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Lightweight Origami structure & daylighting modulation

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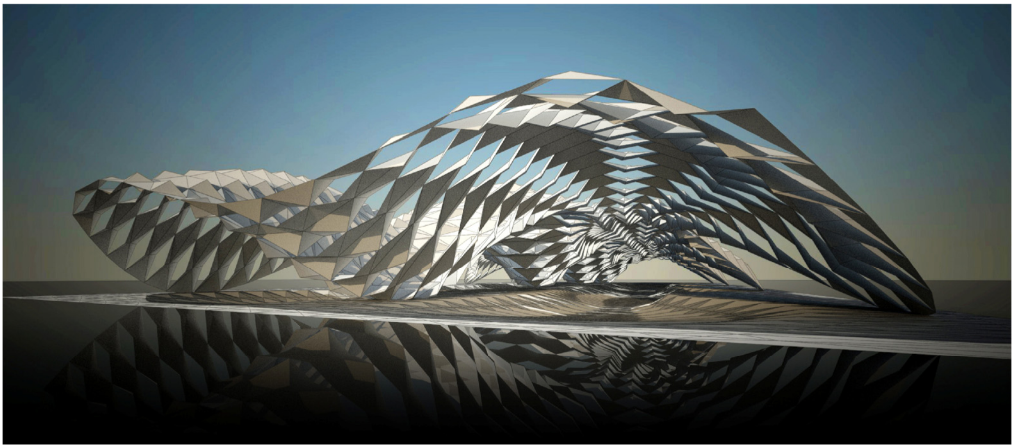

Figure 1: Lightweight Origami structure

1. Abstract

Long-span roof structures are often employed for certain building typologies like airports, train stations, sports facilities, or market halls. Naturally those are frequented by a wider public. This implies that a designer has to take the programmatic requirements and comfort of many more people into consideration while ideally the energy use should stay low. Apart from climatic comfort sufficient lighting of those facilities is an issue for orientation, well being and security. Existing long-span roof structures often show a lack of day lighting and relation to the outside like view in their design. This is a result out of structural but also thermal requirements which makes it difficult to incorporate sufficient openings on top of the roof where it receives the highest amount of direct and indirect light.The research tackles these issues while simultaneously exploring the design potential in terms of architecture, lighting atmosphere and aesthetics.

The research Lightweight Origami structure with daylighting modulation investigates in the sufficient use of daylighting in long-span structures while developing an inclusive design approach which synthesizes, materials, fabrication and environmental control within one parametric, architectural system.

Keywords: Parametric-design, long-span, performance, tesselation, Origami, Yoshimura, fold, daylighting, sustainability, shading

2. Introduction

Parametric design approaches have become a mandatory in architectural practices and education. Those are often rationally argued but in the end stay speculative and do not meet their proposed performative demands.

The research proposes to bridge this gap and investigates into a parametric design system where any roof shape can be tessellated into flat elements taking the Yoshimura Origami fold as a point of departure. Through an alteration of this folding method it is possible to create varying saw-tooth like apertures in order to modulate daylight factors as well as automatically generate self-shading elements. This tessellation method additionally adds structural height to the geometry as well as it enables an organic shape to be built entirely out of planar members resulting in its very own distinct aesthetics. Instead of generating a certain shape under the consideration of pure architectural design interests which later happens to be materialized, a material and construction system becomes the initiator for spatial and ornamental qualities. The overall shape, the structure with its ridges and grooves, their interaction with light and daylighting design integrates several performative aspects and blurs the boundaries between architecture and engineering. It negotiates between qualities and quantities. It further tackles as Foreign Office Architects [1] put it:.. *an oscillation between material and will: between the Baukunst and the Kunstwollen, between technique or material and interpretation or style.* The research tries to give an answer to the above stated polarization under the notion of form finding versus form giving.

3.0 Methods

In the course of the research 4 fields of interest have been identified. Those are Parametric Design, Daylighting & Sunlighting, Structure and Material & Manufacturing.

