Additive Manufacturing for daylight

Towards a customized shading device

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ABSTRACT

The demand of customized solutions to product design and to the building sector, has become more and more evident during the last years. Researchers and architects are experimenting the potential of new technologies of digital fabrication, like Additive Manufacturing in order to facilitate the process of customized products. This project is motivated by the potential of digital fabrication in personalized solutions, leading to a “new industrial revolution” in the product design sector the industry of contraction.

The research is focusing in “customization” by Additive Manufacturing where individuals are invited to be part of the design and production process, introducing a non-standardized solution for daylight and shading. The proposed sunshading devices for window frames, are customized by each individual according to his/her needs, exploring different geometries for efficient and aesthetically pleasant shading systems for facades. The performance of the sunshade is regulated by its geometrical characteristics. Therefore, a direct relation between geometry, fabrication and light control performance is suggested. This project tries to connect product design with shading performance by taking advantage of parametric and computational design techniques, for personalization of the design and, also, by utilizing additive manufacturing for the final customized product.

The proposed external sunshading device for window frames is a “from file to factory” product, while every customer can create his own individual sunshade for a specific window frame. The concept introduces an interface, where the user will choose one of the specific geometries existing in an library of designs. Then he will adjust the geometry by changing the parameters given by the interface regarding his own individual situation, and he will 3D-print the sunshade to his printer or he will order his object printed, also, from the web. Finally, he will assemble the object with snap-fit connections and he will adjust it to his window frame.

Since AM permits digital designs to become into physical products at any location in the world (i.e., “design anywhere, build anywhere”) and web 2.0 is able to propagate product ideas and designs fabricated through AM, it is obvious that the combination of the above -Web 2.0 with AM- can start a new approach of product design and new models of entrepreneurship.

The “Egg project”, Michiel van der Kley
1. INTRODUCTION
1.1 MOTIVATION

This thesis is motivated by the potential of Additive manufacturing in personalized solutions and customized products, leading to a “new industrial revolution” in the product design sector and why not, in the traditional way of thinking and constructing in the building sector.

1.1.1 Against standardized solutions

Standardization is to produce uniform products available to consumers by reducing the variety and the right to the personal choice. Standardization focuses on many customers, without individual contact with them, addressing individual as a passive participant. On the other hand customization means to create according to individual needs and preferences. Customization can, therefore, change the way we design and produce goods for common users and products for the building environment, both from an engineering point of view and a user point of view.

Currently, “building sector uses industrial standard parts. I-beams, rivets, bricks leading to similar standardized solutions, and therefore repeating products” (Strauß H , 2013). In the macro scale, buildings have to perform to different climate conditions, withstand unique amounts of loads and conditions, require different foundations etc. In the micro scale, standardized parts, screws, hinges, nodes are normally modified with subtractive methods in order to fit and connect other parts for each specific occasion.

Additionally, different buildings are used by different people with unique preferences. Each building has to fulfill inhabitants’ expectations both regarding their comfort and aesthetics. Customization both in products and buildings leads to thinking “out of the box” and approaching from very simple to very complex solutions for different requirements.

1.1.2 Additive Manufacturing (AM)

“A new digital revolution is coming, this time in fabrication. It comes through communication and computation, but now what is being programmed is the physical world rather than the virtual one. Digital fabrication will allow individuals to design and produce touchable objects on demand, when and where they want them. Widespread access to these technologies will challenge traditional models of business, and education. This revolution is the ability to turn data into things and things into data.”( Gershenfeld 2012)

“Additive Manufacturing is the official name of 3d printing which is any of several processes to produce a three-dimensional object”. (Excell, J. 2010) The technique used in 3D printing is additive process in which the real object is printed slice by slice on top of each other under computer control. During the process, the printed objects are produced from a 3D printer which is a type of robot. The objects are firstly developed from a 3D model having simple or complicated shapes or geometries. Currently the term has extended to a variety of techniques like extrusion and sintering based processes. So the term has become broader to “Additive manufacturing (AM)” . The Industrial 3D printers use powdered metals, casting media (e.g. sand), plastics or paper, and their main function is rapid prototyping.

The first applications of AM technologies starting in the 1980s in product design and development, visualization of data, rapid prototyping, and specialized manufacturing. In the early 2010s industrial production roles within the metalworking industries (Zelinski P . 2014) increased the built object scale for the first time. Since the start of the 21st century the growth in sales of AM machines increased dramatically and as a result their price has dropped sharply. (Sherman, L. M. 2004) More specifically the cost of 3D printers has dropped significantly
since 2010, regarding the fact that machines that used to cost $20,000 now costing less than $1,000. (Bilton N. 2013)

“There are many applications for AM technologies, including architecture, construction (AEC), industrial design, automotive, aerospace, military, engineering, dental and medical industries, biotech (human tissue replacement), fashion, footwear, jewelry, eyewear, education, geographic information systems, food, and many other fields. An additional use being developed is building printing, or using 3D printing to build buildings. This could allow faster construction for lower costs”. (Zolfagharifard E. 2014)

As far as a study in distributed manufacturing is concerned (Heather K. 2013), additive manufacturing has the potential to become a mass market product giving the opportunity to consumers to save money when it comes to buying common household objects. (Wittbrodt, B. T, 2013) For example, instead of going to a store to buy a factory-constructed brand, a client may prefer to 3D print it at home from a downloaded 3D model.

“The development of AM is still in the beginning stage, however, AM technologies offer the potential to lastingly change design and construction methods. The change in our way of thinking has long begun: file-to-factory, Building Integrated Modelling (BIM), digital materials are the key words in this ongoing discussion in the day and age of Grasshopper”. (Strauß H 2013)

1.1.3 Customization by Additive Manufactiring

The progress of 3-D printing is related with “customization,” where individuals are invited to contribute to the design process of products like a jewelry, a mobile case, headphones or toys. Since 3D printers fabricate one piece at a time, it can fit the buyer’s identity, geometry, form or preference, and his opinion becomes part of the design and fabrication process. As Shapeways marketing director Carine Carmy put it to Re/code, “The printer doesn’t care whether it’s 1,000 of one thing or one of 1,000 things.” (Carmy C. 2013) So we are going from the DIY culture (Do it yourself) to the DYO phase (Design your own). The attractiveness of mass-customization, the mass-production of individually customized products, is the potential of manufacturers to decrease costs and gain an advantage in the competitive market.

With additive manufacture people can customize and order products directly. And although the current available goods from 3D printing to the market are not that much yet, this fabrication method is definitely promising. It’s establishing a new world of creativity for every consumer, new opportunities for manufacturing, and a new era for entrepreneurs. Right now what happens in the process of the design is that experts are designing, manufacturers are producing and the mass is buying what the others are creating. Instead, the revolution of digital fabrication offers people the opportunity to produce their own things, what they want -and not what others want them to- use-consume.
Everything designed from the paper to the computer can be realized in the near future. It is just a matter of time. New technologies of Additive Manufacturing are improving so fast, in terms of new materials, sizes of printed objects, production time, accuracy etc. that one can guess that they will be broadly used in the future in many new sectors, even in the stereotypical building sector and more specifically, in the facades technology field.

1.1.4 Facade and Shading

The facade represents a thermal and visual border between indoors and outdoors. Therefore, it is responsible for controlling the indoor climate and also affects the lighting, heating, cooling and ventilation demands and as a result the overall operational energy expense of a construction. Environment and climate change and sustainability issues force professionals mostly in the built environment to design innovative solutions focusing on an adequate level of human comfort in buildings. That is why, it is really important that architectural solutions integrate passive strategies for thermal and visual comfort.

From an engineering point of view, a facade is a technical challenge because it combines many functions, which depends on the indoor comfort and the outdoor external conditions, that differs for the unique context of every case. On the other hand, facade is what is visible of a building from the outside, so apart from the technical aspects, it should also fulfill aesthetics. Both technical approach and aesthetics of the envelope lead to unique design solutions for each building in order to be essential for its particular conditions, which is exposed to.

As mentioned before, building envelope combines many functions that could be customized. However, this particular research focuses on the scope of non-standardized solutions for daylight and shading. Considering the visual comfort of a facade, shading plays a critical role, as it is related with the amount of heat and light entering the room. The facade needs to deal with conflicting demands as solar heat gains on one hand and daylight access on the other. Thus, the facades transmittance of solar energy and light has to be flexible. This adaptability can be achieved with the application of sun protection, exterior or interior shading, incorporating shading elements with windows. The possibility of daylighting depends on the shape of the construction-geometry of the window and the sunshade.

So, would it make any sense to take advantage of a new fabrication method to customize shading devices? Additive manufacturing is this new fabrication method that allows the uniqueness of each object without affecting the time, cost and complexity during the fabrication process. However complicated the geometry of the object, is the same for the fabrication technique, since every model of the computer can be directly fabricated, no matter if it has a different shape. The cost of transportation and the assembling process of the pieces is eliminated as it is a process from the file to the factory. One can download the file and fabricate the object directly in 3d dimensions!

Imagine if we give people the tool to customize their own sunshade regarding the shape, the size, the color and even the material they prefer, fulfilling both comfort needs and aesthetics. Then, they can print it to their home or to the fabrication lab of their neighbor. What is next is just adjusting it to their own window frame and probably it works! What relates the fabrication process, on the one hand and the performance oriented design of external shading device for windows -in this case- on the other hand, is parametric design.

1.1.5 Parametric associative design

“From the software side, parametric design is the setting up of computable models, composed by objects that are defined by a series of geometric items based on variable parameters.” (Cinici et al, 2008)
These objects can be linked together through a set of relations, which allow adapting the variables anytime during the design process. Thus, it is offering the ability to quickly compose, adjust and estimate different design alternatives and the impact of design choices appears quickly.

The opportunity for such parametric modelling is provided by programming interfaces like Grasshopper. “Grasshopper is a graphical algorithm editor tightly integrated with Rhino’s 3-D modelling tools.” (Grasshopper3D) Developed by David Rutten at Robert McNeel & Associates (Grasshopper, 2011) is now a prominent modelling tool. One of the potentials of the program is the fact that it allows designers to become familiar with the concept of parametric or associative design without being experts on scripting/programming. Instead of using programming languages, it uses an interface where definitions are created by dragging components onto a canvas and connecting them. The components consist of outputs and inputs that can be used to connect other components. The script based software is fast growing to become a potential platform for architects and engineers, to experiment with new ways of representing design concepts, build generative algorithms and explore new shapes and forms. Additional benefit of Grasshopper is that it provides analysis and optimization tools for building performance such as daylighting and energy, helping designers create an environmental approach in architectural design, using mathematical equation for building physics.
1.2 PROBLEM STATEMENT

In this research there is an attempt for an old problem which is shading to be solved by taking advantage of new design methods and fabrication techniques, that is Additive manufacturing. This problem is the lack of customized shading devices for different contexts, uses-occasions (temporal use, permanent use) and user’s preferences regarding that shading is a dynamic phenomenon.

Additive manufacturing is directly related with customized products, as it makes easier the manufacturing process of totally different parts of the construction. Although this potential exists, neither building sector has taken advantage of additive manufacturing benefits (“file to factory” approach, for customised building parts) yet, nor individuals have the opportunity to personalize their own items, when it comes to the building sector.

Therefore, what is missing so far is the exploration of computational-performance design and fabrication in the building sector and how that would allow average costumers to customize their own objects. In this research, this is an external sunshading device for windows, which would be fabricated in accordance with a unique context and specific needs.

1.3 RESEARCH OBJECTIVES

This study focuses on exploring the potential of additive manufacturing in building sector, by introducing a product design for a sunshading device which is customized by each individual according to his/her needs. The performance of the shading is regulated by its geometrical characteristics. Therefore, a direct relation between geometry, fabrication and light control performance is suggested.

Research and development in the fields of architecture and computational design suggest a pyramidal relation between computation, fabrication and performance. This project tries to connect product design with shading performance by taking advantage of parametric and computational design techniques, and, also, by utilizing additive manufacturing for the final product. When AM is used as a production technique, the design will become different than when contemporary production techniques are used. There is a wide range of options available for additive manufacturing. Geometric freedom, material properties and the fact that the design is independent of production eliminate a lot of boundary conditions for the design process. However, they introduce other limitations like materials, limited dimensions, production cost etc. with the current techniques.

The aim of this study is to explore the relation between digital modelling, digital manufacturing and performance through the paradigm of a product, an external sunshading device.

The specific goal of the study is to propose a product by exploring different geometries for efficient and aesthetically pleasant shading systems for facades. Based on the objectives, the project focuses on developing the design proposal for changeable solar shading devices according to every user’s needs and occasions, in order to create a different aesthetic effect, while being environmentally efficient.
The parametric modeling tool is used because it can easily generate various different designs with different variables while provides information regarding building performance as a result of design parameter updates. This can help to make proper decision during the design process. Additive manufacturing method is used because it can easily produce customized products. Therefore, this product is a result of the cooperation between both the above.

1.4 RESEARCH QUESTIONS

- How common users could customize their sunshading device, becoming part of the design and fabrication process and taking advantage of additive manufacturing techniques?

- How could solar control and sunshading systems be designed to take advantage of the opportunities that digital fabrication brings?

- What is missing in the industry of sunshades?

Subquestions

- What are the parameters that affect daylighting control and shading in a facade and which are the user’s requirements?

- What are the Additive manufacturing methods and the available materials used?

- What assembling methods could be used for 3d printed items?

- How the performance of an external sunshade could be tested?

1.5 RESEARCH OUTPUT

So this thesis proposes an external sunshading device for window frames “from file to factory”, any client-user can create his own individual sunshade for a specific window. The concept introduces an interface, where the user-customer will choose one of the specific designs-geometries existing in a library of the website. Then he will adjust the design by changing the parameters given by the interface regarding his own individual situation. (dimensions, sun latitude, orientation etc.) and he will print the sunshade to his printer or he will order his object printed, also, from the web. Finally, he will assemble the object and he will adjust it to his window.

A specific case study is used in order to design a shading device for a specific context and then print it “factory” to the final product and test the engineering aspects.

Digital Fabrication intent to play a significant role in the building design. The use of associative design, supported by environmental parametric, material properties and mass customization is opening new ways of work in architecture.

“How could solar control and shade systems be designed to take advantage of the opportunities that digital fabrication brings?” This is a potential path for exploration.

“This newfound ability to generate construction information directly from design information, is what defines the most profound aspect of much of the contemporary architecture.” (Kolarevic, B. 2003).
1.6 RESEARCH METHODOLOGY

1. The first two chapters (chapter 2, chapter 3) of the thesis include literature study related to light, light properties, visual comfort and control/shading systems and relevant mechanisms, in order to define the variables that affect shading, and the requirements that they have to address. In addition, literature study and research on digital fabrication and Additive Manufacturing processes is included in order to define the limitations of the techniques, the materials which could be used for the final product and the revolution of AM in product design, reaching a high degree of freedom in the design process.

After the literature review, the research includes the development of the concept and the product design proposal. -In the fourth chapter the logical framework of the user scenario and the technological concept of the product is developed. The boundary conditions and the variables which the customer will be able to change regarding his needs, in order to create his own-efficient sunshade, will be developed here. Then, these variables will be used for the shape generation, through parametric design and generic algorithms, of several sunshades and screens to form the available library of patterns of the interface accessible from the user.

In the same chapter CES edupack software will be used in order to check the performance of the available 3d printed materials according to the requirements of an exposed to weather conditions sunshading device. In this stage also, investigation through websites, relevant forums and discussions with companies, and people with experience on 3dprinting is included.

After that, assembling methods of plastic parts, designed according to the literature, will be tested with physical models. This phase includes becoming familiar with the 3dprinting process in order to check material behavior, printer settings, tolerances for correct modeling of the parts, etc.

Chapter five includes the selection of a case study with specific conditions where the whole concept will be applied in order to achieve the final design of a sunshade and test the engineering requirements of the final product:

- Shading performance through computer simulations and a physical model.
- Structural performance-connections-assembling of physical models and engineering test of the joint.

This phase includes the fabrication process of the final mock up 1:5 in order to test the illuminance performance of the sunshade with the a physical model and several connections based on the results of the previous phase of assembling will be fabricated for the final prototype.

The described part above, after the literature review, is a circular methodology, where the design generation and logical framework gives feedback to the fabrication process and vise versa and both of them “inform” the case study, whereas during the case study analysis, updates to the other two approaches are given (design and fabrication).

The last part of the report consists of an initial business plan for the proposed product, which has been formed through on-line research on products: coverings for windows additive value, customer validation, market analysis etc.

Finally, the evaluation and the conclusions of the whole process follows the recommendation of further research development.
LITERATURE


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AIM OF RESEARCH
Product design
-A sunshading

RESEARCH METHODOLOGY

Literature review

- Light
  - Performance
- Shading Systems
  - Variables affecting shading
  - Requirements of shading
- AM
  - Processes
  - Limitations
- AM & Product design

User scenario
- Communication of the product with the user

Technological concept
- Process of product design & fabrication

Logical framework
- Shape generation
- Parametric modeling

Fabrication process
- Physical models by FDM

Case study

Form
- Translation of shading requirements to variables
- Design variations
- Performance (computer simulations)

Fabrication
- Testing connections with physical models
- Illuminance performance with physical model

Assembling
- Assembling of modules
- Assembling to the window frame

Engineering aspects

Conclusions

Fig. 6: Overall research process
2. STATE OF ART LIGHT
2.1 DEFINITION OF 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.” (A.J.N. van der Brugge, 2010)

If the atoms are heated enough, the outer electrons get to a higher energy level. When an electron goes back to a lower energy level, the liberated energy will be radiated as a photon. The amount of emitted energy determines the frequency and the wavelength and therefore the color of the light.

“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”. (A.J.N. van der Brugge, 2010)

The luminous efficacy of direct sunlight is about 93 lumens per watt of radiant flux, including the visible spectrum, infrared and ultra-violet light. (G.D. Ander, 2003)

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. 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, glare, on the screen or too strong contrasts within a room causes people to adjust their working environment by covering the windows and turning on the artificial lighting.

2.1.1 The importance of daylight

Nowadays, global warming, carbon emissions and sustainable design are important factors during the design process. Besides, natural light in non-residential buildings mostly has become a very important method to reduce the energy consumption by minimizing lighting, heating and cooling amounts. Daylight in architecture is not only used for art and aesthetics but also as a result of scientific studies about the necessity of people on natural light. Nowadays, the façade is often as transparent as possible aiming to the daylight entering the working space and permitting views of the outside world. However, the light of the sun can cause overheating and glaring, resulting in serious threats for the working environment. It is common that light controlling systems and shadings protect people from annoying light while they abuse artificial light.
It is well known that properties and the advantages of sunlight cannot be substituted by artificial lighting. Artificial light cannot copy the complete light spectrum with high intensity of daylight. It is proved that people need the complete light spectrum for mental and health reasons. Artificial light is very monotone compared with daylight, which changes over the day and the year because of the rotation of the earth around its axis and the axis of the sun respectively. Also, different weather conditions cause changing angles and intensity of sunlight.

The human metabolism requires sunlight, due to the blue part of the spectrum which slows down the bodies’ production of Melatonin, the hormone that controls for day and night rhythm. The morning light consists of relatively much blue light, whereas in the late afternoon the light becomes red, triggering the melatonine production again. When there is too little light, the human body is confused causing sleepiness. This effect can even cause depression or sleep disorders.

The sun shading in an adaptive facade has to be responsive on different thermal requirements during the year. What is different from summer to winter regarding the sunlight are angles of the sun and the weather conditions. This difference requires a system that can be effective for the occurring situation. For instance, in the winter the heat gain has to enter the room, while in the summer it is better to block it, preventing overheating.

2.1.2 Properties of light

The human eye can only identify wavelengths of daylight in the range of 380-780nm without mechanical equipment. When a ray of light reach a surface three phenomena can take place. These are reflection, refraction and absorption. These phenomena depend on material properties, like color, thermal properties and glossiness.

Reflection
In most of the cases we expect to have a combination of specular reflection (the light is reflected with the same angle as the angle of incidence) and diffuse reflection (the light is reflected to different directions with different angles due to the roughness of the surface). This combination is called scattered reflection.

Reflected light can be expressed in the light reflection factor RL. 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%

Refraction
The light is refracted as it is transmitted from one material through the next. In this case the direction of the electromagnetic wave is changed (the light is refracted) Refraction is dependent on two factors: the incident angle, $q$, and the refractive index, $n$ of the material, as given by Snell’s law of refraction: $n_1 \cdot \sin(q_1) = n_2 \cdot \sin(q_2)$, a light ray entering the glass at 30 ° from normal travels through the glass at 10.5 ° and straightens out to 30 ° when it exits out the parallel side. (A. Ryer, 2000)

Absorption
The light is absorbed by the materials and is transformed in another kind of energy, usually heat. (Baker, N, 2010)

Sun position
The sun position with reference to the horizon is usually expressed by altitude and azimuth. Altitude is the angular distance above the horizon measured vertically to the horizon. Its maximum amount is 90 degrees at the zenith, which is the point overhead. “Azimuth is the angular distance measured along the horizon in a clockwise direction. Astronomers measure it from the south point, navigators from the north point”. (Olgyay, 1957)
2.1.3 Measuring the light

- **Daylight factor (D)** is the ratio of illuminance at a point on a given indoor plane due to the light received directly or indirectly from the sky of assumed or known illuminance distribution to the illuminance on horizontal plane due to an unobstructed hemisphere of this sky, the contribution of direct sunlight to both illuminances is excluded.

\[ DF = \left( \frac{E_i}{E_o} \right) \times 100\% \]

where, \(E_i\) = illuminance due to daylight at a point on the indoors working plane, \(E_o\) = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky.

The daylight factor can be considered to be made up of 3 components: the sky component (SC) the externally reflected component (ERC) and the internally reflected component. It also depends on the transmission coefficient of the glazing. (IRC) (EN 12665:2002)

- **Daylight Autonomy (DA)** uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that an occupant can work by daylight alone. (J. Mardaljevic, et al. 2006)

- **Illuminance.** “In photometry, illuminance is the total luminous flux incident on a surface, per unit area. It is a measure of how much the incident light illuminates the surface, wavelength-weighted by the luminosity function to correlate with human brightness perception”. (Illuminance, wikipedia, 2014) Illuminance is measured in “lux (lx)” or “lumens per square meter (cd·sr·m−2)” and it is independent on the material properties of the surface being illuminated.

- **Luminance** “is a photometric measure of the luminous intensity per unit area of light traveling in a given direction. It describes the amount of light that passes through, is emitted or reflected from a particular area, and falls within a given solid angle.” (luminance, wikipedia, 2009) In SI the unit for luminance is “candela per square metre (cd/m2)”. Climate-based daylight modeling can be carried out using either computer simulation techniques or scale models in a sky simulator (physical models).

However, most of the studies carried out today use computer simulation techniques. In this project DIVA-for-Rhino, developed by Solemma LLC, a highly optimized daylighting and energy modeling plug-in for the Rhinoceros - NURBS modeler is used for daylight simulations. DIVA-for-Rhino uses validated simulation engines like Radiance, Daysim and Energy Plus. (http://diva4rhino.com/) Radiance is one of the most advanced computerized daylighting/lighting simulation tools available. The effectiveness of the tool lies in the fact that it can adequately calculate direct and diffuse light (from the sky dome) and that it can estimate the effect of multiple reflections in the scene. (Mardaljevic, 1999; Aizlewood et al., 1998, Ubbelohde & Humann, 1998, Jarvis & Donn, 1997)

- **Useful daylight Illuminances (UDI)** proposed by Mardaljevic and Nabil are when daylight levels are useful for the occupant, neither too dark <100lux, nor too bright>2000lux. Nowadays, 500lux on the workplace are often recommended for office work (Canadian Labor Code, Part II: Occupational Safety & Health 1991, IESNA Lighting Handbook, 9th Edition, 2000). Optimal illuminance levels for office buildings is 500lux on each working space, or even 1000lux when it comes to a more detailed work.

