Evolutionary objective optimization of free form architectural paneling facades.

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Abstract

The large scale free form structures in architecture poses a challenge for the fabrication. A major part of this problem is to approximate the surface with a network of cells or patches in which the curve network forms the structure and the internal cell surface forms the panels, generally made out of glass, plastic or metal sheet etc. Since glass is the most popular material between architects and designers for external skin of these structures, it becomes very important to choose the right cell size, orientation, quality to approximate the surface and optimize it to minimize the cost of production and fabrication as the cost of producing curved panels , which are important to achieve aesthetic quality of the form is comparatively much higher than planar panels. This research will focus on the modelling and optimization of the initial mesh taking into consideration the cost of production and fabrication of panels but also affecting the cost related to building energy efficiency and structural performance at a very large scale. The early development of a tool simultaneously computing the production panelling cost , cost savings for solar radiation and structural mass reduction is presented.

Keywords: Multi-objective optimization, Quad mesh, solar radiation analysis, Structural performance, Pareto solutions,

1. Introduction

With increasing advances in computational design-related technologies freeform shapes are gaining popularity in the architectural industry. The essential challenge arises on how to progress from a geometrically complex problem towards a feasible and affordable solutions not just in terms of the initial cost of production and fabrication but also long term future costs related to building energy efficiency and cost for structural mass for the mesh.

Recent technological advances enable the production of single and double curved panels that allow a satisfactory approximation of doubly curved surfaces. Though planar glass panels are still much cheaper, with new techniques and technological advances like cold bending technique, reusing the mould for producing similar panels of curved panels has started to reduce and hopefully should reduce even more in the near future. In such a scenario choosing the right mesh for building just on the basis of cost efficiency related to producing planar panels might not be the best fit solution for overall cost of the building. Other aspects like future cost of energy to handle the solar radiation on building in due course of time or cost of structural mass which is directly affected by the number, size of panels also the thickness of the frame system which in return affects the solar radiation heating, the building must also be taken into consideration.

The objective of this study is to create a tool with the use of advanced computational aids, to find out the most optimal solution from the generated pool of meshes which will potentially reduce the overall cost of building in different aspects. The best solutions are chosen by dynamic solver on the basis of overall cost parameter in multiple scope of areas. The dynamic solver evaluates each possible solution in the scope of given parameters with overall estimated cost gives a couple of good solutions to choose from.

2. Hypothesis

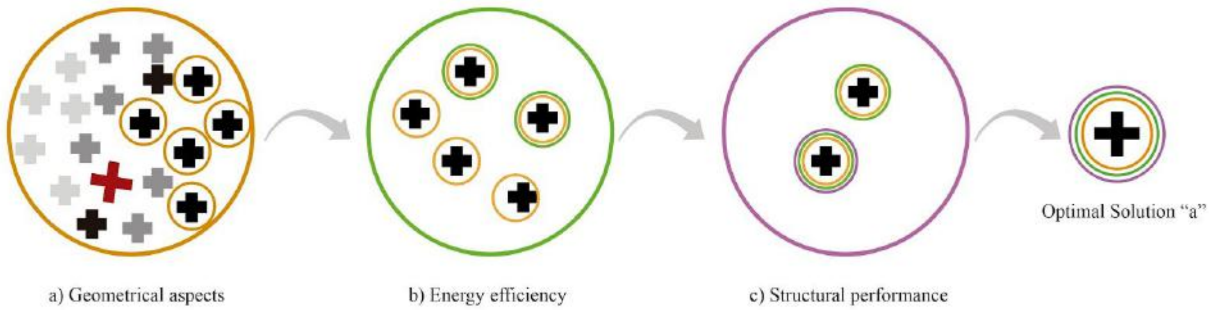


***Figure 1**: First optimization method*

Since, while optimizing the meshes for a designed surface the foremost goal for selection criteria towards surface approximated mesh is most planar and similar panelled meshes with minimum surface deviation to reduce the overall cost of production and fabrication **(figure 1)**, the aim to search for solutions which might not perform very well from geometrical point of view (Ex. planar panels) but outperform when taken in the account the other aspects of cost which lowers the overall cost of the design. **(Figure 2)**