3.1 Parametric Design

To set up parametric design it is necessary to think the system in terms of its variations and potential outcomes and not as fixed and absolute entities. This dichotomy can be traced back to Heraclitus of Ephesus with *everything is in a state of flux* and Platon's *Theory of Forms*. Peter Trummer [2] quotes Ernst Mayr an evolutionary biologist who described variation as following: *For the typologist, the type (eidos) is real and the variation an illusion, while for the populationist the type (average) is an abstraction and only the variation is real.* In architectural terms this means that research in typologies maps the differences between the samples in order to understand the driving force which cause the variation. This understanding can be utilized in a second step to set up a parametric system which applies a similar research based logic. Therefore parametric design tools are often used by practices which rather look into performances be it infrastructural, structural, climatically or cultural.

For the parametric setup of the solutions two different software packages were used. The initial design was setup in *Rhinoceros 3D* in combination with the *Grasshopper* plug-in. For the later development of material thickness and jointing *Top Solid* integrated CAD/CAM software was used.

The Yoshimura folding was translated into a parametric surface model. This tessellation system enables the members to adapt within the software environment to any change of the overall geometry while automatically being updated. In order to experiment with different configurations and test certain outcomes and affects, a parametric spline scaffolding where the surface components are hung into was developed. In later design stages this initial scaffolding can be replaced by any other spline/curve/line shape required and actualized through the design process. Those can be derived from form finding or form giving processes. The component A is the extended Yoshimura component, which is able to modulate the amount of light and view by increasing or decreasing the opening size. Two surface graphs determine the opening size of each component A. The component B is dependent in its dimension, location and amount on the component A.