- **Luminance contrast**

As it is presented on the fig.8 in order to define if the luminance contrast in a space is comfortable or not, we can use the rule of thumb that describes as comfortable contrast the ratio of minimum luminance levels in a space to maximum luminance levels to be equal or more than 1:30 for the panorama view. When it comes to the ergorama view the ratio should be 1:10 or more.

Fig.8 _ Comfortable Luminance contrast.
2.1.4 Visual comfort-Light control: glaring

In daylight design, comfort is related with the glaring problem. The International Commission on Illumination (CIE) defines glare as: “visual conditions in which there is excessive contrast or an inappropriate distribution of light sources that disturbs the observer or limits the ability to distinguish details and objects”. (I. Murray 2007).

The Daylight Glare Index (DGI) is a value for assuming the glaring probability as a consequence of daylight entering a room. The glare index is affected by the size and relative position of the glazing, the orientation, sky luminance, and interior luminance. Although there are some limitations of DGI, it is the most widely used value for prediction of glare. While DGI may overestimate the glaring near the window, when it comes to the centre or the back of the room the assessment is more accurate. (J. Wienold, et al., 2006)

DGP
The Daylight glare probability (DGP) is being used as an indication of the glare effect that is anticipated in the interior. DGP is a function of the vertical eye illuminance as well as on the glare source luminance, its solid angle and its position index (Mardaljevic, 2005):

\[
DGP = 5.87 \times 10^{-5} \cdot E_v + 9.18 \times 10^{-2} \cdot \log(1 + \sum \frac{L_s^2 \cdot \omega_s}{E_v^{1.87} \cdot P_i^2}) + 0.16
\]

*Ev* : the vertical eye illuminance (lux)
*Ls* : the luminance of source (cd/m²)
*ω* : the solid angle of source (sr)
*P* : Guth position index

“The position index of a source, P, is an inverse measure of the relative sensitivity to a glare source at different position throughout the field of view”. (Zhi, M. et al., 2012)

The following equation specifies the position index P.

\[
\ln P = (35.2 - 0.3189 \tau - 1.22e^{-2\tau}) \cdot 10^{-3} \cdot \sigma + (21 + 0.26667 \tau - 0.0029 \tau^2) \cdot 10^{-5} \cdot \sigma^2
\]

\(\tau\) : the angle from vertical of plane containing source and line of sight (in degrees)
\(\sigma\) : the angle between line of sight and line from observer to source (in degrees)
(R.D. Clear, 2012)

---

<table>
<thead>
<tr>
<th>Glare Type</th>
<th>DGP Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperceptible Glare</td>
<td>&lt; 0.35</td>
</tr>
<tr>
<td>Perceptible Glare</td>
<td>0.35 - 0.40</td>
</tr>
<tr>
<td>Disturbing Glare</td>
<td>0.40 - 0.45</td>
</tr>
<tr>
<td>Intolerable Glare</td>
<td>&gt; 0.45</td>
</tr>
</tbody>
</table>
Through light studies, either photometric or radiometric values could be estimated. Radiometric values access the power of light at different wavelengths, estimating the energy loads in an area. Radiant energy and radiant flux density refer to irradiance, which is measured in watt/m² and they are radiometric values, while photometric values access the perceiving brightness to the human eye. In this study the visual comfort of the proposed shading device is evaluated, so performance will focus on photometric values, the measurement of illuminance (lux) in the spaces, the luminance contrasts and the DGP factor for glaring assessment.

2.2 SHADING SYSTEMS

As mentioned above, the façade needs to achieve opposing demands regarding solar heat gains on one hand and daylight access on the other. Thus, the façades interaction to solar energy has to be adaptable. Sun protection can fulfill this demand of flexibility in facades.

A part of this research aims to learn how to design efficient shading systems, “a structure” that offers shading for a specific period of the year while allowing solar exposure for another period. A study of typologies of existing conventional shading systems follows in order to define the needs and requirements of shading systems.

“Shading devices perform triple duty: they keep out the sun’s heat, block uncomfortable direct sun, and soften harsh daylight contrasts.” (O’connor et al, 1997)

According to Eisele J. and Kloft, E., (2003) “The sun is a dynamic light source, which not only changes its position but its intensity and color too. Cloud formations enhance the natural daylight conditions. The variations in daylight depending on season, location or latitude, and cloudiness”.

There are two ways that solar radiation reaches the surface of the earth: direct radiation from the sun and diffuse radiation from the sky. Direct radiation is very high energy light that can be directed and focused. It can easily cause overheating, so sun protection (shading) is necessary. A cloudy or overcast sky causes diffuse radiation, which is comfortable for viewing task. Both kind of light are involved to the brightness of the room.

**Natural light** depends on natural conditions such as climate zone, the surroundings of a building, the orientation and the form of the building, as well as the dimensioning of the place. As this research focuses on shading devices that will be attached to the windows of existing buildings mainly, the surrounding buildings will not be taken into account.

**Climate zone**: Geographical location-availability of daylight. Defining the sun path is necessary to predict the amount of daylight that enters the room. We can calculate sun position, the angle of incidence of solar radiation and the duration of the sunshine by defining the latitude, time of day and the season for every site at any time. Meteorological conditions of the sky-ranges from diffuse to clear and overcast- is another important factor which depends on the climate zone. In northern Europe, as the position of the sun is lower, shorter days in the winter and longer days in the summer are observed. For locations closer to the equator there is more light available.

**The orientation**: Southern light is very intense and dynamic while northern light is more constant and cooler. Sun protection in the east and west is more challenging, as the sun is in lower position. Thus it is hard to both maintain views to the outside and protect from solar irradiation and glaring. (Eisele J. and Kloft, E.2010). As we will see in the next chapter, as a rule of thumb, south orientation requires horizontal shading, while east and west orientation require vertical shading. In the north, sun shading is not necessary at all.

**The building volume and façade**: The orientation of the building gives initial information about the main angles of the incidence of natural light and direct sunlight as well as the shade conditions of the building. The amount of natural light that enters the room depends on the size of the window openings and their position to the wall.
The objectives of the daylight control systems are:
- To improve daylight for task illumination through redirection of light.
- To protect from glaring.
- To achieve solar shading and thermal control.

This research focuses on shading devices that aim to protect from glaring and to achieve shading to the indoor, so light-enhancement devices such as reflectors, horizontal-anidolic light shelves, anidolic collectors, light ducts and Light tubes are not analyzed in this research.

Shading systems can be categorized in terms of position, geometry-orientation and adaptiveness.

Specification in terms of position.

### 2.2.1 Specification in terms of position

Regarding their position, shading devices can be categorized into three groups: exterior shading, interior shading and in-between shading. Exterior systems are more effective than interior systems, because they block sun rays before entering the building, avoiding heat development inside. In this research we will focus on exterior shadings as they are more efficient and and also because the scope of the research consists of already existing buildings.

**Internal glare control**
Venetian blinds, curtains, sliding shutters, opening shutters, rolling textiles, stretchable textiles, tensioned fabric systems. Internal shading devices act like radiators. Solar radiation is reflected to the inside and overheating between the shading structure and the glass pane occurs. Therefore, internal shading should be defined as glare protection devices as they cannot keep the heat outside.

**External shading**
Rotating panels, brisesoleil, venetian blinds, sliding shutters, opening shutters, rolling textiles, stretchable textiles, tensioned fabric systems, canopies, awnings. External shading devices block the sun before entering the building, however they have to be weather and wind resistant.

**Between glass panes**
Shading systems between the glass panes act similarly to the internal devices producing overheating because of the effect of radiation and convection in the cavity. A solution to this effect could be the ventilation between the glass panes, as it is recommended to double facades.

Fig.10_ These images illustrate the potential position of a sunshading.
2.2.2 Specification in terms of orientation-geometry

**Horizontal shading**
Horizontal devices reduce light coming from the sun at a high profile angle. These can be blinds, overhangs and reflective lamellas in the cavity between the glass panes. Horizontal devices are usually very effective, providing almost full shading according to the requirements of the user and the position of the sun. Overhangs permit views to the outside and they are very efficient for south-oriented façades for sun in high positions. The amount of shading of the overhang depends on its depth. There is the possibility for south or near south-oriented facades (in the northern hemisphere) for the overhangs to reflect direct sunlight into the interior of the room in order to reduce artificial light. Louvers are a very common solution in southern Europe, they can redistribute the light when they are closed, prevent direct light entering the room and allow ground reflected light to enter.

**Vertical shading**
Vertical shading works opposite to the horizontal one, while it is very effective for direct sunlight at a low angle, like during the morning, the afternoon and the evening. Vertical shading blocks low angle sun from the side. Therefore, they are efficient on east and west façades. Regarding southwest or southeast façades where the solar altitude angle is high during the hot season, a combination of vertical and horizontal fins, aggregate shading, are most effective as it obstructs the sun for high and low positions, as well.

2.2.3 Specification in terms of adaptiveness

**Static systems**
Fixed or static can be: brise soleil, tensioned fabric systems, louvers, panels, canopies, awnings. When it comes to fixed shading devices, the incidence angle under which sun rays hit a surface becomes a crucial parameter, as they cannot change their position, dimensions or orientation in accordance with the sun path. This angle is dependent on the orientation of the façade, the time of the day and the season of the year. Static shadings are very common, since they are easier to construct and they don’t need such maintenance or energy to work.

The sun-path diagram presents two overlapping curves, one related to the rotation of the earth around its axis, explaining the daily movement of the sun over the sky, which causes the day and the night and the other related to its revolution around the sun, resulting the seasonal differences in the solar altitude. When designing shading devices, seasonal and daily irradiation have to be observed through the study of solar path, in order to design optimal devices that block sun rays during summer, while allowing them to enter the building in the winter.

**Dynamic systems**
Dynamic called all the systems that can be changed their position through, sliding, open, fold/unfold, stretching, in order to control the daylight enter the interior. These are: venetian blinds, curtains, sliding shutters, opening shutters, rolling textile, tensioned fabric systems, awnings, rotating panels and diaphragms.

The advantage of dynamic systems is that allows users adjustment in respect with his preferences and the sun path. However, we have to consider maintenance cost and energy consumption in this case. Venetian blinds, for instance, consist of adjustable louvers to regulate the incident sunlight. These blinds can be divided into separate parts with different inclination for different needs. More sophisticated motorized systems are even automatically controlled via a sun sensor to adjust the shading device to the sun’s position.
Specification in terms of orientation
- Horizontal shadings
- Vertical shadings
- Egg crate shadings

Horizontal shading devices:

Overhang

Use louvers in place of solid overhang for more diffuse light while still shading

Awnings

Substitute louvers for the solid dropped edge to let in more light

Panels

Rotating louvers

Fig.11. These images illustrate shading devices for the South orientation. (Source: Architectural graphic standards, The American Institute of Architects)
Vertical shading devices:

Vertical louvers or fins for east and especially west facades.

Vertical inclined louvers

Vertical rotating louvers

Egg crate shadings

Mixed vertical-horizontal

Mixed vertical-horizontal with inclined vertical elements

Mixed vertical-horizontal with inclined horizontal elements

Fig.12. Illustration of vertical shading devices for the West and East orientation. (Source: Architectural graphic standards, The American Institute of architects)

Fig.13. Illustration of Egg crate shading devices for the southwest or southeast orientation. (Source: Architectural graphic standards, The American Institute of architects)
In terms of adaptiveness:
- Static shading systems
- Dynamic shading systems

**Static shadings**

*Overhang*

*Louvers*

*Panels/ brise*

*Awnings*

*Screens*

fig.14_ Images of static shading devices.
In terms of adaptiveness:
- Static shading systems
- Dynamic shading systems

**Dynamic shading systems**

**Louvres**

**Venetian blinds**

**Rotating panels**

**Sliding shutters**

**Rolling textiles**

**Awnings**

**Special configurations**

**Sliding patterned panels**

**Sliding-folding panels**

**Diaphragm**

**Rotating**
Movement by rotating elements and parts within their own axis, following the path of the sun.

**Shifting-Sliding**
Movement by changing locations and reorganizing elements and parts.

**Rolling**
Movement by rolling textiles vertically or horizontally.

**Folding**
Movement by folding, opening and closing elements and parts.

**Diaphragm**
Movement by opening and closing apertures inside facade elements.

Fig. 15: Images of dynamic shading devices.
2.2.4 Case studies of innovative shadings-define requirements

There are many examples of innovative sun shading systems worldwide that aim to control sunlight and daylight. These shadings work with the following principles: changing of the geometry or changing of the material properties. As this research focuses on customized shading devices fabricated with Additive manufacturing, systems in which the characteristics and properties of the material affect the illuminance levels will not be presented.

Solar shading always is an issue for daylighting except on north-oriented facades (in the northern hemisphere). If solar shading is only of minor importance as a result of orientation and obstructions, a system to protect from glare can be used for solar shading as well. Daylighting systems have four major functions:

<table>
<thead>
<tr>
<th>Daylight system functions</th>
<th>Shading systems requirements</th>
<th>How</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redirect daylight</td>
<td>Daylight enhancement</td>
<td>Redirect light</td>
</tr>
<tr>
<td>Solar shading</td>
<td>Protection from overheating</td>
<td>Block light</td>
</tr>
<tr>
<td></td>
<td>Solar gain</td>
<td>Allow light</td>
</tr>
<tr>
<td>Glare control</td>
<td>Protection from glare</td>
<td>Filter light</td>
</tr>
<tr>
<td>View to the outside</td>
<td>Obstruction of views</td>
<td>Block-filter light</td>
</tr>
<tr>
<td></td>
<td>Allow views</td>
<td>Allow-filter light</td>
</tr>
<tr>
<td></td>
<td>Optimize views</td>
<td></td>
</tr>
</tbody>
</table>

People adaptation to light conditions can occur, both physically and psychologically. User expectations play a significant role to that. For instance higher light levels are expected on the summer, whereas in spring and winter, lower levels in the interior can be considered as comfortable, following the conditions of the outside environment.

In the next paragraph, there is an effort for some innovative shadings to be analyzed in terms of the above requirements which are related to light control and user preferences. There may be other requirements for sunshading systems related to the complexity of the construction, the complexity of the system and the maintenance. However, as here we aim to produce shadings for a specific fabrication method, we will only take into consideration requirements related to this specific method, like process to be used, accuracy of the process, variety of the materials etc.
2.2.4.1 Al Bahar Towers
Folding Mechanism

LOCATION | Abu Dhabi, United Arab Emirates
LATITUDE | 24°28’N
COMPLETION | 2012
DESIGN | Aedas
USE | Office
FACADE MATERIALS | PTFE (polytetrafluoroethylene) panels

Redirect daylight | -
Solar shading | ++
Glare control | ++
View to the outside | +
Orientations | S,E,W

The specific shading system presents an alternative to the traditional wood-lattice screens called ‘mashrabiya’ using today’s technological abilities resulted in an outer facade of triangular screens supported in a structure of hexagons folding up to create a solid solar barrier. The barrier consists of 1000 panels which can be moved regarding the sun position by a linear actuator. Heat gain and glaring are decreased by 50% thanks to the islamic vernacular representation. The perforated screens filter the light and semi-permit the views to the outside when the system is totally closed.

As the aim of the project is the protection of the sun, there is no redirection of light to the indoors. The linear actuator will progressively open and close in response to a pre-programmed sequence that has been calculated to block direct sunlight from entering the interior.

Figures 16, 17, 18: Images of Al Bajair towers. (http://inhabitat.com)
2.2.4.2 Kiefer technic showroom  
Folding Mechanism

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Bad Gleichenberg, Austria</th>
</tr>
</thead>
<tbody>
<tr>
<td>LATITUDE</td>
<td>46° 52’N</td>
</tr>
<tr>
<td>COMPLETION</td>
<td>2007</td>
</tr>
<tr>
<td>DESIGN</td>
<td>Ernst Giselbrecht + Partner ZT GmbH</td>
</tr>
<tr>
<td>USE</td>
<td>Showroom and office space</td>
</tr>
<tr>
<td>FACADE MATERIALS</td>
<td>Perforated aluminium</td>
</tr>
</tbody>
</table>

Redirect daylight | - |
Solar shading      | + |
Glare control      | + |
View to the outside| + |
Orientations       | S |

The facade consists of 112 metal tiles that form the exterior of the showroom by means of 56 engines. Occupants can control any of them in order to adjust the light. The system can compose many shapes as it is able to move automatically and individually, accordingly to the weather conditions or occupants preferences. However, research shows that “the micro-perforated non opaque panels of the facade which slide vertically appear to function less as a form of daylight control and serve more as aesthetic element.” When the panels are opened, views to the outside are permitted when the panels are closed, the opaque micro-perforated surface neither provide sufficient solar shading, nor appear to act as a diffuser of light. Automated operation could solve environmental comfort qualities. However as it is a random and subjective process there must be an element of manual override and control.

“It has been observed that at least 30% of the people would leave the shades closed during cloudy days (minimizing useful daylight transmission) and open during clear days (increasing the cooling demand).” Also, there are issues with the maintenance of such a complicated shading system. (http://www.ced.berkeley.edu)
The function of the facade system is to control the entrance of light into the building. The shading system consists of 3,150 stainless steel movable vertical fins into which adaptive horizontal stainless steel louvers are fitted. The vertical fins can rotate 180 degrees, while the horizontal louvers perform as mini light shelves reflecting light into the interior spaces. This is an optimized system which takes advantage of both the adaptive horizontal louvers and the adaptive vertical elements. Both the southern, eastern and the western facade are covered with these stainless steel lamellas. They move accordingly to the angle of the sun reducing the need for artificial lighting and air-conditioning creating a highly sustainable and energy efficient system. This systems also tries to maximized the views for the users. (Grefen, 2010)
A dynamic installation for the Stony Brook Foundation’s new Center for Geometry and Physics has been constructed in the facade.

The sunscreen serves both as an artistic installation and as a functional shading device integrated within its south-facing glass facade. A floor-to-ceiling composition of Tessellate™ panels is installed in order to approach the requirements of the building. Every panel presents a geometric pattern highlighting the scope of research the scientists and mathematicians hosted in the building. As the panels are moved, the visual effect of the screen can be changed from hexagons to circles, squares and triangles. The kinetic surface spans 38 square meters and decorates the building providing shading and opacity. The drawback of this shading is that it doesn’t decrease the heat load of the building. However, the views to the outside are not disturbed that much. Finally, a servo motor triggers the movement of the modules.

Figures 24,25,26_ Shading screen of Simons Center. (http://www.adaptivebuildings.com)
2.2.4.5 Arab World Institute

Diaphragm

| LOCATION | Paris, France |
| LATITUDE | 48°52'N |
| COMPLETION | 1987 |
| DESIGN | Jean Nouvel |
| USE | Institute of Arab culture |
| FACADE MATERIALS | Steel diaphragms |

Redirect daylight      | - |
Solar shading          | - |
Glare control          | ++ |
View to the outside    | - |
Orientations           | S,E,W |

Arab World Institute is one of the first buildings to use sensors on the facade to automated response on the environmental conditions. The south facade is divided into 240 sub grids which consist of photosensitive mechanical devices that act like automated irises to control light. The 30,000 light sensitive diaphragms are fitted on 1600 elements, which reminds lens of the camera. All the mechanical devices are automatic and they are connected to a central computer. Based on the light quality inside the building, the irises open or close incrementally. (Arab World Institute, 1989)

According to several articles there are numerous failures of the facade system due to mechanical complexity and expensive maintenance of the operation of the devices. In addition, the heat load of the sun is not much reduced by the diaphragms. When closed and the views to the outside are obstructed due to the large amount of mechanical objects like pistons and rods.

fig. 27, 28, 29, 30_ Arab World Institute innovative shading, (Arab World Institute, 1989)
2.2.4.6 Phoenix Central Library

Vertical shading

| LOCATION | Phoenix |
| LATITUDE | 33°26’ N |
| COMPLETION | 1995 |
| DESIGN | BruderDWLarchitects Steel |
| USE | Library |
| FACADE MATERIALS | Teflon-coated acrylic fabric |

Phoenix’s latitudes is challenging when it comes to sun-shading devices because of the low sun angles, in the sun-rising and sun-set, which are hard to be controlled. The fact that neither overhangs nor vertical fins fully block the intense sun on building elevations facing east or west has affected the design of the facade. The aim of the library design was to limit solar gains and glare while admitting light and views. The “sails” on north facade protect sky glare and direct solar radiation during the summer months in the morning and evening, whereas the rising and setting sun “hits” the north facade.

(Carmody J. S, 2004)

In the fully glazed north facade external, fixed vertical shadings are installed. The teflon-coated acrylic fabric sails protect from glaring.

The south facade is fitted with adjustable, horizontal louvers that perform as light-shelves.

fig. 31,32,33_ Phoenix Central Library, the sails on north facade help reduce sky glare. (http://www.commercialwindows.org)
Retrolux product is an efficient and innovative horizontal kind of blind/louver system. The device can be operated on the interior or in the cavity between the glass panes. It is controlled manually or by a controlled motor. The geometry on each blind reflects daylight out of the building and redirect it deep into the building interior depending on the rotation of the blinds. Experiences of users of this system present that the blinds performed quite well in comparison with traditional mini blinds. From an aesthetic point of view, Retrolux are much more attractive than standard blinds. The louvers have two different sections: a W-shaped retro-reflective part for protection from the overheating summer sun, and a second part that acts as a light-shelf redirecting the sunlight and improving the interior daylighting.
2.2.4.8 Esplanade – Theatres on the Bay

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Singapore</th>
</tr>
</thead>
<tbody>
<tr>
<td>LATITUDE</td>
<td>1° 22’ N</td>
</tr>
<tr>
<td>COMPLETION</td>
<td>2002</td>
</tr>
<tr>
<td>DESIGN</td>
<td>DP Architects</td>
</tr>
<tr>
<td>USE</td>
<td>Recreational &amp; Civic</td>
</tr>
<tr>
<td>FACADE MATERIALS</td>
<td>Aluminum</td>
</tr>
</tbody>
</table>

Redirect daylight -
Solar shading ++
Glare control +
View to the outside +
Orientations S,W,E

Esplanade theatre consist of two domes. The envelopes are lightweight, with curved frames fitted with triangulated glass. A system of sunshades supported in aluminum frames offers an optimized relation between solar shading and views to the outside. Throughout the day, there is a transformation of shadows while filtering natural light. The whole envelope changes pattern to suit the orientation, offering solar shading and controlling the light of the internal environment of the pavilions.

The 7,139 aluminum shields are not all the same as they are designed regarding the sunpath. The fabrication of all these different “families” of shadings was a difficult process with classic fabrication methods that not help customization.

fig. 39,40,41_ Esplanade Theaters optimised shading system with aluminum triangular shields (http://www.worldtopstop.com)
Another innovative shading system is in the city of justice in Madrid. The system consists of sliding integrating external sliding shades to shape a kinetic façade that is adaptive during the day and the season. Madrid’s City of Justice has been designed by Foster + Partners. The 2-D retractable hexagonal shading unit occupies the central circular atrium, and can extend to occupy the roof, as well, or be hidden-into the structural frames of the roof. The shading system has designed in respect to climatic conditions, however there is little documentation on the energy performance and physical environmental comfort of it so far. Each unit is driven by a servo motor with custom array control.
LITERATURE

Jakubiec A. Reinhart C. (2010), 9th International Radiance Workshop, September 20-21, Harvard design school


Bader S. (2011) “High-performance façades for commercial buildings” University of Texas, school of architecture


Murray Ian (12 October 2007). “Glare (C7654)”


URLS

http://www.ced.berkeley.edu/courses/fa10/arch244/?p=2420
http://www.retro solar.de/v_englisch.html
http://www.worldtop top.com/esplanade/
http://diva4rhino.com/
http://www.ced.berkeley.edu/courses/fa10/arch244/?p=2420
3. STATE OF ART

ADDITIVE MANUFACTURE
3.1 DEFINITION OF ADDITIVE MANUFACTURE

The basic principle of AM is that a model is generated using a three-dimensional Computer Aided Design (3D CAD) software and can be fabricated directly without the need for process planning. Therefore, AM fabrication process obviously simplifies the process of producing complex geometries directly from 3D models. Unlike common manufacturing methods which need tooling and processes to be finished, AM needs only a 3D file and an understanding as to how the process works and the materials need to be used.

