is assumed to be in nowadays. In this thesis study, research has been done whether a new technology in the form of rapid manufacturing (RM) could mean a new boost for façade design.

Rapid manufacturing is an additive process which builds up a product layer by layer. It has therefore in fact all the geometric possibilities that other techniques can provide and even a lot more, because it is possible to create internal structures and different scales can be easily handled. The design is independent on production, which can be explained by the comparison to a normal inkjet printer; it is not more economical to print 100 sheets with the same print or 100 sheets with a unique print.

The main advantages of printing applied in the building industry can especially be found in:
- Unique or series production/elements
- Small tolerances
- Combination of techniques and materials
- Small scale; material design on nano-scale
- Large scale; endless printing
- Internal structures and function integration
- To limit the amount of parts and producers

Whether RM is beneficial for a specific project as a production technique should be weighed out against the
other existing production techniques. Where is it useful to introduce printing and what are the consequences for the design; where is extra value created compared to a ‘normal’ production technique and/or how does it use the main benefits of RM? These are important questions that should be considered for each project.

**Implementation**

As a case study, an innovative shading device was developed, where the incidence of daylight into a room is the central focus. With a rotating device, a level of transparency can be combined with a block of heat and light incidence. For the disk, the amount of open surface, the division of the open surface in a pattern and the colour rendering are important parameters that determine the properties of the device concerning appearance, light and heat incidence. The perception of the disks in a room differs over standstill or rotation, because when turned on, the transparency increases and the contrasts in the incident light pattern fade.

The current method of executing a rotating shading device in a curtain wall façade would be by using motors as a drive for the disks. These motors are placed in between two glass sheets and sealed as a double glazing unit. In this way the devices can be integrated in each building project, it is even possible to upgrade an existing building with the shading devices by replacing the glazing. Difficulty will be maintenance and replacement in case of failure, because there is no easy possibility to reach the motors or the disks inside the glass unit.

Using RM to print the rotating shading device provides different boundary conditions. The problem of replacement and maintenance because of wear of the devices can be solved by designing a device where the moving parts totally don’t connect to each other, using the geometric freedom of the process. This is done by implementing a magnetic trail in the perimeter of the disk. When turned on, the disk floats in the casing. Each disk can be different in scale and pattern, because the design is independent on the production. Printing this device means that transparent, load bearing and insulating material in the shape of glass, metal and glass fibre should be printed in one process. The material behaviour of these materials makes it reasonable to presume the development of this graded product.

There will be intermediate steps between the current facade with rotating shading devices and the fully developed rapid manufactured facade. At this moment it is not possible to print a large range of graded materials, the scale of a product is limited and the costs of the specialized equipment and the materials can in most cases not yet compete with current production methods. For the introduction of the technique, printing can be introduced to process a part of the façade in a hybrid or a modular approach, applied in the area where the highest profit can be reached.

After an integrally printed facade, the next step will probably be a fully printed building. The tolerances of tenths of millimetres that the printing process is able to work with are undone when the printed façade
should be connected to a main building structure produced from in situ concrete, with tolerances of centimetres.

Combination
The printing technique can be considered to have a major influence on façade design. New inspirations and concepts can be developed which were unthinkable before. The technique should especially develop its property to print graded materials and printing on a large scale with minor tolerances to become interesting for the fully integral façade.

In a design process the use of RM has to be considered from the concept phase on, in order to develop a design where the technique is used to its utmost advantage. The architect should be well aware of the possibilities of the technique and the state of development; what is possible and what not. Besides, it is important to change the way of designing from thinking in materials that become elements that are connected in a finished product, to a RM approach where a material is immediately processed into the final product using the data in a CAD-file.

7.2 Discussion

The printing of facades requires the building industry to operate in a different manner than it does at this moment; therefore some difficulties exist for the introduction in the architectural world.

- In order to produce a fully integral façade with installations and structure integrated in one building skin, the collaboration during the design process should be very close between architect and the climate and structural designers. Nowadays, in the collaboration of the different parties within a building project, responsibilities are extensively secured in contracts. RM provides the possibility to integrate all functions, including installations, in the façade, produced in one process. Who carries the responsibility for which part of the façade when all parts intersect in the design?

7.3 Recommendations

- The shading device shows large freedom in design for architects to implement the devices. The current production method implements the devices between a double glass unit, therefore maintenance and replacement in case of failure becomes difficult. More research can be done on these specific aspects of the system.