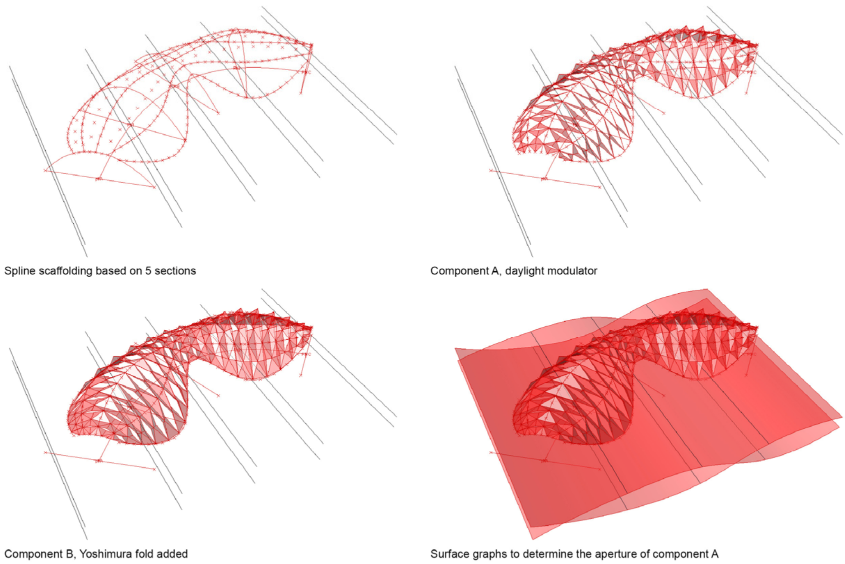

Figure 2: Basic setup of the parametric system

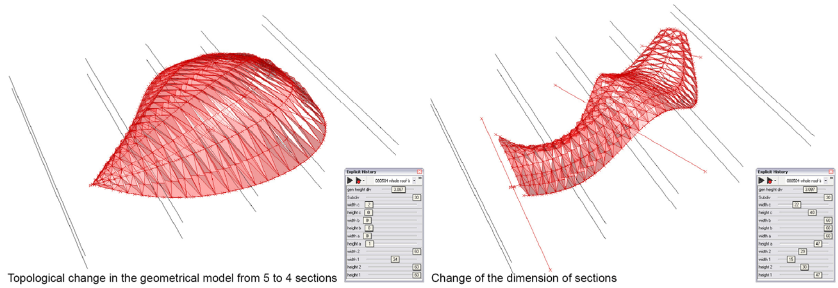

Figure 3: Variations in the overall geometry

3.2.0 Daylighting & Sunlighting

These two aspects of the research are within on umbrella and should not be considered as separated issues since they greatly relate to each other. For the sake of clarity those are none the less treated more independently in the paper.

3.2.1 Daylighting

Daylight from a diffuse Sky has with 150lm/W the highest lighting intensity per watt heat gain in comparison to all the other existing light sources.

This diffuse part of the light emitted by the sky is the desired part to be let into a building since it is evenly illuminating the interior without causing glare, high contrasts and it almost does not cast shadows. Further does it not add up to the heat load which the building anyway receives through different uses and appliances. It is also constantly available even with overcast skies. Current researches [3] show that electricity usage for lighting in administrative buildings occupies between 25-50% of the overall electricity usage. In shopping malls this can add up to 60% through lack of sufficient use of daylight.

The Origami lightweight structure's single components with their pleated geometry act as light collector letting daylight in but shading direct sunlight at certain periods of the year off and bouncing the rays in a diffuse way into the building.

The parametric model is set up in such a way that it is possible to adjust the overall orientation and opening size of the saw-tooth like apertures through surface graphs.

Those surface graphs are the interface between designer and the design outcome. Instead of adjusting all the componet's apertures single handed, a few key values are adjusted and the elements in between are interpolated accordingly. Therefore it is not only possible to get daylight sufficiently into the building but to treat lightning design as a distinct design parameter which generates certain effects and contribute to the overall design approach.

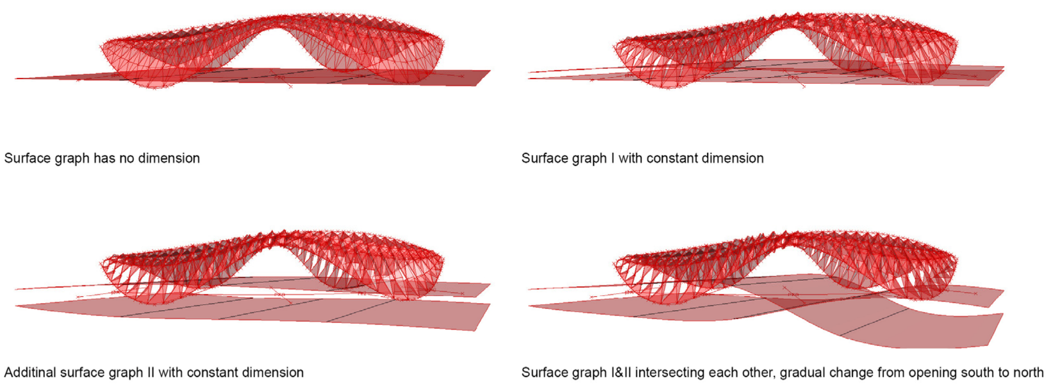

Figure 4: Surface graph and aperture relation

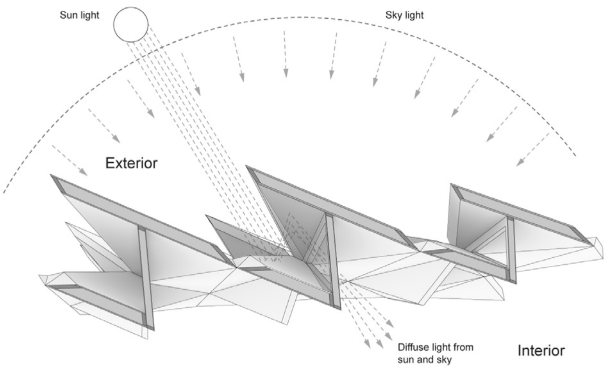

Figure 5: Daylighting principle, section

In *Ecotect* an environmental building design tool different studies were done in order to prove the validity of the shown approach. It calculates the flow of photons and their interaction with obstructing surfaces and materials before those enter the building. The results in terms of daylighting factors in % are represented by a false colour map. The calculation was done according to the IES overcast sky model. It shows that an average daylight factor of 8.42% could be achieved which results in a high perceived luminosity for the user and provides a high quality for inhibiting the space.