The term Additive manufacturing comes from the fact that parts are constructed by adding material in layers differently from formative-the process of forming the product using moulds- and subtractive-the process of forming the product by removing material machining technology that removes, or subtracts material from a block of raw material.

This innovative AM on design and manufacturing has changed the entire product development process. (I.Gibson, 2009)

To differentiate, the process is called Additive Manufacturing if the product is put to direct end use, Rapid prototyping if the product is used for conceptualization, testing, analysis but not as an end product.

3.1.1 The main Procedure

Step 1: CAD
First of all, the object has to be defined digitally. There are several CAD solid modeling software that describe the geometry of the printed object. Alternatively engineering equipment - laser scanning can also be used.

Step 2: STL file
Printer software recognizes STL file format. This file is used for calculation of the slices of the object to be printed and it describes the meshes of the closed surfaces of the 3D model.

Step 3: Transfer to AM Machine
The file must be transferred to the 3D printer where maybe some additional manipulation of the file have to be done in order to be in the correct scale, position in the machine (eg: when structural parts has to be printed, the way that the printer travels to fill the object affects the structural performance), etc.

Step 4: Machine Setup
The settings of the machine have to be properly defined for the building process. That settings depend on the material, the geometry and the printer itself. They are related with layer thickness, timings, temperature, speed, etc.

Step 5: Build
The building process is an automated process and a professional machine can work without supervision. However, some times errors may occur.

Fig.45_ Generic process of CAD to part, showing all 8 stages, (Setaki F. 2012)
Step 6: Removal
When the building process is completed, the part must be removed. Extruder and bed temperature are closed automatically and when the bed is cool, the object can safely be removed.

Step 7: Post-processing
The printed object may require post processing regarding its application, like painting, polishing to give an acceptable surface texture and finish. etc. Also, if supported materials had been added, they will have to be removed.

Step 8: Application
Parts may now be ready to be used. When it comes to large items, parts have to be assembled in order to form the final object.

3.1.2 AM advantages & restrictions

AM ADVANTAGES (+)
- Design freedom
- Easy to create unique objects
- No transferred cost: transferred digitally, printed locally
- Better control over material
- Reduction in progress steps
- Reduction of tools and assembling
- Improvements in product performance
- Potential green (no waste material, recycle)
- Share & exchange files globally
- New opportunities for customization

RESTRICTIONS (-)
- Material variety and properties
- Accuracy
- Size of component
- Economic constrains
- Mechanical performance

One of the main benefits that this project takes advantage of is the opportunity for customization proposing a product and testing the engineering issues through a specific case study.
Material groups: plastic, metals, gypsum, other materials.
SLA stereolithography is the first AM method many others are based on the same principle, building the object layer by layer.
**Plastics:** Core technologies are Stereolithography (SLA), Laser Sintering (LS), Fused Deposition Modeling (FDM), 3D Printing (3DP), (InkJet).
**Metals:** process that use metals as row material were developed following the influence of SLA and were built-up by welding, which is a known and proven technology in machining and engineering.

### 3.1.3 AM Processes

**Binding process:** Using a print-head to bind a per-spread layer of the material, each time tracing and binding the section of the object. An entire layer of material is deposited each cycle, so the printed object is supported by unused material, avoiding the requirement for extra generated support structures. (C. Warnier at all 2014)
**Deposition process:** In this process, material is extruded through a nozzle in the printing head, which deposits the material in a line pattern, layer by layer, on a platform that goes lower, while the object is built. The difference between the two families of processes is that the model is not ingrained in the material but stands freely on the print-bed. Additional support structures for overhanging geometries must be created (C. Warnier et al. 2014).

### 3.1.3.1 AM for plastics

#### Stereolithography (SLA)

This process is the “mother” of rapid prototyping processes. Each layer is fabricated by scanning a laser beam, guided by a moving mirror, to cure selected parts of a thin film of a liquid photo-sensitive resin. When one layer is complete, the part is lowered on a platform into the resin bath (typically by 0.1 mm) and then a new layer of liquid resin can be wiped across the surface. Post-curing is needed to completely solidify the prototype (C. Warnier et al. 2014).

The software used generates automatically support material to print overhangs, undercuts and filigree model parts, which can be removed mechanically after printing. The object surface can be improved with new resin, after heating it to 30°-40° Celsius, which decreases its thickness. Post-processes as polishing, blasting, or coating can be used in order to improve the surfaces of the object. SLA process is a quite accurate method as the layer resolution lies between 0.05 and 0.15 mm.

However, when it comes to applications of the printed object to external conditions, issues regarding resistance to ultraviolet rays and humidity must be solved (Strauß H. 2013).

<table>
<thead>
<tr>
<th>Process</th>
<th>SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>Photopolymers (Epoxy resins, acrylic resins)-transparent or translucent, opaque (black, grey, white), rubber-like materials.</td>
</tr>
<tr>
<td><strong>Layer resolution</strong></td>
<td>0.05-0.15mm (highly detailed smooth part at reasonable speed)</td>
</tr>
<tr>
<td><strong>Building chamber (mm)</strong></td>
<td>2100<em>700</em>800(materialise/Mammoth)</td>
</tr>
<tr>
<td><strong>Manufacturer</strong></td>
<td><a href="http://www.3dsystems.com">http://www.3dsystems.com</a>, <a href="http://www.materialise.com/">http://www.materialise.com/</a></td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>UV radiation sensibility, detailed smooth parts at a reasonable speed, mostly for prototypes.</td>
</tr>
</tbody>
</table>

Table 3: Stereolithography

#### [Selective] Laser Sintering (SLS)

is quite similar to stereolithography, but in this process the powder source material is sintered or melted by a laser that selectively scans the surface of a powder bed to and through a heating process create a two-dimensional solid shape (Hopkinson N., Hague, 2006). Similarly to stereolithography, the layer thickness is approximately 100μm. Here the supporting material is the un-fused powder, so we can avoid the removal of support material after printing. This technique is applicable for polymers, metals and ceramics. However, SLS machines are larger than other rapid prototyping tools which can fit anywhere (Schodek D., Bechthold M., Griggs K., Kao K.M., Steinberg M., 2005).

SLS can reach a wall thicknesses of 0.8 mm, while the layer thickness of the powder bed is usually around 0.1 mm (Strauß H. 2013).
### Fused Modeling Deposition (FDM)

FDM was first started by Stratasys in 1992. It builds parts by extruding material (usually a thermoplastic, wax or nylon material) through a nozzle (head) capable of moving along X and Y axes [HopkinsonN., Hague R.J.M., Dickens P.M., 2006]. There are two different nozzles: one that deposits the material for the building part and another that deposits supporting material. Support material is deposited simultaneously with the built one, so the object that has to be post-processed before its application. A common material that is used in FDM is ABS to build the object and PLA, as support material. Other thermoplastic materials can also be used. Many experiments have been carried out recently for different kind of materials like PET.

FDM technology creates strongly anisotropic parts thanks the anisotropic structure of the material distribution. The material properties and the potential for small wall thickness are better in X-Y axis, than in Z where the fusion of the individual layers define the properties of the object. FDM models can be finished by various post-process methods. [Strauß H. 2013]

Although it is a slow process, it is popular among hobbyists and it is used by the majority of home 3D printers, due to its simplicity and the low-cost both of the printers and the materials used.

<table>
<thead>
<tr>
<th>Process</th>
<th>FDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Plastics: ABS, Nylon, PLA, polycarbonate</td>
</tr>
<tr>
<td>Layer resolution</td>
<td>0.127-0.330mm (limitations related to accuracy and surface finishing)</td>
</tr>
<tr>
<td>max Building chamber (mm)</td>
<td>914x610x910 (Stratasys/ Fortus 900mc)</td>
</tr>
<tr>
<td>Comments</td>
<td>Mechanical strength, easy to set-up, preferable for individual users and consumer applications (fabbing)</td>
</tr>
</tbody>
</table>

Table 5_Fused Modeling Deposition

### 3D printing (3Dp)

The objects can be printed with gypsum, starch, ceramic powder and sand. The process is working with a binder that combines the powder with the ink to a solid mass and glues it to the underlying layer.

The work platform is lowered after every layer printing. In order to construct the object layer by layer, a roll or a slider produces a new layer of powder. The layer resolution of 3d printing process lies between 0.09 and 0.1 mm.
In this process, the unprinted powder acts as supporting material and then it returns to the system to be used again. After the printing process the unused powder is removed, and if it is necessary epoxy resin or instant adhesive can be added to the surface of the model. There are several ways to finish the surface of 3DP models, like sanding, filling, varnishing, polishing or galvanizing. [Strauß H. 2013]

<table>
<thead>
<tr>
<th>Process</th>
<th>3Dp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>starch, gypsum, casting sand, PMMA</td>
</tr>
<tr>
<td>Layer resolution</td>
<td>0.08-0.15mm</td>
</tr>
<tr>
<td>max Building chamber (mm)</td>
<td>4000 x 2000 x 1000 for casting sand,PMMA (Voxeljet/VX4000)</td>
</tr>
<tr>
<td>Comments</td>
<td>Similar to SLS, less durable process than SLA and SLS</td>
</tr>
</tbody>
</table>

Table 6_3D printing

**Polyjet printing**

Polyjet printing uses a series of printing nozzles instead of one print-head or a specific light source and mirror device. The print-head consists of numerous nozzles placed across the width of the platform. The material is placed by drops onto the work platform and the layers of the printing object are created by a light source. As in some previous processes, the height of the model is constructed by lowering the work platform. After one layer is complete, the deposited material is cured with ultraviolet light directly and further, a roll smooths the layer surfaces, and the next layer is constructed on the top of the last one. An acrylic photopolymer is used as building material while the support material-a gel like material that is removed by water- is produced out of a secondary series of nozzles. Polyjet method can reach a layer thickness of about 0.016 – 0.030 mm and guarantees a very precise and smooth surface, avoiding the necessity of post-process after printing. Since the material is deposited in individual particles, the final resolution is very high. [Strauß H. 2013]

<table>
<thead>
<tr>
<th>Process</th>
<th>Polyjet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Plastics: Light-curing, viscous plastics, acrylate, photo-polymer</td>
</tr>
<tr>
<td>Layer resolution</td>
<td>0.016-0.03mm</td>
</tr>
<tr>
<td>max Building chamber (mm)</td>
<td>550x393x300 (3ds systems/ ProJet5000)</td>
</tr>
<tr>
<td>Manufacturer</td>
<td><a href="http://de.objet.info">http://de.objet.info</a> <a href="http://www.3dsystems.com">http://www.3dsystems.com</a></td>
</tr>
<tr>
<td>Comments</td>
<td>Very precise</td>
</tr>
</tbody>
</table>

Table 7_Polyjet printing

Regarding the above, appropriate processes in terms of strength, material variation and availability to the market for plastics are: SLS, FDM, Polyjet.

In general, 3D printers cost from $10,000 to $50,000 and they have typical build chamber of 10 x 10 x 10 in. The materials used are plastics such as ABS, acrylate, photopolymer, polyamide (nylon), epoxy, polycarbonate and PMMA (acrylic glass). In theory, other materials provided as filaments or powder can be, also, used experimentally.

On the other hand, industrial machines cost starts from $50,000 and can reach the amount of $500,000 for the higher-end SLS systems. They have a build capacity of 1 x 1 x 1 ft and the materials used have “premium-grade mechanical and thermal properties” regarding their application. Some of the materials are highly engineered thermoplastics like PEEK and PEI, reinforced materials with glass fiber and currently carbon fiber.
Generally, plastics for AM have several issues regarding resistance against humidity, ultraviolet light and heat. The performance of them, regardless the material, depends on the orientation of the part in the process chamber. [Strauß H. 2013]

### 3.1.3.2 AM for metals

**Direct Metal Fabrication (DMF)**

This is the fabrication method of metal parts. Metal fabrication consists of two principles: ‘powder feed process’ and ‘powder bed process’. Metal powder is used in both fabrication families, while different material mixes and alloys are involved. Generally, metal parts are produced applied heat that melts them. The energy comes from laser or electron beams. During the **powder feed process method** (Fused Metal Deposition), metal powder is blown into a melting bath which is generates on the surface of the object, caused by a laser or an electron beam. Powder bed process produces poor quality surface, as the thickness of the layers exceeds 10mm. [Strauß H. 2013]

**Laser Engineered Net Shaping**

Laser Engineered Net Shaping (LENS) is one of the first technologies of DMF and has been an inspiration for many other methods. A central nozzle is used for the energy source and material nozzles are located around it in a radial alignment. The head can be positioned to different bases and, also, to a robot arm. The material builds the part in the melting bath which rotates in front of the nozzle. The layer resolution is about 0.500 mm. The method is used for tool making, repairs, and and for the direct production of free geometries.

<table>
<thead>
<tr>
<th>Process</th>
<th>LENS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>All kind of metal powders, metal alloys/ titanium, stainless steel, aluminum, and other materials, as composites</td>
</tr>
<tr>
<td>Layer resolution</td>
<td>0.5mm</td>
</tr>
<tr>
<td>max Building chamber (mm)</td>
<td>170x220x145mm (possibilities to be extended with metal arm)</td>
</tr>
<tr>
<td>Manufacturer</td>
<td><a href="http://www.sandia.gov">http://www.sandia.gov</a></td>
</tr>
<tr>
<td>Comments</td>
<td>mainly used for repairs</td>
</tr>
</tbody>
</table>

Table 8_Laser Engineered Net Shaping

**Direct Metal Deposition (DMD™)**

or Laser Metal Deposition (LMD) deposits metal onto existing tools and components in layers, with a layer resolution ranging from 0.1 to 1.8 mm. The source material, pure metal powder that can reach material density of 100%, is sprayed into the CO2 laser melting bath in molecule form. The print-head is supported by a five-axial CNC robot, so that the metal layers can be accumulated three dimensionally. The initial use of DMD™ was to repair industrial tools and to refine tool surface finishes. Optimization of the tool properties regarding resistance and extended lifetime can be achieved by combination of materials ceramic or non-metallic materials with metal powder.
Powder bed process

Powder bed processes are coming from the SLS method. The difference with laser sintering of plastic powder is that during the metal sintering heat is transferred into a base through the model contours and support structures. (Strauß H. 2013)

Selective Laser Melting (SLM)

Selective Laser Melting (SLM) uses reactive metal powders such as aluminum and titanium since, during the development, inert gas is used to create a protective atmosphere in the process chamber. The layer thickness resolution ranges between 0.20 and 0.10 mm. Developers of SLM have significant experience with aluminium powder. This is a very promising process for 3d printed objects from metals.

Direct Metal Laser Sintering

Direct Metal Laser Sintering (DMLS) is an evolution of SLS process. In DMLS process, metal powder, instead of plastic, is sintered in the process chamber. DMLS method was initially developed for Rapid Tooling (RT), and to produce components for tools or machines or end use products. The printed objects need to be reworked with milling, turning, sanding, blasting in order to improve the quality of the surface.

The layer thickness resolution lies at 0.20 mm. Although it uses similar principles with SLS for plastics DMLS is slightly more complicated. Electronic Beam Melting (EBM) is a method that imitates the LS process too and it includes an electron beam instead of a laser.

### Table 9: Direct Metal Deposition

<table>
<thead>
<tr>
<th>Process</th>
<th>DMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>All kind of metal powders, metal alloys</td>
</tr>
<tr>
<td>Layer resolution</td>
<td>0.1-1.8mm</td>
</tr>
<tr>
<td>max Building chamber (mm)</td>
<td>673x749x474mm (3D axis)/ 3.2m x 3.665m x 360˚ (robot arm) POM Group</td>
</tr>
<tr>
<td>Manufacturer</td>
<td><a href="http://www.pomgroup.com/">http://www.pomgroup.com/</a></td>
</tr>
<tr>
<td>Comments</td>
<td>surfaces need further finishing with conventional methods/ material density 100%</td>
</tr>
</tbody>
</table>

### Table 9: Selective Laser Melting

<table>
<thead>
<tr>
<th>Process</th>
<th>SLM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Metal: all kinds of metal powders; metals alloys, also aluminum + titanium</td>
</tr>
<tr>
<td>Layer resolution</td>
<td>0.1-0.2mm</td>
</tr>
<tr>
<td>max Building chamber (mm)</td>
<td>250x250x215mm (SLM Solutions/GmbH Renishaw/ Realizer GmbH)</td>
</tr>
<tr>
<td>Comments</td>
<td>No requirements in terms of material powder to be used/end use parts for aerospace, automotive.</td>
</tr>
</tbody>
</table>
### Laser Cusing

is a powder bed process that uses different metal powders, such as aluminum, titanium, stainless steel and other alloys to produce AM objects. The powder is pure and is melted by energy produced by laser. The unused amount of powder can be used for the next parts without affecting the surface quality. The layer thickness resolution ranges between 0.20 and 0.50 mm.

LaserCusing allows a hybrid fabrication of CNC milled and AM printed parts.

<table>
<thead>
<tr>
<th>Process</th>
<th>Material</th>
<th>Layer resolution</th>
<th>max Building chamber (mm)</th>
<th>Manufacturer</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metal: all kinds of metal powders; metals alloys</td>
<td>0.1-0.2mm</td>
<td>250x250x215mm (EOS)</td>
<td><a href="http://www.eos.info">http://www.eos.info</a></td>
<td></td>
</tr>
</tbody>
</table>

### Contour Crafting

Contour Crafting (CC) produces large structures made of fibre reinforced high performance concrete. The process is based on the FDM method and it was invented by the University of Southern California by Behrokh Khoshnevis. The building material is printed in layers through a nozzle, while the surfaces are smoothed with a trowel. This is accomplished with a print-head that is mounted onto crane rails. Therefore, the system dimensions can easily extend beyond 6000 x 6000 x 6000 mm. Resolution depends on the nozzle used and it lies at several centimeters.

### D-Shape

D-Shape is a process based on 3DP and Inkjet methods scaling. An inorganic binder is used to combine sand and stone powder of all sorts. Large scale process chambers are achieved by using light-weight scaffolding which exceeds the limitations of the geometric restrictions. The dimensions of the building chamber can reach dimensions of 6000 x 6000 x 6000 mm. The process was conceived to create life-size sculptures and buildings, and is called ‘mega scale free-form printer of buildings’. It prints stone powder, marble powder and sand.
After the literature review of AM process, a table which ranks the methods regarding some requirements for the sunshading device follows. The processes are evaluated for each of the below criteria: material variety and properties, accuracy of the final surface (layer resolution), cost of the material used, accessibility of the user to the process, feasibility of the concept and mechanical strength of the final object that the method offers. The evaluation scale fluctuate from 5 which is the highest rate to 1 which is the lowest rate for each criterion.

**EVALUATION OF PROCESSES TABLE**

<table>
<thead>
<tr>
<th>AM PROCESS</th>
<th>Material variety/pr</th>
<th>Accuracy</th>
<th>Cost (related to material)</th>
<th>Accessibility to the user</th>
<th>Feasibility</th>
<th>Strength</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLA</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>SLS</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>26</td>
</tr>
<tr>
<td>FDM</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>26</td>
</tr>
<tr>
<td>3DPRINTING</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>POLYJET</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>19</td>
</tr>
<tr>
<td>LENS</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>DMD</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>SLM</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>DMLS</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Laser Cusing</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>CC</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>D-Shape</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

- Binding process
- Deposition process
- Powder bed process
- Powder feed process

Table 12_Evaluation of processes table

As we can see from the results, FDM and SLS are the two most suitable techniques regarding the requirements of the product that will be described. Both processes produce high quality and durable objects. However, in the frame of this thesis FDM process with either leapfrog or ultimaker machine will be used for the first tests and the final mock-up, as the “Technisch Ontwerp en Informatica” of Architecture department of TU Delft can provide the equipment for this technique.
3.1.2 AM Materials

FDM process uses polymers. The most common material used is ABS, or alternatives to ABS like the above blended with polycarbonate. Another very common material is PLA, Polyactic acid, a biodegradable thermoplastic aliphatic polyester which is commonly used by many 3D printers and individuals having a 3d printer at home. The properties of the printed materials are not that different of the original ones, however, the fact that this is a method of layering melting plastic on the top of each layer may cause printed objects to have lower strength than the presented on the company data sheets. Other materials used by FDM are ULTEM 9085, developed for applications like aircraft marine, etc. Other options for high engineering materials are PPSF/PPSU (polyphenylsulfone), offering high heat resistance, good mechanical strength and resistance to petroleum and solvents and PEEK (Polyether Ether Ketone), a high-performance polymer thermoplastic with very good mechanical properties and resistance to chemicals. PEEK is used on medical implants, aerospace, and motorsports applications. These materials require specialization and proper equipment, so they cannot be used by common users.

Recently, other filaments have become available in the market, like Nylon 12(stratasys), Nylon 680 and Nylon 910 (Taulman), PET and ASA (stratasys), with very good performance to UV radiation.

<table>
<thead>
<tr>
<th>Material</th>
<th>End Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSplus</td>
<td></td>
</tr>
<tr>
<td>Nylon 12</td>
<td>aerospace parts</td>
</tr>
<tr>
<td>Asa</td>
<td></td>
</tr>
<tr>
<td>ULTEM 9085</td>
<td></td>
</tr>
<tr>
<td>PPSF/PPSU</td>
<td></td>
</tr>
</tbody>
</table>

Fig.39 Table with mechanical properties of FDM materials (www.stratasys.com)

Fig.48 Images of the above FDM materials. (www.stratasys.com)
Generally, each material that can be formed as a filament changes to liquid under high temperature and solidifies again, which makes it suitable for this fabrication method.

On the other hand, SLS process uses powder as raw material. Common material for SLS is nylon. There are several types of nylon available for prototypes and modifiednyons for product materials. For example NYLON 12 PA and NYLON 12 AF, Aluminum-filled Nylon 12, with metallic appearance are SLS prototype materials, regarding Solid concepts from Stratasys.

Other modified nylons for products are NYTEK 1200 PA, based on Nylon 12 with good chemical resistance, NYTEK 1200 GF, Glass-filled Nylon 12 with excellent stiffness, NYTEK™ 1200 CF, Carbon-filled Nylon 12 with resistance to extreme temperatures, NYTEK™ 1200 FR (fire retardant), FR-106, fire retardant Nylon 11 with high mechanical strength, etc. (https://www.solidconcepts.com)

Additionally, SLS method, as we have seen above, use several metals and alloys, like stainless steel, nickel, aluminum, bronze, even gold and silver etc, obviously with higher costs than polymers.

Finally, there is the potential of using multiply materials to one part. The consequence of applied multiply materials to building object are: a) Improving the mechanical properties of the resulting parts, b) Providing additional functionality in the resulting part, color, flexibility, etc and c) Improving the performance of the AM process (eg: permits movement between parts after second material removal).