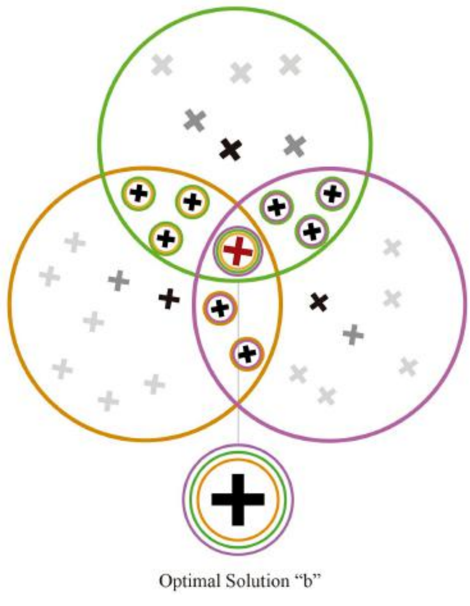


***Figure 2**: Second optimization method*

Hypothesis Question: What if the Cost of the optimal solution a > b?

3. Methodology

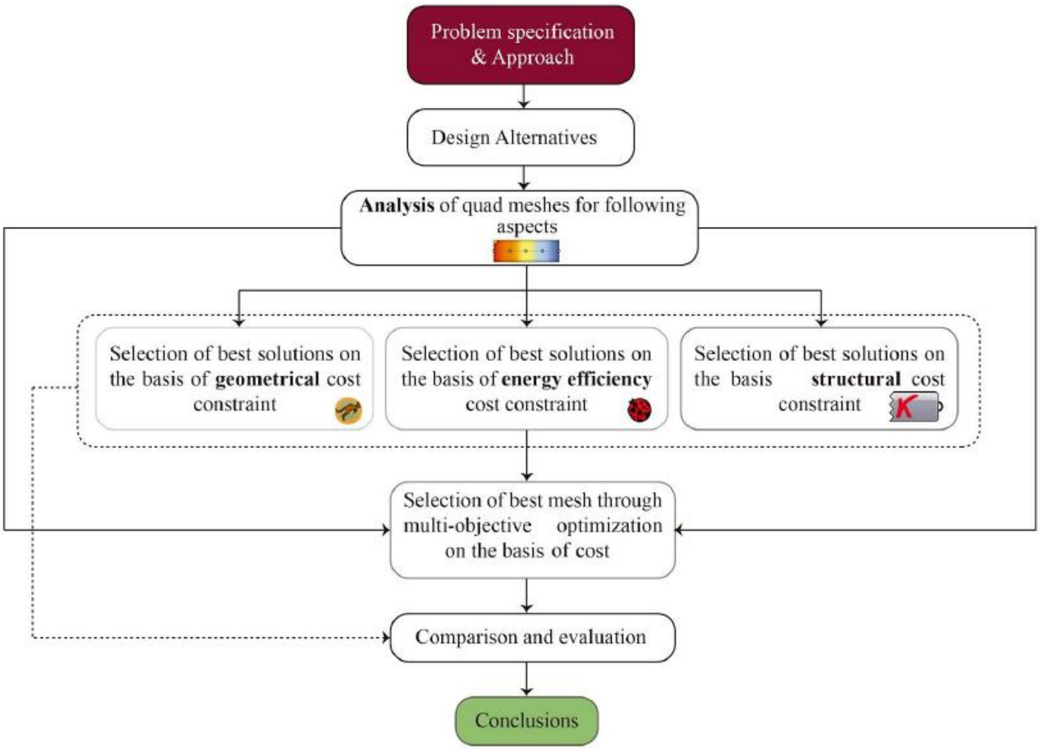


Figure 3*: Flow chart explaining the methodology*

3.1. Design Brief

To evaluate this optimization tool on a free form surface, The Opus by Zaha Hadid was chosen; a hotel building located in Dubai. The building comprises of two separate towers which are connected through a bridge on the top because of which there a freeform surface void which is formed. But, while evaluating and analysing this tool, the research focuses specifically on the interior void of the building. The outer solid envelop for the void will be taken into account just for the solar radiation analysis and some graphical representations. **(figure 4)**