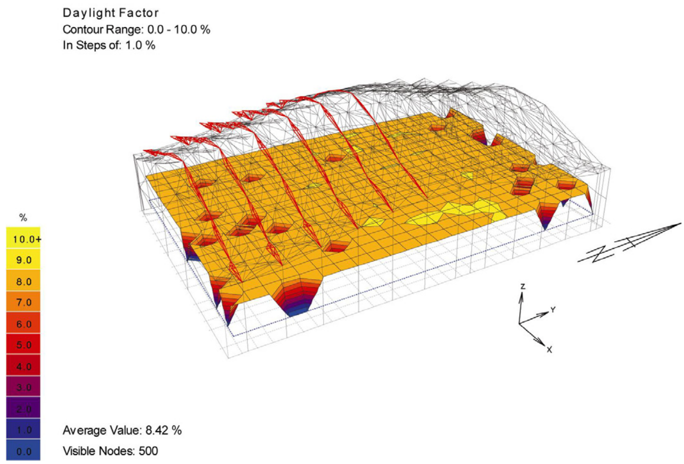

Figure 7: Daylight factor based on IES overcast sky calculation

The amount of needed daylight inside the structure can easily manipulated by the surface graphs. More interesting is the capability of the parametric design system not only to manipulate quantities in absolute terms but that a designer is also able to influence varying luminance intensities resulting in a certain kind of lighting effects which can be achieved inside the building. The aim is to relate a programmatic design need for a specific lighting quality and quantity with the parametric system.

For that another comparison shows how the various formulations of the surface graphs while having one and the same exterior light situation and basic roof layout lead to different lighting outcomes inside the building. For the simulation *Radiance* a lighting simulation tool was used to show the different qualities of the three examples. Two of the examples' openings are or oriented towards north and south, where as the the southern openings are shaded by the later explained system. The third examples' openings are only oriented towards north. All three examples let only diffuse light into the interior. The graph surfaces with their corresponding lighting outcome have an almost one to one relationship.