### SLS Prototype Materials

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
<th>Elongation at Break</th>
<th>Flexural Strength</th>
<th>Flexural Modulus</th>
<th>Density</th>
<th>Heat Deflection Temp. @ 66 psi</th>
<th>Heat Deflection Temp. @ 264 psi</th>
<th>Izod Impact Strength</th>
<th>Tensile Modulus</th>
<th>Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>NYLON 12 PA Datasheet</td>
<td>Standard Nylon 12 material with good chemical resistance</td>
<td>15% 4%</td>
<td>6,850 psi (47 MPa)</td>
<td>188,549 psi (1,300 MPa)</td>
<td>0.034 lb/in³ (0.95 g/cm³)</td>
<td>395°F (177°C)</td>
<td>187°F (88°C)</td>
<td>4.12 ft-lb/in (220 J/m)</td>
<td>6,24 ft-lb/in (440 J/m)</td>
<td>246,500 psi (1,700 MPa)</td>
</tr>
<tr>
<td>NYLON 12 AF Datasheet</td>
<td>Aluminum-filled Nylon 12; superior surface with metallic appearance</td>
<td>3.5% 2%</td>
<td>9,860 psi (68 MPa)</td>
<td>435,113 psi (3,000 MPa)</td>
<td>0.049 lb/in³ (1.36 g/cm³)</td>
<td>351°F (177°C)</td>
<td>291°F (144°C)</td>
<td>—</td>
<td>—</td>
<td>551,143 psi (3,800 MPa)</td>
</tr>
<tr>
<td>NYLON 12 GF Datasheet</td>
<td>Glass-filled Nylon 12; excellent stiffness &amp; dimensionally stable</td>
<td>1.5 – 3% 9,700 psi (67 MPa)</td>
<td>368,000 psi (2,537 MPa)</td>
<td>0.056 lb/in³ (1.25 g/cm³)</td>
<td>354°F (179°C)</td>
<td>273°F (134°C)</td>
<td>0.8 ft-lb/in (40 J/m)</td>
<td>2.3 ft-lb/in (120 J/m)</td>
<td>534,464 psi (3,685 MPa)</td>
<td>5,521 psi (36 MPa)</td>
</tr>
</tbody>
</table>

**Fig. 49.** Table illustrated mechanical and thermal properties of advanced SLS materials (https://www.solidconcepts.com)
3.2 AM AND PRODUCT DESIGN

“Direct digital manufacturing (DDM) is the usage of additive manufacturing technologies for production or manufacturing of end-use components.” (I. Gibson, 2009)

3.2.1 Applications

Nowadays, several examples of customized products fabricated by AM exist to the market. For example, customized sport shoes designed to fit to the specific properties of an individual foot, offering an optimal solution for the client. Another successful example of end use products of AM, are prosthesis which are used in the medical field for the human body in medical sector. Similarly, in dental field, artificial teeth or aligners are designed and printed to exactly fit the patient’s mouth. As mentioned above, the same can be applied to the hearing industry. For hearing-aid apparatus, AM can produce an exact fit for each individual ear.

In the filed of design, artists create customized furnitures, shoes, accessories etc.

3.2.2 Democratizing the fabrication process

“We are now in the minicomputer era of digital fabrication.” (Gershenfeld in TED talk 2007)

“Millions of dollars of equipment at MIT are like the mainframe of digital fabrication. We can make anything we want using those tools. In twenty years we’ll make it so you can have it in the home.” (Gershenfeld in Principal Voices 2007) Neil Gershenfeld offers a class at MIT, called “How to make something that makes almost anything”. It is an open-source tool aiming to create better digital fabrication devices.

“The Internet democratized publishing, broadcasting, and communications, and the consequence was a massive increase in the range of both participation and participants in everything digital — the long tail of bits. Now the same is happening to manufacturing — the long tail of things.” (Anderson 2010)

There are several ways to democratize the opportunity of creation.
- One of them is to make the digital fabrication tools affordable enough for users to be able to acquire them.
- Another way is sharing the tools in order for each person to have easy accessibility to them. This is the idea of fablabs. “ A fablab (fabrication laboratory) is a small-scale workshop offering (personal) digital fabrication” (Troxler, P. 2011).
- Another way of sharing tools is through companies whose machines are used by expert
who offer the service. So, even if users do not have the knowledge or the equipment to fabricate their goods, they can upload their file to the web and after a few days the product will be shipped at their place. Companies like the described above are Shapeways, Imaterialise, Ponoko, etc.

- Finally, the power of sharing and co-creating is another way to fabricate a product. A nice example is the “project Egg” which is a result of 3D printing, creation and collaboration, created from Michiel van der Kley, a Dutch designer. In this project, owners of 3d printers from the four corners of the world fabricated and shipped to him each stone from the 4760 stones form the whole “egg”.

3.3.3 A new approach in product design

Regarding I. Gibson: “Conceptualization means the forming and relating of ideas, including the formation of digital versions of these ideas (e.g., CAD), creation means bringing an idea into physical existence (e.g., by manufacturing a component) and propagation means multiplying by reproduction through digital means (e.g., through digital social networks) or through physical means (e.g., by distributed AM production”).

“Distributed conceptualization, creation, and propagation” has the potential to set aside “concentrated development, production, and distribution” through the solution of AM combined with digital interfaces, offering common individuals the opportunity to create-modify-fabricate objects.

The second generation of Internet, Web 2.0, enables individuals to interact with and change web content. On the other hand, sell-off websites such as eBay and Amazon have changed the traditional selling process of goods, allowing consumers of “web content” to become “content creators”. (I. Gibson, 2010)

Since AM permits digital designs to become into physical products at any location in the world (i.e., “design anywhere, build anywhere”) and web 2.0 is able to propagate product ideas and designs fabricated through AM, it is obvious that the combination of the above -Web 2.0 with AM- can start a new approach of product design and new models of entrepreneurship.

From the engineering point of view AM processes, are becoming more accurate, new advanced materials have been developed and more AM products are being introduced to the market. From a business-strategy point of view, AM will grow into a faster, cheaper, safer, and sustainable technology. All the above leads to physical goods fabricated from AM which will definitely be able to compete with conventional.

3.3.4 Degree of freedom in Mass Customization (MC)

“Mass customization involves consumers in the design process by giving them the opportunity to personalize a product through the use of a toolkit”. (Hermans, 2012)

A well-known mass customization toolkit is NikeID (Nike 2012) which enables individuals to personalize a pair of shoes. When visiting the website one can choose a shoe according to the gender and sport-collection and then for each shoe one can select the color and the material. In this case the “toolkit” is a website and the “solution space” is a pair of shoes that fits the user needs. The designer formulates the boundaries of the solution space by defining which parts of the product can be designed from the customer and which of them are decided. (Hermans, 2012).

MC is related with the need of interaction between customer and manufacturer. In this phase “MC toolkits” aid this communication and expedite the customer to design/modify their own products themselves (Hermans 2011). This is possible through software based tools and interfaces provided by the manufacturer. Customers have poor experience on customization through online interfaces. A
user friendly structure of a “toolkit” could motivate individuals to buy more customized products, even with higher prices or more waiting time of shipping the product to them, in comparison with turnkey industrial products (Huffmann and Kahn 1998).

One of the aspects that affect user motivation to buy a brand is the “Degrees of freedom of customization”. Designing a product or a space is infinite. When it comes to MC, designing a product is limited to finite and constrained one, the “Solution Space” (Hermans 2012). The task of “Solution Space” of MC toolkits is to combine the customer autonomy with some predefined options designed by the designer in order to regulate the image of the product, the manufacturability, satisfaction etc. Thus, there is an equilibrium between customer freedom and designers control (constraints of designer). Customer freedom is defined by the number of options and the variety of these options (navigation sections). For instance, if there are six options to be manipulated, the solution space has six degrees of freedom. For each specific product, there should be an optimum number for the degree of freedom, because of the impact of autonomy, limitations, freedom and variety to the user options.

If customers have too few choices, so low impact to the final product, they are not satisfied with their brand because they need more choices for their shopping. On the other hand, a large amount of options could disorient and confuse users making them postpone decisions due to the effort needed to choose the best option. (Schwartz, 2009)


http://i.materialise.com/
http://www.shapeways.com/
https://www.3dhubs.com/3dprint
http://www.3dsystems.com/
http://www.stratasys.com/
http://3dprint.com/52713/indmatec-peek-fdm-printing-filament/
https://www.solidconcepts.com
4. Towards a Customised Shading
4.1 THE CONCEPT

The aim of this project is to introduce a product design with the benefits of Additive manufacturing, as fabrication process. The general concept of this project is to take advantage of the revolution that digital fabrication brings and combine it with the building sector through the proposal of a customized 3d printed sunshade which fits to every user preferences with different requirements, for different seasons (the user may change the shading three times per year, designing it for the crucial dates: summer solstice: 21st June, winter solstice: 21st December and equinoxes: 20th March and 22th September) and climate context.

The communication of the product with the user would be through an interface where the individual will be able to a) choose a design and modify it according to his needs, b) visualize the shading performance inside the room and then c) fabricate it with Additive manufacturing process:
- either with his personal 3d-printer
- or to a fablab of his region
- or using a service, available from the interface, consisting of fabricating the product and shipping it at his place.

As mentioned in the previous chapter, web 2.0 and toolkits specifically, are the new ways to propagate a product to the potential customers. Thus, exactly this way is used to communicate the specific product with the client. A website (toolkit) is proposed that allows the user to navigate within the site, choose the pattern that he prefers, or design his own, and try different alternatives of the chosen style, changing the given parameters (degree of freedom) till reach the result (solution space) that it satisfies him.

The production cycle of the sunshading device includes the design, the fabrication and the application of it to the window frame (the use) and then the recycling of the whole device. We can imagine each one of these four categories like a big “family” that include other subcategories, which are necessary for the process to work successfully.

Fig. 54. Proposal for the life of the sunshade suggesting to 3d printed it three times per year, in the winter, in the spring-autumn and in the summer.
The process of the proposed product design includes four main parts:
- the design of the sunshade
- the fabrication
- the application of it (the use)
- the recycling of the whole device.

Each one of these parts includes some phases, which are necessary for the process to successfully work.

More specifically, there is an interface with an online library (input) of several designs for sunshading devices. All the patterns are designed parametrically in order to adapt to both different climate - location context (variables: orientation, location, date) and user requirement (variables: room-window dimensions, specification of views, kind of protection)

During the design process, which is the first service that the interface offers, the user can either i) choose the design pattern available in the library, that he prefers or ii) design his own pattern if he wants to. Once he chooses the pattern he has to define the orientation of the window that the device will be applied in order to be appeared the right file with the projections of the sunshade that obey to the rule of thumb for horizontal shading in the south and vertical shading in the east/west orientations. After the completion of the pattern with the correct projections some other requirements have to be, also, fulfilled. The last includes: the definition of the sun path, so information regarding the sun latitude, the month and the hour that the shading will be applied should be provided. Further, the dimensions of the window have to be defined and also the density of the pattern. In this step, the user can ask for the second optional service offered. That is the performance analysis of the shading device through which he can get an extra design that will be more tailored to his case. Otherwise, he can continue with the one that he has already created.

Now, the chosen object is ready for fabrication. So, the user can choose among several ways of fabrication process. The first way is just to i) buy the design-file and fabricate it with his personal 3d printer. Another way is ii) to fabricate it in a fablab where the equipment is shared, as it is mentioned above. An alternative way is iii) ask the experts to also fabricate the object and then ship it to his door, ready to be assembled and supplicated.

The logical framework of the interface is explained in the next paragraph, describing the steps that the user has to follow in order to make his order. After that, the technological concept follows explaining more in detail the different steps and how all these are translated into the design and the fabrication process.
Fig. 55_ The logic framework of the interface
4.1.1 User’s scenario

First step:
Visit the website:
//Designyourshutter.com

Second step:
The user can either Choose one of the already existing designs-patterns in the on-line library, or design his own pattern.

Third step:
Now he has to define the orientation of the window in order to open the correct file based on the chosen pattern. The shading devices are designed in order to have horizontal or vertical projections for the south and the west/east orientation respectively.
Fourth step:
Climate-location variables: Filling in the sun latitude(location) and the season for which he needs his item.
User preferences related variables: Filling in the room and window frame dimensions. Then he has to choose the amount of density of the pattern and the dimensions of the projections regarding the sun incidence as it appears at his screen. Additionally, he can define if he prefers any specific height views to the outside.

Fifth step:
The user has to wait a few minutes to see the render of his device and its shade inside the room. He can still change the above variables to improve his final object.

Sixth step:
Once the design is complete, he can choose if he needs to make a performance analysis of the device in order to make it more efficient.
Seventh step:
Then he has to choose his preferable process and material taking into account the accuracy, the strength and the price he wants.

<table>
<thead>
<tr>
<th>Material</th>
<th>Accuracy</th>
<th>Cost</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLS</td>
<td>*****</td>
<td>*****</td>
<td>*****</td>
</tr>
<tr>
<td>NYLON 2200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NYLON 945</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDM</td>
<td>****</td>
<td>*****</td>
<td></td>
</tr>
<tr>
<td>ASA</td>
<td>**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PET</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Eighth step:
Finally, the user completes his order by filing in his personal details. When the order is fulfilled, it will take few weeks for the item to be delivered at his place. Once he receives the package, he can easily assemble the shading and apply it to the window frame regarding the included manual.
4.2 Technological Concept

The technological concept includes, first of all, the parametric designs that are available on the library. They consist of, the boundary conditions which are the grids and modules which form the sunshade, which can be chosen by the user from the very beginning of the process, and the variables of the designs, which refer to climate and location aspects on one hand and user’s preferences and requirements on the other hand. In this phase, the form phase, the user can also observe the shade inside the room with a provided false color image that is included in the scripts. However, he can always order a more detailed performance analysis in order to ask for a more efficient device.

The fabrication process affects many crucial aspects as the price of the object, the durability of the device and the accuracy of the final surface (depending on which of the above fabrication alternatives he will choose- AM process and material).

According to the literature review of the AM methods, what is observed is the restrictions of the dimensions of the building object. Depending on the dimensions of the window frame, the object will be printed as a whole item or in smaller parts that will have to be assembled together afterwards. Generally, when it comes to a “homemade” object (printed at home, DIY) the building chamber of the common printers is limited, so assembling of the modules is necessary. On the other hand, industries offer big machines with big building chambers as well. Besides, 3d-printers constructed by user - hobbyists try to extend the building chamber dimensions, in which case assembling is not necessary. However, the object will be much more expensive.

After the assembling of the object, the user can directly apply it to his window frame with another simple assembling process, which is described in the next chapter. The endurance of the device will depend on the user’s preferences and also on the properties of the material used. Changing the sunshade in accordance with different seasons (sun altitude) would be a reasonable recommendation to follow.

The object has to be assembled in a way that no different materials are included (nuts and bolts, adhesives) in order to be possible to be recycled. After that, the recycled material can be converted into new filament or powder (depending on the process) if we expect it to be recyclable in the future.

The subcategories involved in the big families of form, fabrication and application to the window frame, forming the technological concept are fully described on the next pages.
Fig. 57_ Diagram of technological concept and associations among the different phases, from design to production.

TOWARDS A CUSTOMISED SHADING DEVICE

69
Several patterns have been designed in order to form the online library with a variety of patterns for election. There are linear shading devices, rectangular ones, sunshades with rhombus or honeycomb patterns, designs based on mathematical diagrams, like the voronoi diagram, perforated panels with the potential to form specific logos, advertisements or even famous paintings or people photos and designs that remind famous buildings facades. All the patterns are designed parametrically in Grasshopper, a graphical algorithm editor tightly integrated with Rhino’s 3-D modeling tools (Grasshopper3D, 2011) developed by David Rutten at Robert McNeel & Associates Grasshopper, in order to adapt to external conditions (climate-location variables) and user requirements (user based variables). The patterns are based on dynamic grids that enable users to change their dimensions, density etc. The orientation of the window affects the design as the patterns following the principles of horizontal protection in the south and vertical one in the east-west projecting horizontal or vertical shields respectively. As the devices are aimed at different contexts and users with different necessities and preferences, an effort has been done to define the general sunshade’s functions and requirements and how they can be achieved according to the literature study of chapter 2. So, the findings of chapter 2 has been translated into design principles for the patterns and into parameters for the parametric script of the designs.

<table>
<thead>
<tr>
<th>Dalight system functions</th>
<th>Shading systems requirements</th>
<th>How</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redirect daylight</td>
<td>Daylight enhancement</td>
<td>Redirect light</td>
</tr>
<tr>
<td>Solar shading</td>
<td>Protection from overheating</td>
<td>Block light</td>
</tr>
<tr>
<td></td>
<td>Solar gain</td>
<td>Allow light</td>
</tr>
<tr>
<td>Glare control</td>
<td>Protection from glare</td>
<td>Filter light</td>
</tr>
<tr>
<td>View to the outside</td>
<td>Obstruction of views</td>
<td>Block-filter light</td>
</tr>
<tr>
<td></td>
<td>Allow views</td>
<td>Allow-filter light</td>
</tr>
</tbody>
</table>

Table 12_Translation of shading requirements into parametric design principles.

The amount of projection can change parametrically, moving the vertices (fig. 61) of the geometry. For the glare protection the density of the pattern increases and for obstructing or permitting views to the outside we use either more or less density to the pattern respectively (fig. 61a, 62b, 63c), or different ratio of perforation to the panel, with bigger apertures when the views are preferred and smaller ones when there is no need for views to the outside (fig. 70).

Another way to control the views to the outside is distorting the grid pattern by using attractors in Grasshopper creating different perforation-distortions to the panel. (fig. 70) The attractor points are located where there is necessity of view to the outside, so the grid is distorted presenting bigger apertures to the eye level. All these parameters, dimensions, density, perforation, distortion etc. can be adjusted through “sliders” in the parametric interface. The sliders are numbered bars, which can be adjusted by the user with the cursor. They are the input, given by the user, the different input changes the configuration of the parametric pattern and give an updated output-geometry which is the design result, based on the specific input.
As it is mentioned above, the user can choose one of the existing “styles” in the online library of designs. After defining the orientation of his window and his location, the right file opens on his screen. Then the definition of his preferences may occur. These are, the dimensions of the window and the room, the density of the pattern which aims the glare control and the dimensions of the projections of the sunshade which aims to the solar protection. He can define all the above writing on the screen specific numbers or words, or moving sliders to see the direct reaction of his design.

<table>
<thead>
<tr>
<th>OIENTATION</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXTERNAL CONDITIONS</td>
<td></td>
</tr>
<tr>
<td>SUN LATITUDE</td>
<td>48° 47'/Delft</td>
</tr>
<tr>
<td>MONTH/DAY-HOUR</td>
<td>21/6-12:00</td>
</tr>
</tbody>
</table>

**USER REQUIREMENTS**

| WINDOW DIMENSIONS   | 3.00 x 1.7   |
| ROOM DIMENSIONS     | 5.00 x 3.75x2.85 |
| DENSITY(GLARING PROTECTION) |             |
| DIMENSIONS OF SHADING (SOLAR PROTECTION) |             |
| SPECIFICATION OF VIEWS |             |

Illustrations on user’s screen from his input/ trying different design variables.

Illustrations on user’s screen from his input / image showing the shading inside the room.

**Fig. 58_ Example of user scenario1 / Delft / Netherlands**

Illustrations on user’s screen from his input / sun-path showing the sun incidence hitting the room.
Once he completes all the required fields, a front and a perspective view of his model will appear on his screen. Then he still can play around with the sliders in order to try different design variables, like different densities and different perforations of the grid that lead to specification of the views to the outside. Thanks to that he can observe how the variables that he changes affect his design, until he makes the final decision.

Furthermore the perspective view that appears on his screen can inform him about the shading that occurs inside the room with a false color image black and white (fig. 58), illustrating with white color the most bright parts of the room and with black the darker parts. As a matter of fact, this false color image is an illustration of the amount of Illuminance (lux) inside the space, as it will be presented in the next chapter of performance. However, as the services of the website are offered to common users, we assumed that the majority of them cannot “read” an image with illuminance levels, so in this stage (1st service) a colored illustration of shading is offered, in case someone needs a more detailed performance study of his shading device, he can always ask for the second service, as it is illustrated on fig. 56f, which is optional. This service can offer, also, interior images of the space, with the expected shadow and glaring probability. Similarly the sunpath of the user’s location is illustrated in order to have an impression of the sun altitude for the specific date that he requires the shading device.

If the user is not satisfy either from the design or from the performance, based on the image that he sees( maybe too black, or too white) he can always change the variables (density, perforation dimensions etc.), which provides him with updated geometries based on his input, in order to have a better result.

**LOGIC OF OVERALL DEFINITION**

Fig. 59_ Logic of overall definition presenting the relation among sunshade definition, room definition and performance definition.
### External Conditions

<table>
<thead>
<tr>
<th>Orientation</th>
<th>East</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Latitude</td>
<td>52°03'04°22'</td>
</tr>
<tr>
<td>Month/Day-Hour</td>
<td>21/6-12:00</td>
</tr>
</tbody>
</table>

### User Requirements

| Window Dimensions | 3.00 x 1.7 |
| Room Dimensions   | 5.50 x 3.75 x 2.85 |
| Density (Glaring Protection) | |
| Dimensions of Shading (Solar Protection) | |
| Specification of Views | |

Illustrations on user's screen from his input/ trying different design variables.

Illustrations on user's screen from his input / image showing the shading inside the room.

Illustrations on user's screen from his input / sun-path showing the sun incidence hitting the room.

---

*Fig. 60_ Example user scenario 2 / Thessaloniki / Greece (Appendix A)*

Towards a Customised Shading Device
Rectangular grid

Grid vertices

Attractor points

Offset grid

Fig. 61_ Illustrations of a rectangular grid translating the design principles into parametric logic / INPUT.

TRANSLATION OF DESIGN VARIABLES INTO THE PARAMETRIC STRUCTURE

<table>
<thead>
<tr>
<th>INPUTS variables</th>
<th>OUTPUT Pattern geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>Grid</td>
</tr>
<tr>
<td>Horizontal panels</td>
<td>Density of grid</td>
</tr>
<tr>
<td>Vertical panels</td>
<td>Projection for South</td>
</tr>
<tr>
<td>Top vertices</td>
<td>Projection for East</td>
</tr>
<tr>
<td>Right vertices</td>
<td>Projection for West</td>
</tr>
<tr>
<td>Left vertices</td>
<td>Opaque/perforation ratio of the offset grid</td>
</tr>
<tr>
<td>Amount of offset grid</td>
<td>Grid distortion</td>
</tr>
<tr>
<td>Attractor points</td>
<td></td>
</tr>
</tbody>
</table>

DESIGN REQUIREMENTS

Redirect daylight
Solar shading
Glare control
View to the outside

ASSOCIATIONS

FINAL GEOMETRY-MODEL

Fig. 62_ Logic of shading definition followed by some of the designs (rectangular grid, rhombus, honeycomb).

projections/moving right vertices

Perforation of grid

Distortion of grid

Fig. 63_ Examples of output grid geometry from an input of a rectangular grid: projections, opaque-perforated ratio/distorted grid. / OUTPUT GEOMETRY
Fig. 64_ Overall definition of one example of sunshading.

Fig. 65a_ Changing the dimensions of the room in length, width & height through sliders_ INPUT

Fig. 65b_ Moving and changing the dimensions of the window in width & height_ INPUT.

Fig. 66_ Changing the dimensions and the density of the shading through sliders_ INPUT.

Fig. 67_ Changing apertures of the shading by moving the points_ INPUT
-Defining the orientation and the amount of shading through projections

Fig. 68a_ SOUTH-horizontal projections, front and side view.

Fig. 68b_ WEST vertical projections, front and side view.

Fig. 68c_ EAST - vertical projections, front and side view.

-Glare control with different densities of the pattern

Fig. 69a_ Density A

Fig. 69b_ Density B

Fig. 69c_ Density C

-Perforation and distortion permits or obstruct views to the outside

Fig. 70_ Opaque-perforated ratio | Distorted grid | Views to the outside

The distortion of the grid achieved with attractors which attract the points of the grid by forces in order to free the density of the pattern where the views are preferable.
Patterns - Variations

Fig. 71. LINEAR PATTERN: From a straight linear shading to a distorted curved one.

Fig. 72. RHOMBUS PATTERN: Design variations.

Fig. 65. RECTANGULAR GRID: From straight conservative rectangular grid to a distorted one.

Fig. 73. VORONOI DIAGRAM: Eccentric Voronoi shading pattern. Every point in the region around a site is closer to that site than to any of the other sites.
Almost all the shadings work with the same principle. The linear, rectangular, rhombus and honeycomb pattern can be from a conventional straight lines or grid respectively to curved one, in order to free the density of the grid for views. The above patterns and the voronoi one, have the potential to project shadings horizontally or vertically, in the same way, as it is presented in the previous page with the rhombus alternatives for different orientations.