- A rotating shading device will need constant power in order to work. The combination with a sustainable
approach should be considered. The façade could generate its own power that is needed to drive the devices (and maybe even more).

- The design made in the case study only covers the integration of a sun shading device in the façade, which also has the properties of insulating and transparency. It is interesting to do further research on an integral façade that covers more or different combinations of functions.

- The design assignment could be extended to see how the façade connects to the main structure. The tolerances of several centimetres for the main structure from in situ concrete does not compare to the tight tolerances of tenths of a millimetre used in rapid manufacturing.

- In this thesis, the choice was made to perform a case study to find the perspective of rapid manufacturing in façade design. The design process has been evaluated into conclusions about the perspective of the technique. A more overall approach could give more general results about how architects can specifically use the technique for a design.
Graduation thesis: Rapid manufacturing in façade design
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Appendix A; Brainstorm results

After the literature study a brainstorm was performed to come to a first vision on the future of the use of RM in façade design. In this brainstorm, the members of the Façade Research Group of the Delft University of Technology were invited to join.

This section describes the process of the brainstorm, gives an overview of the results and describes how the results can be interpreted and used in the process after this initial research.
A.1 Ideation in General

Ideation is the term used for the process of idea generation. People practice ideation all the time, every time when we generate ‘new’ ideas – at least ‘new’ for ourselves – we use techniques to generate them, whether these are our own personal tactics or proven methods is most of the time not clear.

Creative processes have a common course: (Osterwalder, 2009)

For this brainstorm the focus laid on the first half: the divergent thinking process. The aim of this part is to get ‘out-of-the-box’ ideas and develop concepts as broad as possible. The selection criteria and synthesis of the different ideas is reserved for the individual graduation project.
A.2 Brainstorm Process

The creative session was done in a short time span of approximately 1.5 hours and consisted of three basis steps.

1. Analogies (force-fit*)
   Function: energizer / warming up – Quick exercise of making analogies with different industries where RM is already used more often. Participants got an image from an application and had to write down (1) the technical principle and (2) an application in façade or building design.

<table>
<thead>
<tr>
<th>Example: Jaw implant</th>
<th>Principle</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Print structure, grow tissue</td>
<td>Print a 3D complex mold for a building / façade, with all wholes and tubes etc. in it and then fill with concrete.</td>
</tr>
</tbody>
</table>

2. Problem mapping (mind mapping)
   Function: analysis – this part made an overview of the problems regarding modern façade design and the opportunities of RM in general. The group created two mind maps of these issues.

3. Accidental combinations (force-fit*)
   Function: create on fore seen solutions – From the two mind maps which were filled with post-its, the participants blindly took a problem from the façade side and an opportunity from the RM side of the wall. Combined the had to form a concept, with keywords and a small sketch.

<table>
<thead>
<tr>
<th>Imagine... [Sketch]</th>
<th>Description [name, keywords]</th>
</tr>
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<tbody>
<tr>
<td>...</td>
<td>...</td>
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</table>
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<table>
<thead>
<tr>
<th>Aspects</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
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<td>(-) Negative façade post-it</td>
<td>Material:....</td>
</tr>
<tr>
<td>(+) Positive RM Opportunity</td>
<td>Requirements:....</td>
</tr>
<tr>
<td></td>
<td>Scale:....</td>
</tr>
</tbody>
</table>

* The ‘force-fit’ is a procedure used in creative thinking to make connections between some analogy and the original issue: clean textiles. It comes forth from the Synectics procedure (Tassoul: Gordon, 1961).

A.3 Results and Interpretation

An overview of the ‘raw’ results of the different steps in the brainstorm is presented in the appendices. As mentioned above the results form the start of the ideation process for both the students performing their graduation projects.

Depending on the purpose, the raw results can be categorized in several ways. They can be categorized by for example ‘façade problem’, ‘RM opportunity’ or any other way. Next to that there is an overview of which aspects are actually used and combined from step 2 into concepts for step 3. This could be a reason to extend this process in a further stage of the graduation project to be more complete or to focus on a specific aspect. The results from the different steps are presented as follows:

1. Analogies

Per analogy the input is described. All the results, also with scans of the input can be found in the appendices.

2. Mind maps of problem finding (This input is used in step 3)

3. Combinations
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Graduation thesis: Rapid manufacturing in façade design
Appendix B; Facade drawings

Upgrade: view and sections

Rapid manufacturing: view and sections