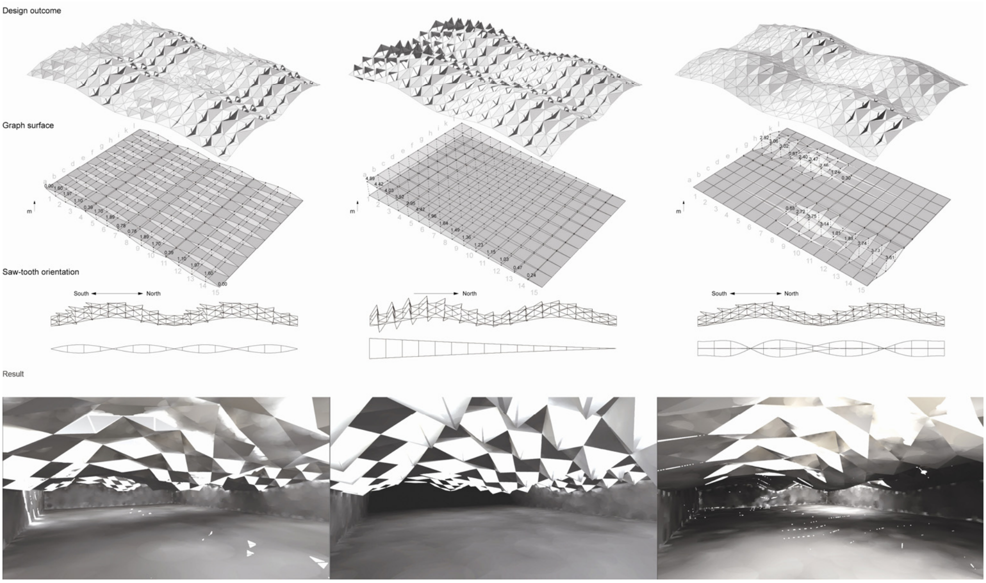

Figure 8: Different graph surfaces resulting in different apertures and lighting qualities in the interior.

3.2.2 Sunlighting

Sunlight, the directed sun rays are not necessarily desired inside. During the summer months it increases the heat load. In the northern hemisphere direct sunlight is only wanted during the colder months to support the heating system. Near to the equator direct sunlight is not desired at all since the overall temperature is quite high and seasonal changes are marginal. The saw-tooth shaped apertures are shaded by an extension depending on their orientation and position. Through adjustments of azimuth and altitude angles any sunvector can be chosen at any time and any position on the globe. The lowest and highest point of the apertures and a sunvector are intersected and as a result the parametric setup formulates the shades in the correct position and layout automatically. That means that a programmatic need for daylight is paired with a local need for shading in relation to the overall geometry.

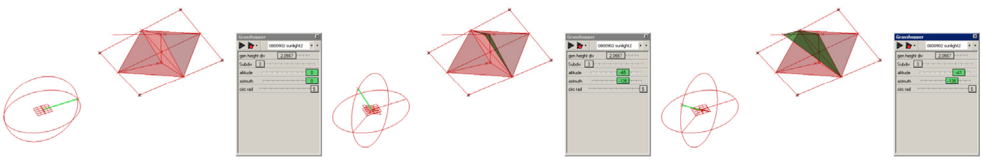

Figure 9. Shading extension single component in relation to different sun vectors

One and the same roof geometry gets a different shading layout depending on its position on the globe. The three examples illustrate how this effects the layout of the shadings. Again the examples have the same basic conditions just differing in location of placement and date when the self-shading should be active. Based on monthly average temperature charts for the three locations, Amsterdam, Algier and Abu Dhabi the dates for active self-shading were picked. For Amsterdam with high precipitation, lesser sun hours and coolest climate the 15th of May was picked, for Algier the 15th of March and for Abu Dhabi due to the hot climate in the UAE the 21st of December was chosen. The 21st December in case for Abu Dhabi with the lowest sun vector was chosen because the outside temperature during the year is always so high, that the shading has to be active constantly.

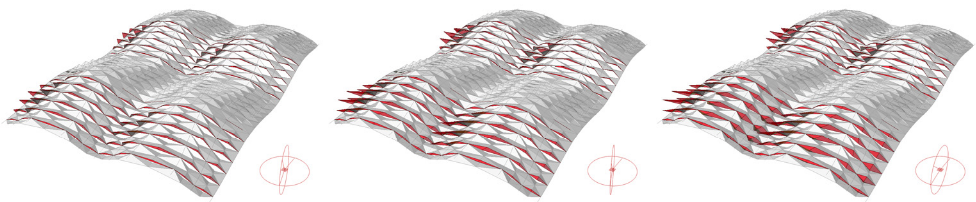

Figure 10: Shading extensions. From left to right Amsterdam, Algier, Abu Dhabi

It further shows, that certain layouts of the overall roof geometry are not suitable for sufficient shading. This happens especially when the roof is placed in the northern hemisphere. Here some orientations of the apertures especially in dome like geometries are simply not shade-able and the shading extension would dart of because the sun altitude angles are except for the summer months too low. Therefore it is necessary find the right date when a the structure has to be self shading. Other steps for optimization are either changing the overall geometry or the surface graph determining the size and orientation of the openings. In the course of lay outing the roof for a certain design task the formulation is always a negotiation between structural, climatic and lighting needs. Here the designer hast establish a hierarchy between the different design parameters since it can happen that otherwise the parameters contradict each other and the design outcome.