In the perforated with holes patterns (fig.75-76) the perforation could be achieved either with small or with big holes, according to the relationship between the amount of sun that we need inside the room and the views to the outside. All the above patterns can, also, dynamically be changed to different densities, in accordance with the protection glaring of the user. Finally, the user can try to design his own pattern and lay around with the different variables.
4.2.2 FABRICATION:
AM method | Material

One of the crucial steps of the fabrication phase is the material election related to the AM process. In chapter three, an analytical overview of the AM processes has been done and a table of evaluation of them as well. Regarding the table in chapter three, SLS and FDM processes are the most suitable for this application. Although SLS is a more accurate and professional process, its high cost may not be a motivation for the majority of users. On the other hand, FDM is much cheaper and accessible from individuals, as it is the process that hobbyists and reprap community use. However it is a low speed procedure.

The methodology for the material election consists of an overview of the materials available from manufacturers for these two processes and use them as an input to the CES Edupack 2014 software in order to filter the properties needed for an outside use. In this stage, some information collected from manufacturers (sculpteo, taulman) and discussions in related web-sites (www.3d-hubs.com) was also useful.

**Material properties required**

<table>
<thead>
<tr>
<th>NATURAL CONDITIONS</th>
<th>RELATED MATERIAL PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Mechanical properties (shear strength, ( \tau ), yield strength)</td>
</tr>
<tr>
<td>Rain</td>
<td>Water absorption/resistance</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>UV radiation resistance</td>
</tr>
<tr>
<td>Temperature differences from -30 to 80 degrees</td>
<td>Min service temperature (Tmin) at most -30°C, Max service temperature at least 80°C</td>
</tr>
<tr>
<td>Time</td>
<td>Creep</td>
</tr>
</tbody>
</table>

**Table 13:** Definition of material properties required.

When it comes to a suitable thermoplastic material for FDM process, that means that its properties like, low melting point, thermoplastic behaviour etc, may occur problems when it comes to an outside use. For the extreme condition of fire it is easy to predict that the majority of 3D printed thermoplastic materials cannot withstand the fire load without another protection. However, apart from a fire scenario, a 3D printed thermoplastic material may lose some of its mechanical properties under a heat load in a summer day. For this reason maximum service temperature (Tmax) and minimum service temperature (Tmin) are applied as filter for the case of Netherlands, taking into consideration the extreme temperatures to which a material that is exposed to the sun, can be heated up to. The maximum temperature of the surface of a roof in the Netherlands is about 80 degrees Celsius and the minimum temperature about -30 degrees Celsius. (Krusche et al., 1982). So these figures will be applied as a filter to the CES software.
Selection of thermoplastic polymers from manufacturers (materialise, shapeways, stratasys, sculpteo, taulman) - enter to CES Edupack 2014, as some of them do not exist because they are modifications of basic materials of the manufacturers, we will use the base material of them as an input to CES. (eg: modified nylons)

**Material selected for SLS** (common materials: nylon several types, advanced materials based on nylon):
Polyamide: PA12, PA11, PA6, PA66, PA 2200, PA2241FR (advanced material, passes aerospace flame resistance test)
NYTEK12000FR9 (fire retardant), FR-106 (fire retardant, exceptional mechanical strength)
PEEK (high engineer material)

**Material selected for FDM** (common materials: ABS, PLA)
ABS plastic: ABS (Acrylonitrile/butadiene/styrene), ABS (Methacrylate-acrylonitrile-butadiene-styrene copolymer)
Nylon: Nylon 945, Nylon 12, Nylon 6 (and other modified nylons)
Polycarbonate: PC, PC-ABS (Polycarbonate/ABS blend)
Polyphenylsulfone (PPSU)
PEI Blend with PC Copolymer for improved flow (ULTEM 9085)
ASA, UV-Stable, Production-Grade Thermoplastic

CES Edupack 2014.
Insert materials (used typical nylons as base for the advanced materials)
39 materials as an input
1st stage: Recycle → 37 materials left
2nd stage: UV radiation, Excellent, good, fair*1 → 28 materials left
3rd stage: Water resistance (Excellent)*2 → 28 materials left
4th stage: Max service temperature (80°C) & Minimum service temperature (-30°C) → 18 materials left at least 80°C
5th stage: Flammability *3 (Slow-burning, Self-extinguishing, Non-flammable → 17 materials (PET has left)

*1 Fair UV radiation resistance: Resist from months to years. The majority of polymers and organic materials – require protection for long-term UV exposure, but short-term may be acceptable: PS, PC, most PA, wood.
- Maybe additional coating for UV radiation is necessary.

<table>
<thead>
<tr>
<th>Poor</th>
<th>Days/weeks</th>
<th>Polymers known to be especially sensitive to UV degradation in absence of protective measures: PE-I, PP, POM, PA66, ABS, unreinforced 'R' rubbers (NBR, BR, NBR, etc.).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fair</td>
<td>Months/years</td>
<td>Majority of polymers and organic materials – require protection for long-term UV exposure, but short-term may be acceptable: PS, PC, most PA, wood.</td>
</tr>
<tr>
<td>Good</td>
<td>Years</td>
<td>Polymers known for inherent resistance to UV: Acrylics, ASA, PBT, PLA, fluoropolymers, silicones. Protected polymers: carbon-black filled (e.g. SBR carbon black reinforced compounds), PP, and POM UV grades. You will see some of these materials described elsewhere as 'excellent' or 'outstanding', but this is relative to other plastics rather than materials as a whole.</td>
</tr>
<tr>
<td>Excellent</td>
<td>Tens of years</td>
<td>UV has little effect: most metals, ceramics, and a few special polymers: polyimides – PI, PEI, PAI, and certain fluoropolymers – PTFE.</td>
</tr>
</tbody>
</table>

Fig. 78_CES Edupack 2014, scientific note
After filtration of the materials through CES according to the required properties, a graph with price in the y axis and density in the x axis has been done in order to observe the related prices of the materials. Although PET is a high flammable material, it is not excluded of the material list because of its low cost and its ability to easy be recycled.

As we can see in the CES edupack database, materials that satisfy all the requirements of the sun-shading are PEEK (Polyether ether ketone) and PSSU (Polyphenylsulfone) with really good thermal performance and superior mechanical performance using them in aircraft components. However, taking into account the price vs density graph it is obvious that they are relatively expensive materials. As alternative cost efficient materials we will propose in the framework of this project on several types of Polyamide (Nylon) like PA 2210 (Appendix B) and PA 945, and other modified of manufacturers, PET (Appendix B) (Polyethylene terephthalate) and ASA (Acrylic styrene acrylonitrile), (Appendix). ASA has not pass the Tmax temperature filter, however stratasys manufacturers confirm that it is suitable for outside use.

PET is a very cheap material that is available in filament for the FDM process. However an additional protection from fire has to be taken into consideration. There is a range of prices for nylons, with the cheapest one, type 6, also, manufacturers use modified nylons with properties presented in the data-sheets in Appendix B. However, nylon’s performance to UV radiation is poor, so an additional protection has to be added both for UV protection and fire.

PA
Polyamide, outdoor protection is quite a challenge. Current available nylon filaments are UV sensitive, as they are intended for indoor use, and have poor fire retardancy. Regarding CES, Polyamide has “fair” resistance to UV radiation, that means that it can resist to external conditions for some months, changing its original color to a yellowish one after a while. A coating or modified material are solutions for this disadvantage. Another property of Polyamide is that it is water resistant but not waterproof. That means that it absorbs water. Although this characteristic makes it stiffer, the weight of the whole structure is supposed to be increased due to the water absorption. Both fair UV radiation resistance and water absorption can be solved through the application of a non-flammable acrylic painting or using a modified nylon filament from the begining, which is resistant to fire and UV radiation.
Fig. 81: Price to density graph for selected materials, CES Edupack 2014.
The fact that Additive manufacturing is a new technology causes everyday news and improvements in terms of the technology and the materials to be used. In order to be updated to that, it’s worth checking related forums and websites where individuals or even professional engineers share their own experiences. www.3dhubs.com is a website where one can upload a file and make and order to 3D print it. According to Michiel Hagenbeek, from “3dhubs” it is possible through experimentations to come up with a modified nylon filament that address issues like UV-radiation and fire protection.

In SLS method, advanced modified nylons, like NYTEK 1200 FR (Appendix) and FR-106 (Appendix)) which are based on nylon 12 and 11 respectively have been used in aerospace application. They are fire retardant materials.

-MoTip Heat-Resistant Spray, available in 6 colors, is for treated and untreated surfaces exposed to very high temperatures. It is suitable for use on exhaust pipes, ovens and grills etc. It can be sprayed on bare metal without the need to prime first. It resists temperatures from 300°C to 800°C. So it is suitable for UV and fire protection -http://www.motipdupli.de/en/products/motip/decoration/universal-lacquers/ipg-1541/tm-1541.html-

-Another alternative for UV stability of polyamide is Ultraviolet Absorbers coatings. Absorbers are a type of light stabilizer that function by competing with the chromophores to absorb UV radiation. Absorbers change harmful UV radiation into harmless infrared radiation or heat that is dissipated through the polymer matrix. A suitable absorber for polyamides which include oxanilides is SABOSTAB UV 312 a non-discoloring oxanilide UV absorber effective for use in plastics and coatings, suitable both for nylon and PET.-http://www.sabo.com/sabo/products_and_markets.php?market_id=5&family_id=5&product_id=21-

Note: According to Justine Anglade, Business Developer at Sculpteo, the plastic offerng from their company, polyamide 2200 (Appendix B), based on Nylon 12 is UV and water resistant. Material degradation in outdoor conditions is mainly due to water absorption and UV degradation. Both water absorption and UV degradation cause chain breakage at a molecular level inducing a decrease in mechanical strength. To tackle this issue, PA2200 is UV stabilized with titanium dioxide (TiO2). Still, it has been observed that properties in outdoor conditions will decrease with time of exposure. Unfortunately, loss in properties has been never tested from the manufacturer, so it is hard to predict the lifetime. One way to preserve mechanical strength is to prevent exposure by protecting the object, with the above mentioned ways. This should protect the object against UV degradation. But still in order to prevent the material from absorbing water, some vernish could be added on the final object.

PET
According to both CES edupack and Job van Noorloos manufacturer of “plastics2print” (they use PET filament which has been purchased or for the fabrication lab of the department of Informatics of TU Delft) PET is resistant to water and UV radiation, so the disadvantage of this material is its high flammability.

The burning behavior of bulk polymers depends on their physical and chemical properties and consists of a three phase process - heating, thermo-pyrolytic decomposition and finally ignition. PET (semicrystalline) has good UV radiation resistance, glass temperature $T_g$ ~ 68°-80° C, (82°C) according to manufacturer, (Appendix B) melting point $T_m$ = 255°-267°C, maximum service temperature $T_{max}$= 115-120°C and minimum service temperature $T_{min}$ = -58 - (-38) °C. The disadvantage of PET is that it is high flammable. Since flammability is a requirement that the sunshade has to meet, the final object printed from PET can be coated with a flame retardant, like - ADK STAB FP-700 (http://www.adeka-palmarole.com/your-polymers/pet.html)

There are two ways to improve PET’s performance against fire, by modifying the filament itself from the beginning (through the addition of flame retardant to that before 3D printing) or by adding a coating after that.
According to Richard Green, Sales Manager of ADEKA PALMAROLE SAS—www.adeka-palmarole.com—the first way will change the properties, such as the viscosity of the PET, which will in turn bring additional challenges to this scenario. R. Green says that, although halogen-free flame retardants for plastics, using in PC/ABS (TV, computers, housing everyday items) like Oligomeric Phosphate Flame Retardant, -ADK STAB FP-700, where the flame retardant is compounded in with the polymer and other additives and the article is either extruded or injection moulded with this compound - according to the literature, brominated products tend to be the system of choice.


Brominated polystyrene (BPS) is a bromine-containing organic flame retardant with a high flame retardancy, thermal stability and light stability, good mechanical, physical and chemical properties. It’s widely used in PET, PBT, nylon -66 and other engineering plastics.

The main applications of the brominated polystyrene in the PA, PBT, PET and other thermoplastic resin combined with antimony antioxidant.

Appearance: White Powder
Bromine: 64.0% - 67.0%
Volatile: 0.1% max
Melting Point: 260-320 °C

4.2.3 Assembling

As mentioned before, the fabrication method and the material used not only affect the price and the durability but also the accuracy of the assembling method. As the dimension limitations of the AM processes are very specific, the assembling of the parts of the shading have to be taken into consideration. Therefore, a research about assembling methods for plastics and printed objects has been done.

Plastics Machining & Assembly
- Snap-Fits
- Hinges
- Mechanical Fasteners
- Bonding
- Welding

“Snap fits are integral fasteners molded into plastic parts, which when assembled lock into place. Snap fits are quick and easy to use in permanent assembly, and they are essential when disassembly is required”. (Society of Manufacturing Engineers, 2002)

Hinges are used mainly when there is a necessity for motion, as repeated opening and closing. “The three basic types of hinges include, one-piece integral hinges, two-piece integral hinges, and multipart hinges. Each hinge type has a particular use with multipart hinges being used for heavy duty applications”. (Society of Manufacturing Engineers, 2002)

Screws, eyelets, and rivets are common mechanical fasteners for plastics assembling. They are installed either manually or automatically. In order to hold the connections of the screws, threaded metal inserts could be, also, added to the parts.

For strong and permanent joints, the method used is bonding. There are two main bonding methods, adhesive bonding and solvent bonding. In adhesive bonding what is used is, obviously, specific adhesive materials followed by a curing. In solvent bonding the surfaces to be joined are melted causing a molecular cohesion, thus a strong connection. (Society of Manufacturing Engineers, 2002)

When it comes to product addressed to common users, common assembling methods like snap-fits, adhesives or mechanical fasteners have to be used. The last category of welding methods is related more with ended-using industrial products requiring specific equipment. Regarding hinges, they work well when it comes to assembling planar surfaces; nevertheless, that’s not the case as some of the patterns doesn’t consist of planar modules. Another argument is the fact that the object has to be assembled and disassembled easily. That explains why adhesive is not an option.

Although, using 3d-printed bolts and nuts it is not a bad idea, it is not an easy and quick process. Additionally, as screws are driven through the material, they cause deformation to the plastic part, resulting in difficulties in the assembling of the other designed and printing parts. (This is not the case when it comes to metal printed parts).

Regarding the above, for easier and faster assembling and disassembling method for a common user, offering the opportunity to disassemble a broken part-maintenance and the potential of recycle the product after the end of life, best solution is snap-fit connections. Here an important factor to be considered are the tolerances of the assembled parts, the male and the female, during the design process. As the printer construct the object layer by layer on the top of each other, the tolerances, between the parts to be assembled, depend on the accuracy, thus on the settings of the machine that is going to be used.
Fig. 82a, 82b, 82c, 82d. The “Egg project”
-consisting of 4760 stones
-5 x 4 x 3 m (http://projectegg.org/project-egg/) Michiel van der Kley

Fig. 83. 2,279 unique triangular panels interconnected by 3,316 hinges, all 3D fabricated as a uniform structure of nylon. (http://n-e-r-v-o-u-s.com/projects/sets/kinematics-dress/)

Fig. 84. Assembling using nuts and bolts (http://www.emergingobjects.com/)

Fig. 85a, 85b. Assembling using aluminum rods (http://www.emergingobjects.com/)

Fig. 86a, 86b. Assembling using clamps (http://www.emergingobjects.com/)

Fig. 87. Assembling: No need any bolting, screwing, or welding
-It is a button-like connection. (http://www.dezeen.com/)
Designing for assembling-disassembling: Snap-fits

When it comes to assembling different parts, there are two types of connections that could be used: linear connections and non-linear ones. As the explode modules of the whole shading cannot be assembled only with linear connections (it depends on the pattern), several tests of the two categories have been done in order to find the optimal assembling method. Several alternatives of connections have been modeled first in Rhinoceros, (2014 Robert McNeel & Associates) and then were fabricated in the design Informatics department using the leapfrog 3dprinter, which is available from TOI. The printer works with the FDM method and the material used is PLA. Tolerances of small parts of the modules to be assembled have been also tested with the relevant settings of the machine, in order to make sure they match the correct ones. Barbed leg snap-fit and cylindrical snap-fit have been modeled according to the literature. This in combination with the fabrication tests leads to the final connection detail.

For barb leg snap-fits, the assembly angle $\alpha_1$ (fig. 88), in combination with the dimensions of the male part and the coefficient of friction, between the parts (0.2-0.3, for plastics), defines the required assembly force $F$. For a great $\alpha$, a higher force is required. When it comes to a great $\alpha$, $\alpha>45^\circ$ in combination with a high coefficient of friction, perhaps the possible parts cannot be assembled. The recommended assembly angle for barbed legs and cylindrical snap-fits is $\alpha_1 = 15^\circ$ to $30^\circ$.

On the other hand, the angle $\alpha_2$ (fig. 89) affects the load bearing capacity of the joint. When $\alpha_2 = 90^\circ$, the maximum load-bearing capacity is reached. With $\alpha_2 = 90^\circ$ the connection is permanent, whereas for detachable joints, $\alpha_2 = 30^\circ$ to $45^\circ$ is preferable. It is recommended during long-term loading and high temperatures, that the angle $\alpha_2$ should be $90^\circ$.

The literature review in combination with the testing of different designed and fabricated parts for joints, lead to a preferable connection for the modules of the shading device. In the next page some modeled and fabricated connections are presented.
Fig 92. Alternatives of cylindrical snap-fit joints, with $a_1=45^\circ$ and $a_2=45^\circ$ or $a_2=90^\circ$. Solid or with empty space in the middle of the joint for assembling through compression of the male part, into the female.

Fig 93. Barbed leg snap-fit with $a_1=45^\circ$ and $a_2=90^\circ$. Inclination of $a_3=20^\circ$ to the bottom of the male part to enter through compression and return to each physical position after the assembling.

Fig 94. Lego connection.
Fig. 95_ Exploded view of exagon modules pattern.

Fig. 96_ Non-linear connections between the modules.

Fig. 97_ Clamp connection, top view, front view, perspective view.

Fig. 98_ Integrated clamp connection combined with barbed leg permanent connection, top view, front view, perspective view.

Fig. 99a_ Detachable snap-fit.

Fig. 99b_ Nondetachable snap-fit.
**Conclusions**

After evaluation of the tested snap fit connections several outcomes were concluded.

Non linear connections are more preferable than linear ones, because the last are weaker when they are located on the top of the shading. As the modules and therefore their snap-fit joints bearing more load (weight of shading) than the non linear ones. The stresses caused by the weight of the shading gathers on the very snap-fit joints when it comes to linear connections, making them weaker.

In addition, non-linear joints are easier to be disassembled for maintenance, for instance replace a broken element-module.

It is observed that specific numbers of the angles $a_1$ and $a_2$ define if the connection will be permanent or detachable. When $a_1 = 45^\circ$ and $a_2 = 45^\circ$ then the joint is detachable. However, a considered amount of force has to be applied deliberately in order to be able to successfully disassemble the joint.

Finally, when the fabrication process used is FDM, the layering way of building the object has to be taken into consideration. The fact that the surface after FDM 3d-printing is not very smooth, but layered, increases the coefficient of friction between the printed parts, resulting difficulties in assembling. Therefore, post-processing after fabrication (eg. sanding) may be necessary.

In the next chapter the described concept is applied to a specific case study in order to examine the engineering aspects of the project, like the performance of a designed pattern-sunshade under specific climate conditions for a specific use as well. Also, the structural performance of the connection of the shading device modules are examined both with hand calculations and experimentally. The fabricated connections will be tested under load in the laboratory of Mechanical engineering and materials department of TU Delft University of technology.
LITERATURE


Grasshopper3D (2011) developed by David Rutten at Robert McNeel & Associates Grasshopper

http://www.taulman3d.com/

www.stratasys.com

www.sculpteo.com

https://www.3dhubs.com

http://projectegg.org/project-egg/

http://www.emergingobjects.com/

http://n-e-r-v-o-u-s.com/projects/sets/kinematics-dress/


www.sme.org, (Society of Manufacturing Engineers, 2002)


http://www.sabo.com/sabo/products_and_markets.php?market_id=5&family_id=5&product_id=21-

www.adeka-palmarole.com

http://www.mpi-chemie.com/category/brominated-flame-retardants/product/cas-88497-56-7-mile-brome-3010.html
5. CASE STUDY
In this chapter a case study has been selected in order to test the engineering aspects of the project. This phase includes the election of a pattern and the adjustment of it regarding the specific characteristics of the case study, like the climate, the location, the use of the space that the shading device will be applied to and the requirements of the user. Once this step is completed, the performance of the sunshade and its alternatives will be tested, for South, West and East orientation, in the summer. After that, a mock-up of one of the South pattern selected will be fabricated in order to check the performance, also, with a physical model of a box office. Then, the fabrication part follows. Finally, both the structural performance of the connections among the modules, and the application of the shading to the window frame will be presented. In this step, the structural performance of the snap-fit connection will be tested mechanically in the laboratory of mechanical engineering department of TU Delft university.

5.1 FORM
5.1.1 Design

The case study is located in Delft in the Netherlands. The climatic profile is an Energy Plus weather file (EPW) for Amsterdam - similar to the climatic data of Delft, developed by the U.S. Department of Energy. The aim is to offer shading to the workplace of the office during the summer. Factors that affect the form of the design are the following requirements. The summer solstice: 21st June is chosen as reference weather condition. The design selected is a rhombus grid pattern. The perforation is changing gradually and smoothly from the top to the bottom of the window, creating a useful illumination to the indoor space. A useful illuminance ratio for the work-plane could range from 1:5 to 1:10. The distribution of light to the interior is a crucial aspect as it is applying in a working space. The smooth perforation of the pattern offers, also, the potential for views towards the outside when it comes to the eye level and even more when it comes to the sitting height of the eyes, as people spend most of the time sitting down in a working space.
USER PREFERENCES VARIABLES

INPUT:

REQUIREMENTS

_ROOM DIMENSIONS | 5.5x3.75x2.85m
_DIMENSIONS FRAME | 3.20x1.80m
_LIGHTING FOR A WORK SPACE | CONTROLLED / DISTRIBUTED
.Views | Higher perforation to the eye & sitting level
_PROTECTION | Shading, glaring
5.1.2 Performance / Computer based

The objective of this chapter is to estimate the performance of a specific shading device for specific climate conditions. In this research is proposed a performance analysis, calculating the illuminance levels of the working plane and translating them as a false color image, enabling the communication of the sunshade performance with the user. This way a common user is able to “read” the results of the device easily. However, there is the potential for more sophisticated ways to estimate daylighting performance through optimization tools, but this is not the scope of this thesis.

As mentioned in chapter 2, there are several dynamic daylight performance, metrics, such us the daylight factor, the daylight autonomy, the useful illuminance levels and luminance contrast etc. However, as the first two above metrics are related with the yearly performance of a building, in this paper the concept of which focuses on static 3d printed sunshades which can be recycled every season and be printed again regarding the specific conditions, the evaluation of the performance will be based on the illuminance levels and the DGP (daylight glare probability) factor of three different sunshades, each one designed for the orientations, south, east and west for the climate conditions of Delft - latitude: 52°01’N, 04°22’E- for the summer season. For the South orientation a physical model will be, also, tested for luminance contrast.

Useful daylight Illuminances (UDI) proposed by Mardaljevic and Nabil is when daylight levels are useful for the occupant, neither too dark <100lux, not too bright>2000lux. Nowadays 500lx on the work plane are often recommended for office work (Canadian Labor Code, Part II:Occupational Safety & Health 1991, IESNA Lighting Handbook, 9th Edition, 2000). Additionally, as a rule of thumb, useful illuminance ratio between the front and the back of the room is 1:5 to 1:10. Comfortable luminance contrast range from a ratio of 1:10 for the ergorama and 1:30 for the panorama view of a user.

Computer simulations

The simulations performed in DIVA for Rhino examined the critical date: the summer solstice 21 of June for the climatic conditions of Delft. The models are set for a clear sky. Apart from computer simulations, a mock up with a south-faced window is also used to verify the results of the simulations.