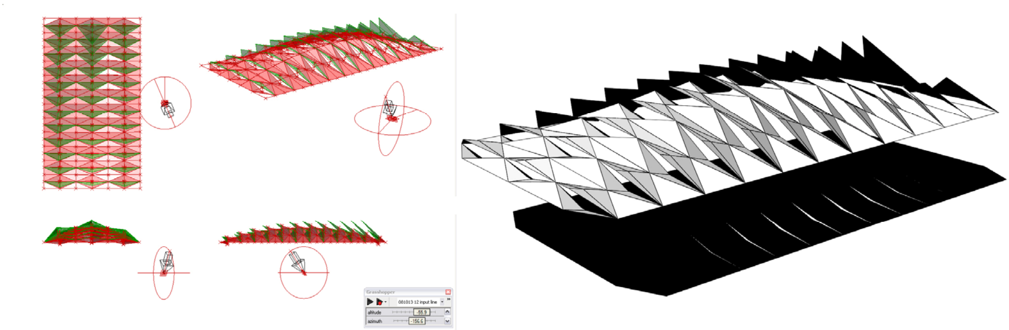

Figure 11: Shading layout and result, Algier 15.03. 2008 12:00

3.3 Structure

For the structural properties of the roof two distinctions have to be made. One is the Origami aspect, the folding up of flat elements into a 3-dimensional configuration. The paper model of the Yoshimura fold shows how increased structural abilities can be achieved through adding ridges and grooves to an otherwise only tension managing material.

The other aspect is the structural performance of a geometrical shape as such. Many examples ranging from Antoni Gaudi, to Heinz Isler and Frei Otto show how form finding processes through hanging or tensile models lead to elegant architectural and structurally integer solutions.

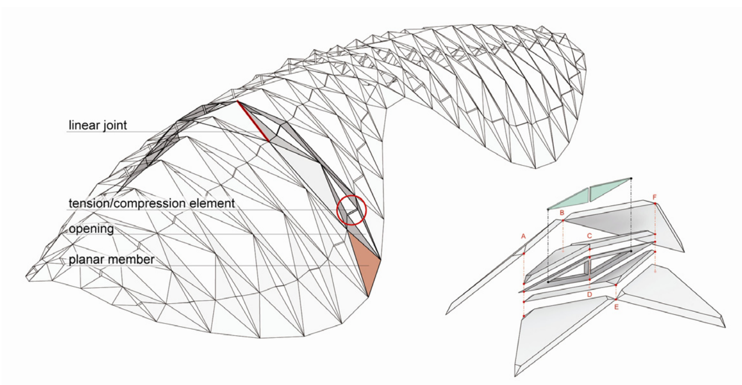

Figure 12: Structural elements

In order to cope with the departure from a more optimal geometrical shape in terms of structural performances through form giving rather than form finding processes the structure has to aquire a greater thickness or structural height within the load bearing system. Within the parametric setup this can be managed by increasing the amount of subdivisions in components. As a result the overall structures' angles between the single planar elements become smaller and therefore the plates orient themeselves more towards a vertical layout.