In order to estimate the performance of the rhombus sunshading device for the South, East and West orientation, a rectangular office space has been designed in grasshopper with a south-faced, west-faced and east-faced window respectively. The dimensions of the box office are 5.5x3.75x2.85m and the window dimensions 3x2m, in order to use the same boundary conditions with the available mock-up box office of the building physics sector of TU Delft.

First of all, in the office model a grid is defined with upward facing illuminance sensors 0.5x0.5m at a work plane height of 0.80m above the floor. Then the materials were assigned to the model.

Input for all the orientations:

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling</td>
<td>80% diffuse reflectance</td>
</tr>
<tr>
<td>Walls</td>
<td>50% diffuse reflectance</td>
</tr>
<tr>
<td>Floor</td>
<td>25% diffuse reflectance</td>
</tr>
<tr>
<td>Glass</td>
<td>double glass pane</td>
</tr>
<tr>
<td>Shading</td>
<td>35% diffuse reflectance (outside facade)</td>
</tr>
<tr>
<td>Ground</td>
<td>25% diffuse reflectance</td>
</tr>
</tbody>
</table>

Fig. 103_ Evaluation of illuminance ratio.
For the **glaring performance** a more detailed model is designed in rhino, with four table offices and computer screens inside. Daylight Glare Probability (DGP), a metric to predict the appearance of discomfort glare in daylit spaces, has been used for glare analysis based on Radiance evaluation tool “evalglare”, it became possible to analyze glare according to a number of daylight glare prediction models. The simulation calculates the DGP factor from a luminance image based on total vertical eye illuminance and contrast. The luminance image presents contrast based glare sources.

**Note 1**: DGP should range between 24 and 30%. DGP>31% is generally not acceptable.  
**Note 2**: For the formulation of both the diagrams below and the illuminance ratio, illuminance levels at 0m and 5.6m from the window were not taken into account.

The rhombus sunshading device follows the principle of vertical protection for the west and east orientation, with the vertical protection on the right and left side of each module (rhombus) respectively and horizontal protection for the south orientation.

The illuminance levels for the three orientations have been defined for the office box with and without shading, while in the south orientation different densities of the sunshade have been tested. Additionally, for the west orientation different levels of perforation in the sunshading have been examined with holes of radius, R=3mm, R=4mm and R=5mm in order to define if there is any difference in illuminance levels when the shading is opaque-blocking the sun - and perforated - filter the sun.
5.1.2.1 South Orientation

South orientation_Summer
Diva for rhino Illuminance nodes analysis
Sky condition, Month, Date, Time: ±s 06 21 12:00

For the south orientation the illuminance calculation at the computer simulation took place on 21st of June at 12:00. The proposed sunshading device, which is going to be tested also with the mock-up, permits views to the outside both to the eye level and when people are sitting, changing its pattern smoothly from the bottom to the top.

Then, two other alternatives of different pattern densities and one with perforated shading (R=5mm) are examined in terms of illuminance levels.

Fig. 107a_Sunpath, Delft, 21st of June/ top view.

Fig. 107b_Sunpath, Delft, 21st of June/ perspective view.

Fig. 108_Alternative densities to be tested.
South orientation
Diva for rhino illuminance nodes analysis
Sky condition, Month, Date, Time: +s 12 21 12:00

Fig. 109_ Performance without sunshade/
Illuminance levels on work plane/ IL. Ratio = 532/51344 ≈ 1/100

Fig. 110_ Perforated sun-shade-R=5mm/
Illuminance levels on work plane/ IL. Ratio = 228/1493 ≈ 1/6

Fig. 111_ Opaque sunshade/
Illuminance levels on work plane/ IL. Ratio = 212/1299 ≈ 1/6
Fig. 114 - The opaque shading device of South orientation selected that will be tested, for glare analysis in the next pages both computationally and with a physical model 1:5.

Fig. 112 - Performance with sun-shade/density A. IL. Ratio = 149/1250 ≈ 1/8

Fig. 113 - Performance with sunshade/density B. IL. Ratio = 253/1755 ≈ 1/7
According to the figures 109-113 and the above diagrams (fig. 115-116), there is a big difference in illuminance numbers between a shaded room and a non-shaded one. For a non-shading window, the difference in contrast inside the room is supposed to be disturbing as the illuminance levels range from 55,000 lux, they drop sharply after a 1.5 m distance from the frame and reach the amount of 500 lux at the back of the room, with an overall illuminance ratio 1/100. (useful ratio = 1/5 to 1/10)

The second diagram, shows that patterns with density A present a good illuminance ratio along the work plane (1/8), however, the numbers at the back of the room drop under 200 lux. On the other hand, the pattern with density B reaches almost 1800 lux near the window, having a ratio of 1/7.

Among the above that have been compared, the preferable seems to be the device with the opaque shields and with an intermediate density between A and B as it is shown in the figures. This specific device shows illuminance ratio of 1/6 (fig. 111), while it is not exceeds 1200 lux in the front of the room nor drops under 200 at the back. Similar ratio presents the perforated sunshading device.

For the opaque sunshading device (fig 111 and fig. 114) radiance and evalglare in DIVA-forRhino has been used in order to calculate the Daylight glare probability (DGP) at 9:00, 12:00 and 15:00 o’clock, in the middle, towards the back of the room and on the eye level of a person sitting on the desk.
South orientation
Diva for rhino Point in time glare analysis
Sky condition, Month, Date, Time: 06/21

Fig. 117. DGP factor for: 06/21 at 09:00, 12:00 and 15:00 camera located to the back of the room / Camera height: 1.65m

Fig. 118. DGP factor for: 06/21 at 09:00, 12:00 and 15:00 camera located to the back of the room / Camera height: 1.65m.
As it is illustrated at the above figures the DGP factor is always lower than 30%. That means that the daylight glare probability is imperceptible, however as it is rational, sitting on the desk on the right side of the room, at the 1.2m eye level is the most probable position for glaring, when the sun is in very low position.
5.1.2.2 West orientation

West orientation_Summer
Diva for rhino Illuminance nodes analysis
Sky condition, Month, Date, Time: +s 06 21 15:00

As we can see in the sun-path for the West orientation, the sun faces the window after 13:00 so the illuminance levels are calculated when the sun turns direct to the window, which is supposed to be at 15:00.

The sun shading device for the west orientation is designed according to the sun incidence on 21st of June at 15:00 in a sunny day in order to block the sun from the side. The device follows the principle of vertical protection for the west orientation; vertical protection is creating through projections of the rhombus on their right side.

Some alternatives of the sunshades have been designed and tested. First, the performance of perforated shading devices with holes of radius, R=3mm, R=4mm, R=5mm is presented, and then opaque ones are presented in order to see the difference in the illuminance levels and ratio. It is supposed that the perforated sunshades will filter the sun, protecting from glaring while in the same time, offering more light to the interior in comparison with the opaque sunshade.

Fig. 121a_ Sunpath, Delft, 21st of June/ top view.

Fig. 121b_ Sunpath, Delft, 21st of June/ perspective view.

Fig. 122_ Different alternatives to be tested. a) opaque shading device, b) perforated shading device R_{hole}=5mm, c) perforated shading device R_{hole}=3mm
West orientation_Summer
Diva for rhino Illuminance nodes analysis
Sky condition,Month, Date,Time: +s 06 21 15:00

CASE STUDY

GLAZING

Fig. 123_ Performance without sunshade,/Illuminance levels on work plane./ IL. Ratio = 431/35985 ≈ 1/83

Fig. 124_ Opaque sunshade /
Illuminance levels on work plane./ IL. Ratio = 141/1323 = 1/9

Fig. 125_ Perforated sunshade
R_hole=5mm/Illuminance levels on work plane./ IL. Ratio = 169/1559 ≈ 1/9
**Fig. 126.** Perforated sunshade $R_{\text{hole}}=4\text{mm}$/illuminance levels on work plane. IL. Ratio $= 156/1536 \approx 1/9$

**Fig. 127.** Perforated sunshade $R_{\text{hole}}=3\text{mm}$/illuminance levels on work plane. IL. Ratio $= 141/1345 \approx 1/9$

**Fig. 128.** The opaque shading device of West orientation tested, for glare analysis.
Similarly to the South orientation results, there is a big difference in illuminance numbers between a shaded room and a non-shaded one, as it is illustrated in fig. 123, 124 and 129, where the illuminance ratio is 1/83 for a non-shaded room and 1/9 for a shaded one.

The graph (fig. 130) illustrates that although all the devices have almost the same illuminance ratio (1/9), the opaque shading device and the one with perforation - radius of holes $R_{\text{hole}}=3\text{mm}$ - performs better than the sunshade with perforation $R_{\text{hole}}=4\text{mm}$ and $R_{\text{hole}}=5\text{mm}$ respectively. However, the performance of the opaque shading device and the one with perforation, holes radius $R_{\text{hole}}=3\text{mm}$ is very similar, while this was not expected as perforated panels, normally, allow more light to penetrate the room. Here it could be assumed that probably DIVA is not that accurate when it comes to too detailed geometries, like small holes of radius 3mm.

The glare analysis in the next page is examined for the opaque device (fig. 128) at 9:00 and 15:00 o’clock in the middle of the room, towards the back of it and on the right and left side of the working plane.
West orientation_Summer
Diva for rhino Point in time glare analysis
Sky condition, Month, Date, Time: +s 06 21

Fig. 131. DGP factor for: 06/21 at 09:00 and 15:00, camera located to the back of the room / Camera height: 1.65m

Fig. 132. DGP factor for: 06/21 at 09:00 and 15:00, camera located in the middle of the room / Camera height: 1.65m

Fig. 133. DGP factor for: 06/21 15:00, camera located on the left side of the room / Camera height: 1.20m in the sitting height of user eyes.

Fig. 134. DGP factor for: 06/21 15:00, camera located on the right side of the room / Camera height: 1.20m in the sitting height of user eyes.
5.1.2.3 East orientation

East orientation_Summer
Diva for rhino Illuminance nodes analysis
Sky condition, Month, Date, Time: +s 06 21 12:00

For the east orientation, the illuminance calculation at the computer simulation took place on 21st of June at 12:00.

The sunshading device for the east orientation is designed according to the sun incidence on 21st of June at 12:00 in a sunny day in order to block the sun from the side. The sunshading device follows the principle of vertical protection for east orientation, the vertical protection is created through projections of the rhombus on their left side, similarly with the west orientation, but with mirrored sunshades.

Fig. 135a_ Sunpath, Delft, 21st of June/ top view.

Fig. 135b_ Sunpath, Delft, 21st of June/ perspective view.

Fig. 136_ The opaque shading device for East orientation tested for glare analysis.
East orientation_Summer
Diva for rhino Illuminance nodes analysis
Sky condition, Month, Date, Time: +s 12 21 12:00

Fig. 137_ Performance without sunshade/Illuminance levels on work plane. / IL. Ratio = 250/1787 ≈ 1/7

Fig. 138_ Performance with sunshade /Illuminance levels on work plane. / IL. Ratio = 197/931 ≈ 1/4

Fig. 139_ Graph illustrating Illuminance levels along the room, both with and without shading device.
Similarly to the previous results, the performance of the room improves thanks to the sunshading device designed for the specific season, having a good distributing of illumination ranging from almost 1000 lux to 200 lux to the back of the room with an illuminance ratio 1/4.

However, what have been noticed for all the designed sunshades for South, West and East orientation is that, although there is an improvement in terms of shading and illuminance ratio inside the room, figures start decreasing at the back of the work-plane. However, they fluctuate always into the frame of the Useful illuminance levels (2000lux>UIL<100lux) and ratios. (1:5 or 1:10).

Also, the critical position for DGP is the sitting desk on the right side of the room, as it is the closest position to the window.
5.1.3 Performance / Physical model based

For the physical model performance experiments, a scaled box-model (scale: 1/5) available from the building physics sector of TU Delft with dimensions 1.10x0.74x0.57cm has been used. The dimensions are the same with the computational model used in scale 1/1 (5.50x3.75x2.85m). The measurements were done in TU Delft faculty of architecture and the building environment (52°01’N, 04°22’E) on 11th of May for two specific times, at 15:30 and 17:00 when the sky was clear, in order to check luminance numbers for two different positions of the sun. The model was placed in front of a southwest faced window which faces Michiel de Ruyterweg road. The window diverges from North-South axis about 40°.

The design arisen after the performance analysis is presented in fig. 114 and 144. This specific sunshading device (fig. 144) is fabricated with FDM by the leapfrog 3d printer in 1:5 scale in order to be tested with the physical box office-model.

For the experiment, a calibrated digital camera, Canon EOS 350D, with a lens SIGMA DC 18-50mm ex macro, was mounted on a tripod at a height of 33 cm from the floor of the box (eye level) to the back of the room through a hole in the box at the eye level. For the first experiment both photos without and with the facade were taken in order to compare the results. For the test, the calibrated camera took three pictures for every scene, one picture is over-exposed to light (too bright), the second one is low exposed to light (too dark) and the last one is a normal picture, with normal brightness and contrast levels. After that pictures were imported to Technoteam software in order to be combined into one brightness and translated into a false color image illustrating the luminance numbers into the space of the room.
Test 1 11/05/2015 at 15:30
Camera height: 1.65m (in real scale, eye level)

According to fig. 147 which represents the amount of luminance of the working space without the facade, it is observed that at 15:30 the numbers exceed the amount of 4000 cd/m² inside the room with a peak of about 10000 cd/m² when it comes to the table surface. Even the floor reaches almost 5000 cd/m² when there is no the self-shadow of the tables. The minimum luminance (600 cd/m²) is under the table caused by its shadow. However, the luminance contrast for a person entering the room of the first image is 10000:600 = 1:16 which is acceptable.

On the other hand, when the facade is attached to the frame, results change significantly at 15:30. More specifically, the numbers show 400-1000 cd/m² on the floor and about 1000 to 2500 cd/m² at the chairs vertical surface and the desk surface. Also, around the window the wall surface exceeds the number of 1500 cd/m² reaching almost 2500 cd/m² on the desk, as it is presented clearly in the zoom image (fig. 149). The luminance contrast for a person entering a room at 15:30 is 250:2500 = 1:10, which is acceptable.

Test 2 11/05/2015 at 17:00
Camera height: 1.65m (in real scale, eye level)
According to fig.150 and fig.151, the difference in the results with the first test is that the sun has turned more to the side and at a lower height, so the right side of the room is less bright than the left. The maximum luminance levels at 17:00 reach the number of 3000 cd/m$^2$ on the desk surface and the minimum luminance number is about 250 on the floor under the desk. That means that the luminance contrast for a person entering the room is almost 250:3000= 1:12 which is again an acceptable number for the panorama view (person entering the room).

What is important to note here is that desks have been located next to the window (0m distance from the window) which is the worst case scenario, as glaring probability is always higher when it comes closer to the glass pane.

Note: The physical model is designed and fabricated according to requirements for south-faced windows for Delft latitude (52°). During the test with the physical model the box-office with the attached facade, was located at a southwest window of the faculty causing the sun to come also from the side, resulting in a higher amount of glare probability than the one that would occur for a south faced window.

In the next paragraph, a computer model, with exactly the same conditions (11/05/2015 at 15:30 and 17:00 for a southwest window, latitude 52°) will be examined in order to provide us with information about glaring probability for a person sitting on his desk. (ergorama)

### 5.1.3.1 Comparison with Southwest orientation computer model

In the images below the performance of the fabricated sunshading device is tested on the computer model. As it is presented the images show similar patterns with the ones of the physical model for the same date and hours of the day. The computer model, provide us, also with information about the glaring probability on the side of the room, while a person is working at his desk. According to the DGP factor the daylight glaring probability is increased when it comes to 17:00, as the sun is in a lower position.
Test 1
11/05/2015 at 15:30
Camera height: 1.65 at the back and 1.20m from the side

*Fig. 152_ DGP factor and luminance numbers for: 05/11_at 15:30, camera located to the back of the room / Camera height: 1.65m*

*Fig. 153_ DGP factor and luminance numbers for: 05/11_at 15:30 on the right side of the room / Camera height: 1.20m*

*Fig. 154_ DGP factor and luminance numbers for: 05/11_at 15:30 on the left side of the room / Camera height: 1.20m*
Test 1
11/05/2015 at 17:00
Camera height: 1.65 at the back and 1.20m from the side

Fig. 155_ DGP factor and luminance numbers for: 05/11 at 17:00, camera located to the back of the room / Camera height: 1.65m

Fig. 156_ DGP factor and luminance numbers for: 05/11 at 17:00 on the right side of the room / Camera height: 1.20m

Fig. 157_ DGP factor and luminance numbers for: 05/11 at 17:00 on the left side of the room / Camera height: 1.20m
5.1.4 Conclusions & performance customization

In the previous paragraphs an effort has been done in order to design an efficient sunshading device for the South, West and East orientation for the summer period in Netherlands. What it is observed is that the designed sunshades, especially for the west and southwest orientation, where the sun comes from the side, do not solve at all the glaring problem when it comes to a position next to the window. Figures 153, 154, 156, 157 presents annoying luminance contrast mostly on the left desk entering the room, when the DGP factor is higher than the right side.

The solution to that could be:
- Position the working desks in a minimum distance of 1 m from the glass pane.

-Use translucent material for the sunshading device, in order to minimize the contrast caused by the shadow of the sunshade.

However, the potential of this product is not that it is an optimised solution, for several periods during the year, but, the fact that the user can customized the performance of his device. More specifically, he can adjust the given parameters of the design in that way that the sunshade can affect the illuminance levels inside the space, according to his needs. For instance he could design the device according to the organization and decoration of his space. Furthermore, after a period he can also, change the design of his sunshade and the organization of his working space, according to the illuminance levels that the new device offers.

In the example below it is assumed that the user doesn’t want to have views to the outside in order to work without being distracted. In that way he can organize where his office is accordingly. On the other hand, when he wants to change the organization of the space he can order a different shading device, designed according the changes inside the room.
Fig. 160a,b. Organizing a working space according to two different alternative sunshades. Each one of them provide views to the outside in the sitting area of the office and useful illuminance levels in the working space.
However, the potential of customization of the shading performance, could, also, work, the other way around. If, for instance, we have a rectangular space divided by different uses, that require different performance for a specific day, like dark space for an auditorium, controlled light for a working space and locally bright pots for specific kind of work, the facade that matches to its of the different uses, can be designed that way, in order to have the required performance, for a specific hour of a day.

Fig. 161a. Rectangular space. divided with different uses and required shading performance and brightness.

Fig. 161b. Facade providing extreme brightness levels and contrast.

Fig. 161c. Facade providing dark levels.

Fig. 161d. Facade providing controlled light.
5.2 FABRICATION

5.2.1 Process-Material

The fabrication process and the material selected are FDM process and PET filament as they were accessible from the department of informatics. TOI (Technisch Ontwerp en Informatica) of Architecture and the building environment of TU Delft university provided the leapfrog 3d printer which uses FDM process, and has a building chamber of 200x270x200 mm. This affect the design as the higher possible dimensions of one module—one rhombus is 200x270x200mm.

The Assembling process consists of i) the assembly of the modules, ii) the assembly of the modules with the connectors and tubes to create the whole panel (device) and iii) the attachment of the device to the window frame.

5.2.2 Steps of Assembling

According to the assembling of the modules, the tests of the 3d-printed snap-fit connection showed that connections with integrated “clamps” are the most efficient compared to the other types of joints, for this application. The angle of the female and male part defines if the joint will be detachable or non-detachable. The four edges of the rhombus have either holes-female or clamps-male parts that they can be assembled together. What is important to take into consideration in this step is the modeling of the connections, as the settings of the machine affect the correct tolerance between the assembling parts, and play an important role when avoiding loose connections. The settings of the machine are crucial factors for the structural performance of the final object, as well.

When the modules are assembled together, the whole device is attached to two aluminum tubes on the top and the bottom zone of rhombus, where the modules are perforated in order for the tube to pass through them and be fixed with bolts in order to protect the device from movements, caused by the wind.

Once, the device-panel is ready and supported by the tubes, four 3D printed connectors are screwed to the aluminum tube. Each of them is located in the edge of the tube. After that, the whole device is glued to the Aluminum or PVC frame with cyanocrylate adhesive which performance permits to support the weight of the sun shading device. The application to the timber frame could me done with six short screws, four of them at the top corners of the frame, and just two screws at the bottom, one on each of the bottom corners. Short screws are used in order to avoid thermal bridges. The device can be attached to both fixed and operable windows. When it comes to an outward opening window the device is glued to the inner movable frame. When it comes to a fixed window, the device could be glued to the outer fixed frame.

So the sunshade is provided like a panel which can be attached directly to the window frame.

Fig. 161a,b_ Attach sunshade to the movable, or fixed part of the window respectively.
Fig 162_STEP 1 | Assembling of modules

Fig 163_STEP 2 | Assembled panel

Fig 164_STEP 3 | Assembling of aluminum tubes on the top and the bottom zone of the rhombus. The modules on the top and the bottom consist of an integrated perforated connector with holes, in order to be fixed to the tube.
Fig 165_STEP 4 I Attaching the 3D printed connectors to the aluminum tube.

Fig 166_STEP 5 I Attaching the whole panel to the aluminum / PVC frame with cyanocrylate adhesive.

Fig 167_STEP 6 I Attaching the device in each window frame.
5.2.2.1 Assembly of modules

One every two modules consists of eight snap-fit connections, two at each of the four edges of the rhombus, the male module. The other module is the female part having eight slots, two at every edge of the rhombus respectively. The assembling of the modules follows the principle of the puzzle.
Fig. 171. Perspective view of snap-fit joint

Fig. 172. Section of two assembling modules

Fig. 173. Zoom of the snap-fit joint.
CASE STUDY

- Snap-fit connections dimensions calculations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Shear strength (τ)</th>
<th>Shear axial (yield)</th>
<th>Tensile strength (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon Pa12</td>
<td>33 MPa</td>
<td>43 MPa</td>
<td>55 MPa</td>
</tr>
<tr>
<td>PET</td>
<td>33 MPa</td>
<td>43 MPa</td>
<td>55 MPa</td>
</tr>
<tr>
<td>ASA</td>
<td>33 MPa</td>
<td>43 MPa</td>
<td>55 MPa</td>
</tr>
</tbody>
</table>

|                | 15 MPa              | 21.7 MPa            | 27.5 MPa             |
|                | 27.6 MPa            | 38.6 MPa            | 51.7 MPa             |
|                | 20 MPa              |                     |                     |

|                | 60 MPa              |                     |                     |
|                | 51.7 MPa            |                     |                     |
|                | 25MPa               |                     |                     |

Shear strength: 1/8 (ql**2)**
The detailing part is divided in two parts.
Detail 1: Snap fit connections
Detail 2: Assembling with the window frame

**Detail 1: Snap fit connection**

The structure is a sunshading device consisting of modules which are assembled together with snapfit connections. The top and the bottom zone of modules are supported to the window frame through two metal tubes one on the top and another on the bottom. From now on, the whole device will be considered like a panel. The two metal tubes are hanged to the window frame through 3D printed connectors that are attached with the frame with adhesive bonds. The construction has been simplified like a beam in order for the calculations to be done.

The forces applied to the panel are the distributed load of the wind (1kN/m²) and the weight of the device itself. For the calculations of the dimensions of the length of the panel and the modeling of the snapfit connections, the CES edupack2004 was used in order to define the mechanical properties of PET and Nylon. The calculations have been done for the PET material, considering a safety factor of 1/2 for the mechanical properties, as the mechanical properties of a 3D printed material decrease because of the layer-building process. (not a uniform material) (A.Veen 2014)

**Axial force in the point P calculation**

The critical point of the device is where the maximum basic moment, causing by wind. It is located in the middle of the panel causing a shear force to the connections. The permitted shear strength (τ) of PET has been used in order to define the maximum force in the middle point of the panel-if we consider the shading device supported from the metal tube to behave like a panel. As the weakest point of the structure is the joint of the male part of the snapfit connection with the body of the module, the shear force caused by the maximum moment in the middle of the panel is calculated.

Then, the moment in the P point (weakest point) is calculated and the axial force that stresses this point as well.

After that, the permitted axial (yield) strength of PET is compared with the calculated one in order to see if the joint is going to break.