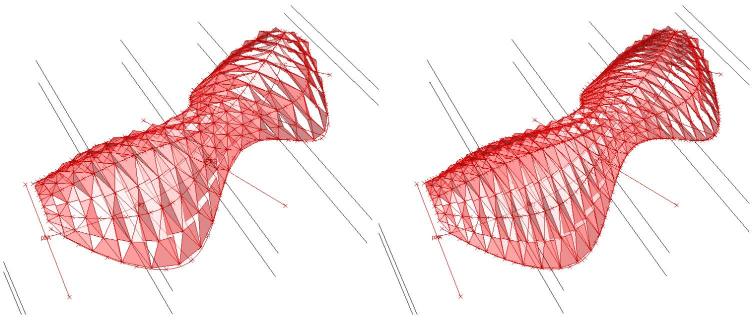

Figure 13: Densities in component layout

Within the realm of computational form finding processes and structural/geometrical morphogenesis the origami structure can draw from previously done researches . The paper *Particle-spring systems for structural form finding* by Axel Kilian and John Ochsendorf [4] describes a computational approach how physical form finding for hanging models can be simulated within a software environment. This was further developed into the *CADenary tool V2*. Here the outcomes of the hanging model simulation which the tool provides can be utilized and set up as a basis for further design explorations.

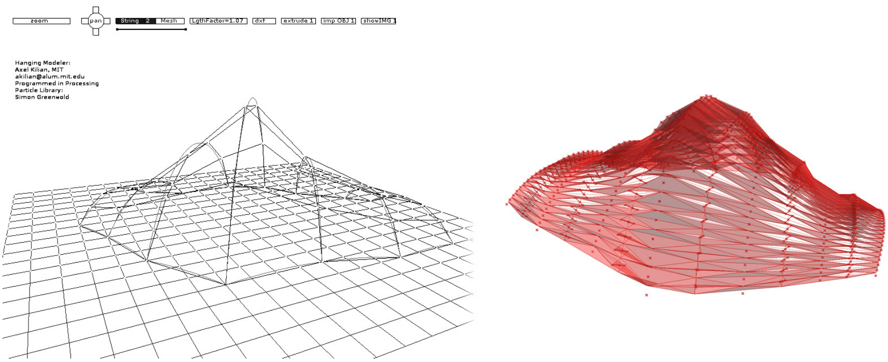

Figure 14: Left Cadenary Model, right Origami structure outcome

3.4 Material & Manufacturing

The research looks into the possibility of using Oriented Strand Boards (OSB) for materialization and manufacturing. Currently there are new material developments which are using straw, literally waste material from agricultural production such as wheat or rice as basis for the their products. Those Oriented Structural Straw Boards (OSSB) have similar material properties as OSB but are made up by less valuable resources and therefore are a much more sustainable choice.

In case a roof structure does not have any special requirement for the inner climate, but has a sheltering function against environmental impacts, like for example trains station platform roofs, it could be manufactured from single OSSB plates.

In this case it is looked at the application where a different inner climate from the outer one is desired. One of the choices which were further followed up is OSB/OSSB foam core panels. Those satisfy the need for structural strength as well as sufficient insulation values.

This thickness and the joining of the foam core plates in different positions in space post various demands on the manufacturing process and the joints.

Through the use of parametric CAD/CAM software *Top Solid* each member of the structure is defined in space and shape. It is set up in such a way, when a planar member meets 3 others, the front ends are adjusted automatically in their inclination through the angular relation with its direct neighbours. This information can be used to instruct a CNC milling machine which then cuts out the individual elements.