In the same way, the maximum shear strength of PET is compared with the shear stress that the maximum moment causes.

The maximum moment, the shear force and the axial force are calculated both for l=2, and l=1.5m.

Wind: 1kN/m², \( q=\frac{wx}{l}=0.065kN/m \)
\( d=0.093m \)
\( A=0.00009m² \)

\( l=\frac{yh^3}{12} \)
\( W=\frac{l}{2}=\frac{yh^2}{6}=0.005^2\times0.018/6=0.000000075m³ \)
- Check axial strength regarding σ permitted of PET

\[ \sigma_{\text{PET}} = 30000 \text{kN/m}^2 \]

\[ 42000 \text{kN/m}^2 > 30000 \text{kN/m}^2 \]

so for a panel length of 2mm the area of the snap fit joint has to increase.

- Check shear strength regarding τ permitted of PET

\[ \tau_{\text{PET}} = 27579 \text{kN/m}^2 \]

\[ 3888 \text{kN/m}^2 < 27579 \text{kN/m}^2 \]

Both axial force and shear force are smaller than maximum PET axial and shear strength respectively, so the joint connection can resist the applied loads.

- For l=2m we recalculate the area of the joint as it is what affects the strength of the joint.

\[ W = \frac{l}{2} = \frac{y \cdot h}{2} = \frac{0.006}{2} = 0.000000108 \text{m}^3 \]

In the point P:
\[ M_p = F \times d = 0.035 \times 0.009 = 0.00315 \text{kNm} \]
\[ \sigma = \frac{M_p}{W} = \frac{0.0028}{0.000000075} = 42000 \text{kN/m}^2 \]
Enginnering test

As it is mentioned before, 3D printed objects have sometimes unpredictable behavior when it comes to their mechanical properties. In the previous paragraph the dimensions of the male part of the snap fit joint were calculated, taking into consideration a shape factor of 1/2 for both the permitted shear and yield strength of PET. According to the above, the designed male joint can withstand a load till 0.360 kN. That means 36 kg. In this chapter the engineering test of the snap-fit connection realized in the laboratory of the Mechanical engineering department of TU Delft University is described.

First of all, the proposed snap-fir joint, was modeled and 3D printed three times with the FDM method with PET material, having a rectilinear infill of 100%.

Fig 175_3D printed connection with FDM method, PET material.
The joint has been modeled in that way in order to be tested for the axial force, caused by the wind as it is mentioned before. So the male and female part of the connection are 3D printed with an arm which is attached to the clamps of the machine that apply the axial force. The layers have been positioned vertically to the direction of the expected failure, due to the fact that the printing material presents “clear directional behavior in the way that tensile strength parallel to the grain is significantly higher than perpendicular to the grain”. (A.C. van der Veen, 2014)

Fig 176a. Location of joints to the printing bed, b. zoom of joints with rectilinear pattern.

Fig 176c. Rectilinear pattern vertical to the direction of expected failure.

Fig 177a,b. Setting up of machine in order to test the axial force applied to the snap-fit joint that that causes failure.

Fig 178a,b. Results after the test. Specimen 1, 2 are broken only in the female part and Specimen 3 is broken on both expected points of failure.

497.3151245 N

687.7719727 N

545.9266357 N
According to the results the most sensitive part of the joint is the female part, as it is the first that broke at the first and second specimen. The male part of the second specimen withstand a load more than 697.7 N which is more than the estimated load that the joint could withstand during the hand calculations. However, the third specimen is broken in both the male and female part under a load of 545.9 N. Which is again more than the calculated one (360 N). That means that the estimated yield strength of PET material has to be considered with a shape factor of less than 1/2 when it comes to a 3D printed object from PET with the setting used and the layers have been positioned vertically to the direction of the expected failure.
If we take into consideration the worst scenario, which is the 3rd specimen which broke under a load of 545 N:

\[ F = \frac{M_p}{b} \]

\[ M_p = F \times b = 0.545 \times 0.009 = 0.0049 \text{ kNm} \]

\[ \sigma = \frac{M_p}{W} = \frac{0.0049}{0.000000108} = 45416 \text{ kN/m}^2 \]

Thus, the axial strength \( \sigma \) permitted for PET, when it comes to a 3D printed object with the layers positioned vertically to the direction of the expected failure is 45416 kN/m\(^2\). That means that for a panel of max 2 m height the male part of the joint can have the initial proposed dimensions of:

\[ b=9\text{mm} \]
\[ y=18\text{mm} \]
\[ h=5\text{mm} \]
\[ A=90\text{mm} \]

The results of this test showed that the designed connection both the male and female part is able to withstand the load, if the layers of the object are positioned vertically to the pot of failure, as the force caused by the wind for the specific structure is calculated to be 350 N, and both the male and female part of the snap-fit joint were not broken in this force magnitude.

The above test can prove the structurally performance of the module if it is positioned, as it is presented in fig. 183. However, this positioning to the printed bed, requires more support material to be produced, thus more printed time. Therefore, the engineering test is recommended to be realized, also, for printed connections with layers positioned horizontally, and with an angle to the direction of expected failure (break).
5.2.2.2 Assembling to the window frame

-Shading device weight calculation

In order to define how the shading device will be attached to the frame the weight of the whole system has to be calculated. To calculate the weight of the whole shading we assume that dimensions of the panel are l=2m (calculated maximum length above) w=1.5m. The panel is supported in the four corners of the frame, so the top corners bear a load of half the weight of the sunshade (G/2).

Weight Calculation
The area of half the designed sunshade is calculated in Rhinoceros 5.
A=4.40m²
V=3.5 x 0.003= 0.0105m³
Pet density: p=1.38 x 10³ kg/m³

\[ p = \frac{m}{V} \]
\[ m = p \times V = 1.38 \times 10^3 \times 0.0105 = 14.49 \text{ kg} \]

\[ G = m \times g = 9.81 \times 12.14 = 142.14 \text{ N} \]
\[ G = 0.14 \text{kN} \]

\[ G/2 = 0.07 \text{kN} = F \]

\[ F = 71 \text{ N} \]
**CASE STUDY**

**-Aluminum - PVC frame**

**-Detail 2 : Component dimensions calculation**

For the assembling to the window frame four 3D printed receptors will be attached to the four corners of the window frame. The two receptors-components on the top and on the bottom of the frame will be attached with the shading device with two aluminum tubes that pass through the perforated module, since the top and the bottom zone of rhombus have holes in order to be attached with the tube. The metal tube is fixed both with the device and the receptors with bolts in order to avoid the movement, caused by the wind, and as a result the noise of the device, to be avoided.

The two receptors on the top of the frame are bearing a load of 142N, so each one of them bears a load of 71N.

\[
F = M \times d \\
M = F \times d = 0.07 \times 0.05 = 0.003 \text{ kNm} \\
\sigma = M / I \\
I = M / \sigma = 0.014 / 30000 = 11 \times 10^{-8} \text{ m} \\
2l = 22 \mu m
\]

The adhesive solutions that can be used are the followings and they **have to perform well in shear stress:**

1. Adhesive: cyanoacrylate adhesive such as Permabond 737 or 910 (Appendix B). Cyanoacrylates are very good for bonding PVC and aluminum frames plastics, as ABS plastic, which is a printable material. They have good adhesion and high strength. Permabond 737 could be used where dissimilar surfaces are involved. Permabond 910 is very good for bonding metals.
For safety reasons, as adhesive bonds exposed to high temperature may cause failure, an extra loaded point could be glued in the middle of the frame in addition to the ones at the corners of the frame. It should be placed in a lower position than the main receptors to avoid bearing load. If the two others fail, then the middle one will support the device, until the maintenance of the main components.

### Adhesive performance

\[ 71\text{N}/800\text{mm}^2 = 0.088\text{N/mm}^2 < 6\text{ N/mm}^2 \]

amount of shear strength for adhesion with PVC and ABS that may occur failure (see Appendix B). Therefore even wider panels can be attached to the frame without more connectors involved. The next table shows the dimensions, the weight and the load that it is applied to the one receptor of four possible panels.

<table>
<thead>
<tr>
<th>Device Dimensions (m)</th>
<th>Weight (Kg)</th>
<th>Load applied to the receptor (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 (height) x 1.2 (width)</td>
<td>10.9</td>
<td>53</td>
</tr>
<tr>
<td>2 (height) x 1.5 (width)</td>
<td>14.49</td>
<td>71</td>
</tr>
<tr>
<td>2 (height) x 2 (width)</td>
<td>20</td>
<td>98</td>
</tr>
</tbody>
</table>

Table 14. Three possible panels dimensions and weight.

For safety reasons, as adhesive bonds exposed to high temperature may cause failure, an extra loaded point could be glued in the middle of the frame in addition to the ones at the corners of the frame. It should be placed in a lower position than the main receptors to avoid bearing load. If the two others fail, then the middle one will support the device, until the maintenance of the main components.

### Timber frame

The attachment of the device to the timber frame is realized with short wood screws on the four corner of the frame. As the panels are light enough, till 20 kg, the screws can be short enough in order not to damage the frame and create thermal bridge. As the two top connectors bearing the load of the device, each one of them is attached with two screws to the frame. The bottom connectors, can just be bolted with one screw, as they do not bearing any load.

As wood is a porous material and plastic is a non-porous material, an adhesive bond may not perform well. For this reason short screws attached directly to the frame seems to be the best solution.

![Fig.184_Assembling of the panel to the timber frame.](image-url)
The adhesive alternative, explained above, is a permanent solution.
- A more temporal alternative solution, which leave the window frame intact, could be vacuum lifters for transportation of glass. However, we cannot assume the performance of these devices as the long extension to the outside could reduce performance. Therefore, further tests should be done before they can be proposed as a safe solution.

In the next two pages, fabricated modules from FDM, PET material in 1:1 scale are illustrated. (See appendix C for more photos)
Drawings of the sunshade applied to a typical aluminum frame

Applying the sunshade to a typical operable aluminum frame 1.20 x 1.50m with operable window. Similarly it works to a PVC frame.
CASE STUDY

- Typical operable aluminum window frame 1.20 x 1.50m

Double insulated glass (32mm)
Wooden lintel
Existing masonry
Water barrier
Air cavity
Mineral wool insulation 150mm

Aluminum window frame
Cyanocrylate adhesive Perma-bond 737
Fixing screw M3.5
Aluminum tube Φ10 fixed with bolts to the sunshading device
3D printed shading device, PET plastic, coated with brominated polysyrrene

3D printed shading device, PET plastic, coated with brominated polysyrrene
Cyanocrylate adhesive Perma-bond 737
Aluminum window frame

Detail 1_Vertical section, scale 1:5
Detail 2_Horizontal section, scale 1:5
-Typical operable timber window frame 1.20 x 1.50m

Detail 1_Vertical section, scale 1:5

Existing masonry
Water barrier
Air cavity
Mineral wool insulation 150mm

Outer frame timber
Outwards opening timber vent profile
Wood screw M3, 25MM
Fixing screw M3.5
Aluminum tube Ø10 fixed with bolts to the sunshading device
3D printed shading device, PET plastic, coated with brominated polystyrene
Double insulated glass(32mm)

Detail 2_Horizontal section, scale 1:5

Existing masonry
Mineral wool insulation 150mm
Air cavity

3D printed shading device, PET plastic, coated with brominated polystyrene
Wood screw M3, 25MM
Outwards opening timber frame
Fig 186. Exterior Visualization.
3D model showing the BK city building of TU Delft using the proposed facade system for the student studios.

Fig 187. Interior Visualization.
3D model showing interior space of a studio in BK city building of TU Delft using the proposed facade system, which creates interesting shadow patterns to the interior.
Fig 188. Interior Visualization.
3d Model showing interior space of the studio. The facade system blocks the sun from the side in the west side and allow more views in the south.

Fig 189. Interior Visualization.
3d Model showing interior space of the studio. Enjoying views to the outside.
As the main scope of the research is a product design, an initial approach to form a business plan for the product is presented in this chapter. The part of the customer validation and the definition of the additive value of the product started during a two days start up event in YES Delft. Along with this event, research on the Internet has been carried out in order to find useful information to form the business plan for this thesis product. It should be pointed out, that this on-line research is based on trustworthy websites which have provided us with some of the figures that were needed.

In the framework of customer validation, a questionnaire (appendix V) was sent to both personal and non-personal contacts in order to verify first, if people have issues with sunlight and if they are satisfied with their already installed sunshades. Additionally, they were asked, as potential clients, if they would like to create and fabricate their own sunshading device. 71 people participated in the on-line survey and 8 people were interviewed. 38% of them verified that the major issue they usually address due to daylight is overheating in the summer and glaring (screen reflection), while 39% of them claimed that they were not satisfied of the aesthetics of their existing sunshades. An amount of 82% participants asserted that they care about the aesthetics of their sunscreen, whereas 63% would like the opportunity to create their own. However, here it should be mentioned that, in order to have a more scientific approach, the current customer validation should have a wider sample of population.

The business plan below, has been created on the figures from on-line research for a UK case study. The main reason for that is that this case study was the most accurate information which was available, regarding the window coverings market.

6.1 COMPANY DESCRIPTION

“Design your shutters.com” will produce a specific product that forms part of the domestic window covering market. This market is made up of several items the aim of which is to cover windows with different purposes, such as privacy, light, glare and heat.

“Design your shutters.com” will produce customizable shutters that will be sold on-line. Thanks to the 3D printing process and the unique design that will involve the whole production of the shutters will be able to solve all problems that users are faced when using any window covering item: blinds, curtains, shutters, awnings, etc. Currently, none of these items listed before can solve all the problems that users are still experiencing when it comes to windows, these are, solar shading, redirection of light, view to the outside and glare control. The fact that our product can solve all the problems that users would like to solve when asked about problems connected to their current window covering systems (solar shading, redirection of light, view to the outside and glare control) is precisely its Unique Selling Point (USP).

The target group audience of “design your shutters.com” product is the freelancers that work at home and, therefore, need to recreate an appropriate working environment, most of the time in a room with a window.

As a unique product, the competitive advantage of the items sold by “design your shutters.com” rely on the capacity to provide a solution for the main problems or needs that users experience when it comes to windows: privacy preservation, view to the outside, maximization and redirection of daylight, glare control and solar shading. In addition, the unique designs of “design your shutters.com” shutters will give an extra value to our product.

6.2 MARKET ANALYSIS

Industry Description and Outlook
The domestic window coverings market in the UK, which will be worth around 1,1 billion by 2016 and £1,3 billion by 2018 in accordance with estimations, consists of four major product sectors: curtains, blinds, lightweight curtains and curtain suspension systems. The upturn in the market in 2013 followed two years of decline, which was basically the result of improvements in the housing market, with signs
of economic recovery boosting consumer confidence despite the fact that household spending was still constrained by rising utility bills, inflation, stagnate wages and levels of unemployment which remained high in some areas of the UK. (AMA research, 2014)

Replacement purchases account for 68% of the sales. New housebuilding and moves to a new home account for 22%, and home improvements for 10%.

As for different trends for this industry, it should be taken into consideration: a stronger new housing market; a higher level of housemoving activity; the improvement of householders’ spending power; an expected rise in e-commerce; the domination of mail order, Internet and catalogue stores regarding the distribution mix, which account for an estimated 30% of sales; and the dramatic increase of the time that people spend at home as freelance jobs keep on increasing.

6.3 TARGET MARKET

The main target group for this project are freelance professionals aged between 25 and 65 who work at home and have their table and/or computer next to a window.

Context of the Target Market
The average length of a workday is 8 hours. During those hours, the work environment –chairs and tables, temperature, light and, of course, all problems connected to window coverings- have gained importance as it is well known that comfort and happiness at work increase productivity. This also applies for freelancers, who are actually a one-person company.

Size of the Target Market
According to Forbes (Wald, J. 2013), “by 2020 freelancers are expected to make up 50% of the full time workforce. As independent work is becoming more common across all generations, and as companies are undergoing a major shift in how they hire (they’re staffing up and down as needed, eluding fixed costs and being able to effectively hire variable cost talent), offices are gradually moving from huge buildings to small rooms inside houses.” This means that, every year, more and more professionals will have to set up their own “office” at home.

Therefore, there is an audience made up of people between 25 and 65 that will be increased every year and who will be concerned by setting up a comfortable office at home, usually next to a window so that they can get some daylight while working. Since the great majority of freelancers use computers to do their jobs, problems and needs connected to window coverings will become increasingly important.

Expected market share
The total working UK population (16-64) accounts for approximately 42M people. If we stick to Forbes expectations –they refer to the USA, but here we can say that both the American and the British labor market do follow similar patterns-, over a third of all British workers are already freelancers. This leaves us with a figure of about 15M freelancers in the UK, and this would be exactly our target audience for the UK, which is expected to increase up to 20M by 2020. (Office of national statistics, http://www.ons.gov.uk/ons/index.html)

Let’s put some figures together before defining our final market share for the UK case study in 2016:
• 15 million of UK freelancers
• 1,1 billion domestic UK window covering market turnover
• New housebuilding, moves to a new home, conservatories and home improvements account for 3.500 million (33%).
Taking all these figures into account, we can state that our target market is made out of 15 million people in the UK. We also know that 3.500 million pounds will be spent in the UK on next 2016 on several domestic window covering items for new householding, moves to new homes, conservatories and improvements, which we believe are the main reasons why potential clients would buy our product. Obviously, further research should be done in case one wanting to come up with the precise figure of potential clients.

Cost, pricing and gross margin targets per unit

<table>
<thead>
<tr>
<th>Cost per unit</th>
<th>Cost per unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printing cost*</td>
<td>99.0€</td>
</tr>
<tr>
<td>Row material</td>
<td>99€</td>
</tr>
<tr>
<td>3D Printer Depreciation</td>
<td>2.6€</td>
</tr>
<tr>
<td>Consumables</td>
<td>2€</td>
</tr>
<tr>
<td>Electricity Usage</td>
<td>0.5€</td>
</tr>
<tr>
<td>Repairs and Upgrades</td>
<td>1€</td>
</tr>
<tr>
<td>Failures</td>
<td>1.5€</td>
</tr>
<tr>
<td>Packaging</td>
<td>0.1€</td>
</tr>
<tr>
<td>Shipping</td>
<td>2€</td>
</tr>
<tr>
<td>Professional monitoring</td>
<td>5€</td>
</tr>
<tr>
<td>Customer service</td>
<td>3€</td>
</tr>
<tr>
<td><strong>Final Cost</strong></td>
<td><strong>116.7€</strong></td>
</tr>
<tr>
<td>Business Margin profit</td>
<td>38€ (33%)</td>
</tr>
<tr>
<td><strong>FINAL PRICE</strong></td>
<td><strong>154 €</strong></td>
</tr>
</tbody>
</table>

Table 15_ Cost and gross margin per unit.

*Specifications: In order to come up with a figure that truly represents the cost of producing on unit, we have previously made some decisions which are based on King, L. (2014) research.

- The dimensions for a standard window frame are 1.50m*1.20m
- The weight of a shutter that fits a 1.50m*1.20m window frame account for 10.9 kg approximately.
- 10 kg of PET filament cost 99 € (https://www.indiegogo.com)

5.4 COMPETITIVE ANALYSIS

The main competitors of “design your shutters.com” are the online shops that sell blinds, shutters, curtains, awnings and shades that either rank high in organic searches on Google (SEO), which means only the very first page result, or appear as the main Google Ads results searches (SEM)

SEO competitors:
Blinds (89 M results by “Buy blind online” search): Blinds.com, Blinds to go, Argos
Shutters (2M results by “Buy shutters online” search): The Shutter Store, Horizon Shutters, Premier Shutters
Awnings (1,5M results by “Buy awnings online” search): Awnings.com, Awntech Corporation, General Awnings
Curtains (22M results by “Buy curtains online” search): Snapdeal, Overstock.com, FabFurnish.

SEM competitors:
This type of competitors changes according to the country in where one does the Google research, as Google Ads detects users’ IP address and tailor the ads shown in the results so that they belong to the country of research.
In addition to the current competitive brands, a different type of competitor is Ikea, as it has become a common and easy way for people to buy their furniture in the last years. Shutters and similar items can of course be found in Ikea.

5.5 COMPANY & ORGANIZATION

Setting up of the company

<table>
<thead>
<tr>
<th>Activity</th>
<th>Executed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Online Shopping</td>
<td>Web Design Partner</td>
</tr>
<tr>
<td>Online Marketing Strategy</td>
<td>Partner</td>
</tr>
<tr>
<td>Purchase of 5 3D Printers</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Set up of an office, pc, software, etc</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Packaging and shipping suppliers election</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Raw material suppliers election</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Online payment supplier election</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Online security system supplier election</td>
<td>design your shutters.com</td>
</tr>
</tbody>
</table>

Table 16_ Required activities in order to set up the company.

Ongoing activity of the company

<table>
<thead>
<tr>
<th>Activity</th>
<th>Executed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marketing online and Advertisement</td>
<td>Partner</td>
</tr>
<tr>
<td>Sales</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Design</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Performance</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Fabrication</td>
<td>design your shutters.com</td>
</tr>
<tr>
<td>Packaging and shipping</td>
<td>Supplier</td>
</tr>
<tr>
<td>Costumer service</td>
<td>design your shutters.com</td>
</tr>
</tbody>
</table>

Table 17_ Required activities of the company while it starts selling products.

Fig 190_Relationship of the customer with the product and related activities.
Ongoing business expenses

<table>
<thead>
<tr>
<th>Ongoing business expenses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed costs</td>
</tr>
<tr>
<td>Rent</td>
</tr>
<tr>
<td>Insurance</td>
</tr>
<tr>
<td>Advertisement</td>
</tr>
<tr>
<td>Equipment maintenance</td>
</tr>
<tr>
<td>Online shopping website maintenance and online security</td>
</tr>
<tr>
<td>Software</td>
</tr>
<tr>
<td>Variable Costs</td>
</tr>
<tr>
<td>Raw materials</td>
</tr>
<tr>
<td>Design, performance and fabrication</td>
</tr>
<tr>
<td>Packaging supplies</td>
</tr>
<tr>
<td>Shipping costs</td>
</tr>
<tr>
<td>Customer service</td>
</tr>
</tbody>
</table>

Table 18. General starting and ongoing expenses of the company.

5.6 RISKS

Technological risks
There is one main technological risk about this business plan. This concerns the development of the additive manufacturing technology; it’s difficult to predict how fast this new technology will develop, but such a company as “design your shutters.com” will of course depend on this development in order to be competitive. As long as 3D printers become more affordable, “design your shutters.com” should faster become more competitive in a growth sales scenario as it will be cheaper to acquire new 3D printers (fixed costs).

The technological risk includes the materials available by this technology. Their structural and thermal performance are challenging, so further research has to be done to some extend in order to verify the ISO of the product to be safe for outside use.

Financial Risk
The setting up of the company requires an approximately investment of at least 50.000€. The creation of a shopping online infrastructure which needs to be –and to seem- extremely secure and safe; the design of a website that should be as appealing as possible, as well as intuitive; the money invested on online advertisement and marketing online, which needs to be a lot as “design your shutters.com” will compete with huge companies in the “Google research” arena; and other indispensable costs that cannot be eluded when starting the company make it difficult in terms of financial resources.

![Fig 191_Graph showing the valey of death for a start-up.](image-url)
LITERATURE


7. CONCLUSIONS & RECOMMENDATIONS
7.1 FEASIBILITY OF THE CONCEPT

This research proposes a product design using the potential of dynamic parametric tools and Additive Manufacturing as fabrication process.

Parametric design is used in order to generate dynamic grids and patterns that can meet user preferences and aesthetics as shading devices, and provide information about shading performance as a result of variable updates. AM is used in order to fabricate a "homemade" sunshade for window frames.

Relation between fabrication method, parametric design and performance.

Through the research presented in the previous chapters, it is made clear that the triangular relation among parametric and computational design, performance and 3D printing is a relation that works, when it comes to a personalized sunshade which becomes from a file to a physical object. Thus, the project shows that it is feasible for a user to customize both the shading performance of a sunshade in an interior space and the aesthetics of a facade-sunshading device. This fact leads a revolution to product design sector and personalized solutions.

However, the challenging part of the concept is the use of AM as a fabrication method for an end-use product exposed to the outside conditions due to both the structural and thermal performance of the object.

Structural performance

For this project PET material was proposed and tested structurally for a specific module of a sunshade device. The results showed that the calculated dimensions of the proposal snap-fit joint can form a sunshade panel of 2 m height, when it is supported at the top and at the bottom. Width varies from 1.20 to 3.00 m.

The above is tested for the specific snap-fit joint in chapter 7 which is fabricated with FDM method, PET material taking into account a shape factor of 1/2 for the mechanical properties of the joint and locate the connection horizontally to the heated bed in order for the layering to be horizontal to the applied force, thus vertical to the direction of the predicted failure. This positioning of layers, is the stiffer one, due to the behavior of the printed objects. However as the geometry of the modules is not rectangular, engineering tests have to be done for all the orientations, also for connections horizontal and with an angle to the direction of failure.

Thermal performance

A printed object from PET is resistant to water and UV radiation. However, PET it is a high flammable material, thus for an extreme case of fire, the object has to be coated or sprayed with fire retardant or the filament itself has to be modified with a retardant before the printing process. In the first case the coating has to be removed first (mechanically or chemically) in order for the object to be recycled and be used as a filament again.

Applying the device to the window frame

The proposed sunshading device can be applied to fixed and outwards operable windows, for aluminum, pvc and timber frames. For this project the application to the window frame (aluminum, PVC) is realized with cyanocrylate adhesive. This is a permanent joint, so the proposed receptors are permanently glued to the frame and only the tube with the attached 3D printed modules can be removed and be replaced. For a timber frame the device is screwed to the frame with six short wood screws.
7.1 CONCLUSIONS

During the study was made clear that Additive Manufacturing and product design is a potential field for exploration. The combination of parametric tools and the specific fabrication process leads to customized products, as it makes possible to customize, by changing different parameters of the design, on the computer screen (file) and then fabricate it directly through 3D printing technology (factory). If this relation takes into advantage the commercial potential through Internet, then a new approach of product design is reality bringing the revolution in the field of industrial design and the way people buy and consume. This argument transform individuals to a dynamic part of the design and fabrication process, changing the existing facts of the industry market.

More specific conclusions for the proposed product are presented below:

-Light and shading device
As it is observed from the performance analysis of the shading device for all the orientations: South, East and West, the designed shutter improves the illuminance levels inside the room, protecting from glaring most of the hours per day. However as this is a fixed shading device, and daylight is dynamic phenomenon, it does not protect from glaring any hour of the day, for instance when the sun is in a very low position. For this reason, may a translucent material, like PET, for the sunshade could be ideal to use, in order not to create disturbing contrast between bright and dark pots inside the room.

-AM and shading device
Materials: from the material selected and available thermoplastics in the market for common users (apart from aerospace applications), there is no appropriate material producing end-use parts for outdoor use in buildings, with reasonable prices, so far. Nylon and PET need extra coatings to improve their thermal performance. More specifically, they need protection from the fire (PET, nylon) and the UV radiation (nylon). Therefore, recycling a coated printing object in order to transform it to new filament is not possible, unless the removal of the coating with mechanical or chemical processes proceed.

However, as it is clear from the research, there are advanced engineering materials for end-use parts with improved properties for specific applications, mostly in the aerospace industry. In addition, modified materials, that fire protection or UV protection is added to the filament from the beginning is also an option.

Mechanical properties of the printed objects from FDM method are challenging. The fact that it is a layer building process leads to a non-uniform material with lower mechanical properties compared to an object with the same material, produced uniformly by another fabrication method. Normally, a shape factor of 1/2 has to be considered for the mechanical properties of the final object. What affect the structural performance of the 3D printed object are also, the settings used (temperature, speed), the nozzle for extrusion and the infill pattern of the object. For a stronger connection, the layers have to be positioned vertically to the direction of the expected failure (break).

Finally, through the market analysis it is evident that the value of this product is its uniqueness to the existing market of similar products, in terms of performance, patterns, colors, transparency, specification of views and type of required protection. Therefore, there is available market for the 3D printed sunshade, but more extended research has to be done, for customer validation, technological and financial risks, for a real setting up of a company.


7.1 FUTURE RECOMMENDATIONS

The combination of the limited time of this thesis with the broad approach of the research lead to several future recommendations for different aspects of the product.

-Light and sunshading device.

The design selected to study further in the case study I focuses in the protection of sunlight in the summer. However, when it comes to winter with an overcast or cloudy sky, for climates of northern Europe, may devices that enhance the illuminance levels through redirection of light inside the room, could be considered in order to cover a broader market of sunshading devices and customer needs.

More research could be also, done for the levels of translucency of the 3D printed materials for a facade. Research in this field could be result in better shading performance when it comes to filter the sun for glaring protection and not totally block it. (e.g winter). Thus, the broad sector of materials could also be explored in order to test different levels of transparency and translucency of the device, leading to interesting effects and patterns inside the room.

-Parametric logic and performance.

Another recommendation is to include more variables into the parametric scripts of the patterns that may cover more user preferences and fulfill both daylight and thermal performance. Here optimization tools could be also considered.

-Additive manufacturing and shading device.

Future recommendations related with the exploration of new materials for the AM processes are very potential. Exploration of materials with better mechanical and thermal properties are very important for a product exposed to outside weather conditions, as it is crucial for the product to meet the “ISO” of a sunshade - facade. This field is already under development by companies and engineers, who make available in the market modified materials with better properties for specific applications.

According to materials field an important aspect to be considered is the potential of some printers to extrude two or more materials in the same printed object. This advantage leads to an object with different properties in its parts. Therefore, when it comes to a product like the proposed in this research, different materials could be used for the connections of the parts and others for the main body of the design itself in order to have more efficient and stronger connections which may permit motion between the different modules of the device. If motion is permitted between the assembling parts, the device could be also, dynamic, having the potential to change geometry in respect with the weather conditions. The material to be used for the joints could be more flexible than the one of the main body of the device in order to be more resistant to applied loads. With a flexible material used for the joints, they will show higher levels of deformation till failure in the end, compared to rigid parts. For rigid parts, the critical points, joints, is recommended to be positioned that way, in order for the layers to be vertical to the direction of possible break.

![Fig 192_Ideal position of layering during the building process for a good structural performance.](image-url)
- Applying to the window frame.

The alternative of using vacuum lifters for glass, could be integrated into the sunshading device. This way it is easier for the user to attach it to his frame without being a permanent solution and leave the frame intact. It is recommended vacuum lifters for glass to be tested in order to prove that they can carry the weight load of the device for extended time.

-Business plan and product design.

In the scope of this project an initial effort of the product business plan has been done. However, this field is very extensive itself, thus more investigation about the customer validation and the target group of the product have to be considered. Finally, more detailed numbers and costs of the company setup and the product itself is crucial to investigate further.
Personal Reflection

This document is a reflection of the process and methodology that I follow during my research. The main aspects that have to been examined are the following:

The relationship between research and design

This study focuses on exploring the potential of additive manufacturing in building sector, by introducing a product design for an external sun shading device for windows which is customized by each individual according to his/her needs. The main topic that this thesis investigates is customization. How people could become part of the design and the building process? This is the basic question that the research tries to answer through an example of a sunshade. The project introduces an interface that the user can access online in order to choose, modify, some already parametrically design patterns, or create himself a shading device and order it through the website. The device is fabricated with 3D printing fabrication process and is shipped to his place.

The methodology that I follow includes literature review in the beginning of the process, in order to get familiar with terms like light, shading, additive manufacturing and product design and define the requirements of a shading device on the one hand and explore the potential of Additive Manufacturing and customization, on the other hand. After this phase, the methodology followed a circular process among the logical framework of the interface, the parametric designs that the user can choose and modify, (variables that the user can change) the fabrication process through physical models and a case study. This circular methodology gave feedback to each of the different processes of the above, during the whole thesis.

Research process, design and tests with physical models worked together in a circular way. Through research the base for the logical framework of the designs and the fabrication process set up, while both design and fabrication informed each other giving feedback and arising questions to the research. The circular process, helped to improve every approach of the project and evaluate the results.

Finally, a case study was used in order to apply the concept to a real context and check the engineering aspects of the product, like the illuminance performance, the assembling methods and the structural performance, as well.

The relationship between the theme of the graduation lab and the subject/case study chosen by the student within this framework (location/object)

The sustainable design graduation studio belongs to the chair of Building Technology. The aim of this studio is to explore new innovative technologies either in façade design, or in structural design or in climate with a sustainable approach.

The subject selected explores the innovative technology of Additive Manufacturing in the building sector-façade through a case of a sun shading device. The sustainable approach of the technology itself is crucial. Additive manufacturing decrease many steps in the building process. It eliminates transferred cost: as it is transferred digitally and it is printed locally and it has a better control over the material, as, almost, there is no waste material after the process. In addition it reduces the progress steps of the building process, the tools needed and the assembling. Finally, it is potential green as it creates objects that can be recycled after their use and reuse them as row material.
On the other hand, shading devices, as the term presents, aiming to solar and glaring protection, resulting to decrease the heating and cooling load in the winter and summer respectively and the artificial light in the room as well. Thus, shading, as a passive design strategy decrease the energy consumption of a building.

Therefore this project explores a new innovative technology with a sustainable approach, testing engineering (assembling) and performance (light-shading) issues.

The relationship between the methodical line of approach of the graduation lab and the method chosen by the student in this framework.

The methodical line of approach of the graduation lab is technical-scientific study and design research or execution of a design.

The method chosen in this thesis is technical-scientific study and design by research and tests with physical models, which is the method used by the graduation studio. This methodology aims to a circular relation between research and design, where research is the base for the design and experiments with physical and computer models are the validation of it. These two different types of methodology give feedback the one to the other improving each aspect of the project and validating the results.

The relationship between the project and the wider social context.

The impact of the project to the wider society is obviously the industrial revolution that Additive manufacturing brings to product design and the potential for a consumer to be involved in the design and creation process.

According to I. Gibson (Gibson, 2009): “Conceptualization means the forming and relating of ideas, including the formation of digital versions of these ideas (e.g., CAD), creation means bringing an idea into physical existence (e.g., by manufacturing a component) and propagation means multiplying by reproduction through digital means (e.g., through digital social networks) or through physical means (e.g., by distributed AM production)”.

This is exactly what this project does. First an idea-concept-design is introduced through a website. The design is already a 3D printable file, which will be shared through internet to the user. Once, he adjusts the design to his needs (customization) he can 3D print it at his place or ask an online service to fabricate it and ship it to him.

As we can see, the project introduces a new way of creation and fabrication. It focuses to customization by additive manufacturing, studying the case of a sun-shading device that meets every user’s needs, as individual can change it regarding his own preference.

This research transforms individuals to a dynamic part of the design and fabrication process, changing the existing facts of the industry market.
APPENDIX A

The example of Greece

For design variation purposes another example with different context is presented in the chapter 4.1. As reference weather conditions for this example, weather climate data of Thessaloniki in Greece is selected.

The design selected is curved louvers in vertical position designed for the east orientation. The distortion of the straight louvers permits open spaces to the eye level, for contact with the outside. In this Appendix is presented the performance in lux of the specific device and in which amount it improves the brightness of the space.

CLIMATE-LOCATION VARIABLES
INPUT / CONTEXT
_LOCATION | THESSALONIKI | GREECE
_LATITUDE 52°03’N | LONGITUDE 04°22’E
_DATE | 21th JUNE, TIME | 12:00
_ORIENTATION | EAST
_USE | OFFICE

USER PREFERENCES VARIABLES
INPUT / REQUIREMENTS
_ROOM DIMENSIONS | 5.5x3.75x2.85m
_DIMENSIONS FRAME | 3.20x1.80m
_LIGHTING FOR A WORK SPACE | CONTROLLED / UNIFORM
_VIEWS | HIGHER PERFORATION TO THE EYE & SITTING LEVEL
_PROTECTION | SHADING, GLARING
Performance without sun-shading device/ Illuminance levels on work plane.

Performance with sun-shading device/ Illuminance levels on work plane.

Graph: Comparison of the device performance

Assembling: Separation of modules

Transparent material for assembling clear PET or nylon
Material of sunshading device opaque PET or nylon

Assembling: Exploded front view of modules
APPENDIX B

Permabond Adhesives_Datasheets

PERMABOND® 737
Cyanacrylate
Technical Datasheet

### Typical Performance of Cured Adhesive

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength*</td>
<td>15-19 N/mm² (2800-3500psi)</td>
</tr>
<tr>
<td>Female strength</td>
<td>25 N/mm²</td>
</tr>
<tr>
<td>Peel Strength</td>
<td>40-60 N/25mm (9.13 IW)</td>
</tr>
<tr>
<td>Impact strength</td>
<td>5-10 kJ/m² (2.4-4.8 ft-lb/in²)</td>
</tr>
<tr>
<td>Dielectric constant @2kHz</td>
<td>2.5</td>
</tr>
<tr>
<td>Dielectric strength</td>
<td>25 kV/mm</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>90 x 10⁻⁶ mm/mm/°C</td>
</tr>
<tr>
<td>Coefficient of thermal conductivity</td>
<td>0.3 W/(m.K)</td>
</tr>
<tr>
<td>Hardness (ISO868)</td>
<td>85 Shore D</td>
</tr>
</tbody>
</table>

*Strength results will vary depending on the level of surface preparation and gap. **SF = Substrate failure

737 can withstand higher temperatures for brief periods (such as for paint baking and wave soldering processes) providing the joint is not unduly stressed. The minimum temperature the cured adhesive can be exposed to is -55°C (-65°F) depending on the materials being bonded.

---

PERMABOND® 910
Cyanacrylate
Technical Datasheet

### Typical Performance of Cured Adhesive

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength*</td>
<td>23-29 N/mm² (3900-4900psi)</td>
</tr>
<tr>
<td>Female strength</td>
<td>25 N/mm²</td>
</tr>
<tr>
<td>Peel Strength</td>
<td>50-60 N/25mm (11.8 IW)</td>
</tr>
<tr>
<td>Impact strength</td>
<td>15-20 kJ/m² (0.8-1.2 ft-lb/in²)</td>
</tr>
<tr>
<td>Dielectric constant @2kHz</td>
<td>3.5</td>
</tr>
<tr>
<td>Dielectric strength</td>
<td>25 kV/mm</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>90 x 10⁻⁶ mm/mm/°C</td>
</tr>
<tr>
<td>Coefficient of thermal conductivity</td>
<td>0.3 W/(m.K)</td>
</tr>
<tr>
<td>Hardness (ISO868)</td>
<td>85 Shore D</td>
</tr>
</tbody>
</table>

*Strength results will vary depending on the level of surface preparation and gap. **SF = Substrate failure

910 can withstand higher temperatures for brief periods (such as for paint baking and wave soldering processes) providing the joint is not unduly stressed. The minimum temperature the cured adhesive can be exposed to is -55°C (-65°F) depending on the materials being bonded.
Short term influence of temperature on mechanical properties

An overview about the temperature dependence of mechanical properties of PA 12 can be retrieved from the curves for dynamic shear modulus and loss factor as function of temperature according to ISO 527.

![Graph](image)

In general parts made of PA 12 show high mechanical strength and elasticity under steady stress in a temperature range from -40°C till +80°C. Short-time loading of parts made of PA 12 without stress is possible up to 160°C.

Long term properties under mechanical load and temperature

In general thermoplastics have higher mechanical strength under short term load than under long term load (> 1000 h) as result of creep. This occurs mostly at higher temperatures and leads to a reduction of modulus ( creep modulus). Usually the creep resistance (mechanical properties under continuous load) is determined with the uniaxial tensile creep test (ISO 52444) under different loads and temperatures.

![Graph](image)

Creep modulus curves PA 12 at \( T = 23^\circ C/100^\circ C \)

![Graph](image)

Creep elongation curves PA 12 at \( T = 23^\circ C/100^\circ C \)

Electrical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Measurement Method</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Resistance</td>
<td>DIN 53482, IEC-Publ. 93</td>
<td>( \Omega )cm</td>
<td>10^-10</td>
</tr>
<tr>
<td>Surface Resistance</td>
<td>DIN 53482, IEC-Publ. 93</td>
<td>( \Omega )</td>
<td>10^1</td>
</tr>
<tr>
<td>Relative Permittivity (1 kHz)</td>
<td>DIN 53483, IEC-Publ. 250</td>
<td>( \varepsilon )</td>
<td>3.8</td>
</tr>
<tr>
<td>Dielectric strength</td>
<td>DIN 53481, IEC-Publ. 250</td>
<td>kV/mm</td>
<td>92</td>
</tr>
<tr>
<td>Dielectric dissipation factor (1 kHz)</td>
<td>DIN 53483, IEC-Publ. 250</td>
<td>-</td>
<td>0.05 - 0.29</td>
</tr>
</tbody>
</table>

The electrical properties depend on temperature and relative air humidity strongly. The above mentioned values characterize polyamide 12 at following conditions: storage at 23°C, 50% air humidity up to saturation.
ASA_stratasys_Technical Datasheet

- UV-resistance
- End-use parts for outdoor commercial and infrastructure use
- Wide selection of colors

### Mechanical Properties

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Standard</th>
<th>English</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XZ Orientation</td>
<td>ZX Orientation</td>
<td>XZ Orientation</td>
</tr>
<tr>
<td>Tensile Strength, Yield (Type 1, 0.125&quot;, 0.2&quot;/min)</td>
<td>ASTM D638</td>
<td>4,200 psi</td>
<td>3,850 psi</td>
</tr>
<tr>
<td>Tensile Strength, Ultimate (Type 1, 0.125&quot;, 0.2&quot;/min)</td>
<td>ASTM D638</td>
<td>4,750 psi</td>
<td>4,300 psi</td>
</tr>
<tr>
<td>Tensile Modulus (Type 1, 0.125&quot;, 0.2&quot;/min)</td>
<td>ASTM D638</td>
<td>290,000 psi</td>
<td>280,000 psi</td>
</tr>
<tr>
<td>Elongation at Break (Type 1, 0.125&quot;, 0.2&quot;/min)</td>
<td>ASTM D638</td>
<td>9%</td>
<td>3%</td>
</tr>
<tr>
<td>Elongation at Yield (Type 1, 0.125&quot;, 0.2&quot;/min)</td>
<td>ASTM D638</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Flexural Strength (Method 1, 0.05&quot;/min)</td>
<td>ASTM D790</td>
<td>8,700 psi</td>
<td>6,900 psi</td>
</tr>
<tr>
<td>Flexural Modulus (Method 1, 0.05&quot;/min)</td>
<td>ASTM D790</td>
<td>270,000 psi</td>
<td>240,000 psi</td>
</tr>
<tr>
<td>Flexural Strain at Break (Method 1, 0.05&quot;/min)</td>
<td>ASTM D790</td>
<td>No Break</td>
<td>4%</td>
</tr>
</tbody>
</table>

### Thermal Properties

<table>
<thead>
<tr>
<th>Test Method</th>
<th>English</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Deflection (HDT) @ 66 psi</td>
<td>ASTM D648</td>
<td>208°F</td>
</tr>
<tr>
<td>Heat Deflection (HDT) @ 264 psi</td>
<td>ASTM D648</td>
<td>196°F</td>
</tr>
<tr>
<td>Vicat Softening Temperature (Rate B/50)</td>
<td>ASTM D1525</td>
<td>217°F</td>
</tr>
<tr>
<td>Glass Transition Temperature (Ts)</td>
<td>DMA (SSYS)</td>
<td>226°F</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion (flow)</td>
<td>ASTM E831</td>
<td>4.50E-06 in/in/°F</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion (xflow)</td>
<td>ASTM E831</td>
<td>4.65E-06 in/in/°F</td>
</tr>
</tbody>
</table>

### Electrical Properties

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Orientation</th>
<th>Value Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Resistivity</td>
<td>ASTM D257</td>
<td>XZ</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>ASTM D150-98</td>
<td>XZ</td>
</tr>
<tr>
<td>Dissipation Factor</td>
<td>ASTM D150-98</td>
<td>XZ</td>
</tr>
<tr>
<td>Dielectric Strength</td>
<td>ASTM D149-09, Method A</td>
<td>XZ</td>
</tr>
<tr>
<td>Dielectric Strength</td>
<td>ASTM D149-09 Method A</td>
<td>XZ</td>
</tr>
</tbody>
</table>

PET_madesolid_Technical Datasheet

**Physical (When Injection Molded)**
- Water Absorption >0.15%
- Rockwell Hardness 50-122 R-Scale

**Mechanical**
- Tensile Strength - Yield 66,400 psi
- Tensile Strength - Break 26,300 psi
- Elongation - Break 18%
- Flexural Strength 98,800 psi
- Izod Impact Strength 0.69 ft-lb/in
- Impact Resistance Energy 20-25 lb-ft

**Thermal**
- Heat Distortion Temp 71.8°C @ 0.455 Mpa (66 psi)
- Heat Distortion Temp 65.6°C @ 1.82 Mpa (264 psi)
- Vicat Softening Temp 84°C
- Glass Transition Temp 82°C

**Electrical**
- Dielectric Strength 14-18 kV/mm
- Volume Resistivity 10*15 Ohm cm
- Surface Resistivity 10*16 Ohm

**Flammability**
- UL Flammability Classification 94V-2
APPENDIX B

Fabrication Process

Printing process, FDM /leapfrog

Part of the mockup 1:5 scale

Mock-up for glaring performance analysis/1:5 scale
LEMONIA KARAGIANNI  GRADUATION REPORT

Cylindrical snap-fit connection test

Barbed leg connection test

Clamp connection test

Cylindrical snap-fit connection test
Combination of Clamp with barbed leg connection test

Combination of Clamp with barbed leg connection test - Non-detachable

Combination of Clamp with barbed leg connection test - Detachable

PET translucency performance in front of a bright source.

Difference in the stiffness of the same digital model due to the different speed on the settings of the printer.
Rhombus-module / 1:1, PET material

Assembling of four rhombus-modules / 1:1, PET material

Assembling of four rhombus-modules / 1:1, PET & PLA material
Assembling of four rhombus-modules / 1:1, PET material, different set-up
APPENDIX D

Online survey for customer validation

Market Research Survey Sunshades

In this survey we would like to ask you a few questions regarding sunshades. We focus on (external) sunshades attached to your windows meant to keep the sun out, and/or to act as privacy screens against people outside. Even if you don’t have any external sunshades, your input is valuable to us. Thanks for helping!

Background questions

**1. What is your gender?**
- Male
- Female

**2. What is your age?**

**3. Below we list some potential issues you may have with your home’s external sunshades, or lack of such sunshades. To what extent are these issues bothering you?**

<table>
<thead>
<tr>
<th>Issue</th>
<th>Not at all</th>
<th>A little bit</th>
<th>Quite a bit</th>
<th>A lot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glaring/glare reflection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overheating of your home in the summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not enough light</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>People can too easily look inside your home</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other issues (please explain briefly)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**4. Do you like (aesthetically) your home’s external sunshades?**

- Very much
- Yes, a bit
- Neutral
- Not quite
- Not at all
- Not applicable

**5. Do you care about the aesthetics of your home’s external sunshades?**

- Yes, very much
- Yes, a bit
- Neutral
- Not quite
- Not at all
- Not applicable

**6. Would you like to have the opportunity to design (customize) your own sunshades regarding your specific location, climate conditions and personal preferences? (for example: write your name on it, make creative patterns. See also some examples below) **

- Yes
- No

Please comment

**7. Would you like to get your customized sunshade at home and apply it easily to your window frame?**

- Yes
- No

Please comment

**8. If there was an easy and affordable way to do so, would you like to build your self-designed and customized sunshade at home?**

- Yes
- No

Please comment

9. Thanks very much for your contribution! In case you can enter any additional comments you would like. In case you are interested in future developments of this topic, feel free to leave your email address.

Buisness model canvas_YES DELFT! start-up participation event.