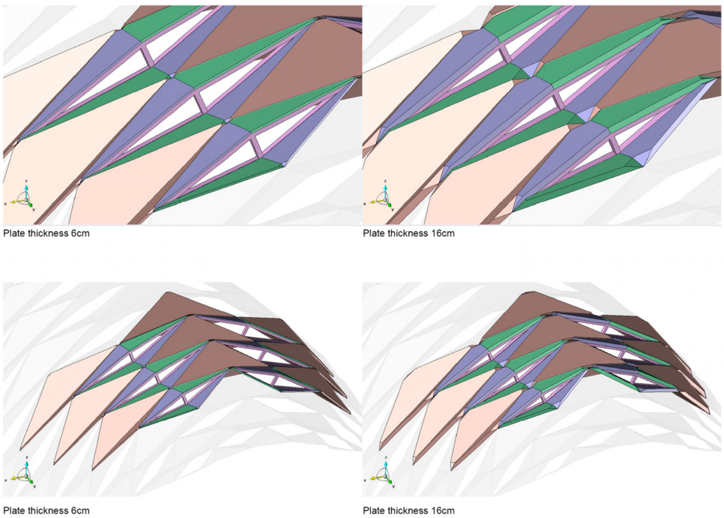

Figure 15: Top Solid parametric model, variation in plate thickness

4.0 Design Examples

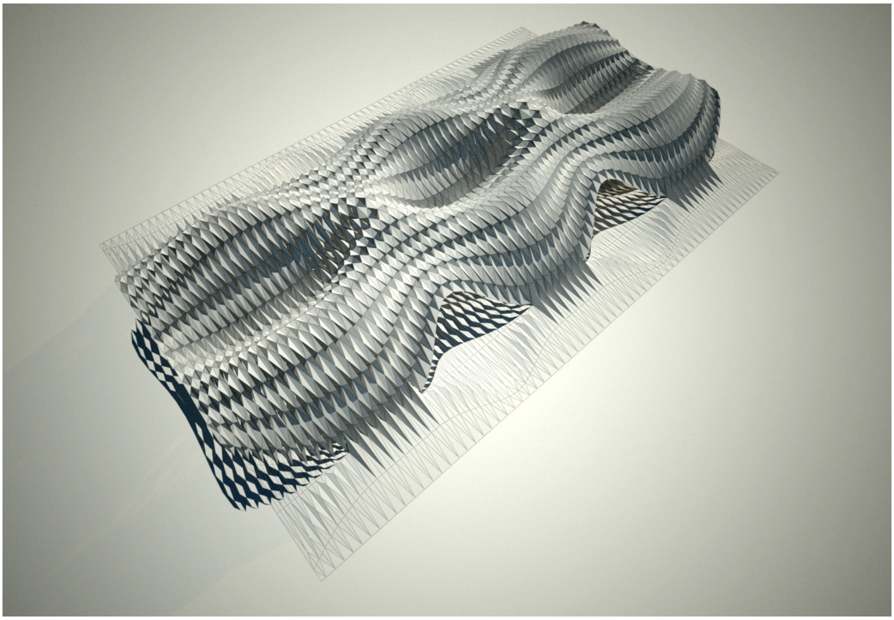

Figure 16: Market hall exterior perspective

Figure 17: Market hall interior perspective

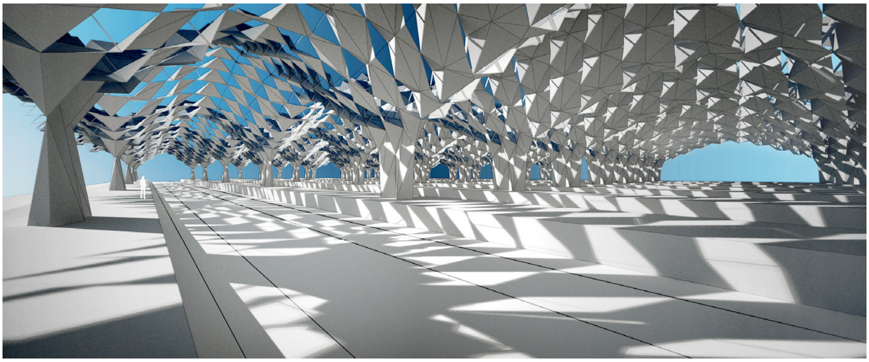

Figure 18: Train station, platform roof

[1] Foreign Office Architects, Phylogenesis (Barcelona: Actar 2004), 7

[2] Peter Trummer, article in Morpho-Ecologies (London: AA publications 2006), 348

[3] Licht Grundlagen der Beleuchtung (Bern, Schweizerische Lichttechnische Gesellschaft), 69

[4] Axel Kilian and John Ochsendorf, Particle-spring systems for structural form finding in the IASS Journal Volume 46 (Valencia 2005)