Figure 4*: From left to right, Building outer facade, Building void*

3.1.1. Target surface development & Analysis

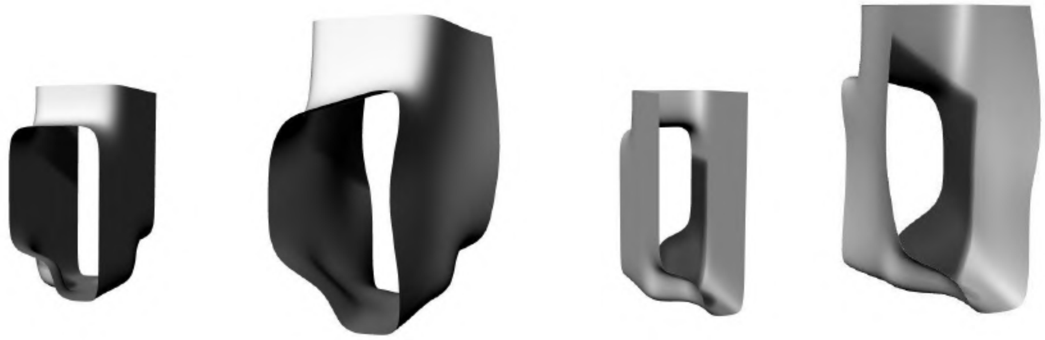


***Figure 5**: Manipulation of surface to create void similar to context.*

The target surface of the void of the building has been developed in Rhino 3D using T-spline Surfaces by scaling, comparing the pictures and tracing the online available plans of the building, the surface is a close approach to the real void surface but is not an exact representation of the same. But the overall scale of the model is comparable with that of the real building. The building volumetric dimensions match to that of the model.

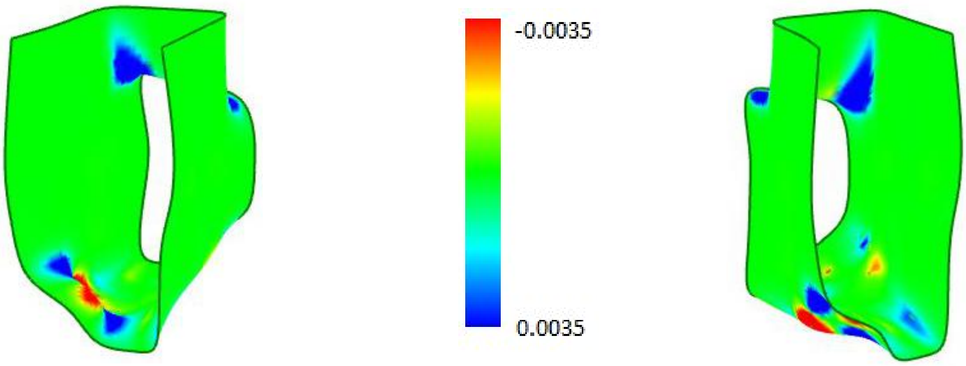


***Figure 6**: Analysis of curvature*

The surface curvature as can be seen in **Figure 6** ranges from -0.0035 to 0.0035. Most of the surface can be seen as green which represents Gaussian curvature to be almost 0. Very less area for positive curvature (Red) can be observed. Analysing this,most of the non-planar panels after optimization would be cylindrical and hyperbolic paraboloid.

3.1.2 Why free form?

Freeform is a surface or shape which is not conforming to a regular or formal structure or shape. Unlike defined surface free form surface shows different types of Gaussian curvature ($K>0$, $K=0$, $K<0$) because of which it makes it even harder to get totally planar panels keeping in mind the balance with surface deviation or fairness. So as already when it is hard to optimize the quad mesh to achieve totally planar panels (keeping in mind fair balance of surface deviation) which plays a major role in cost of a design, the doors for other aspects of optimization (structural mass, solar radiation) open up more to control overall cost of the design globally. So precisely the conventional solution like mesh approximation at coarse level to have more planar panels can still be investigated, but other solutions which do not follow this conventional path (Diagonal grid) of optimization can also be analysed to check if these unconventional solution might perform even better in terms of global cost of design because global cost of design depends on a lot of interdependent factors explained in *section 4.*

4. Problem Specification & Approach

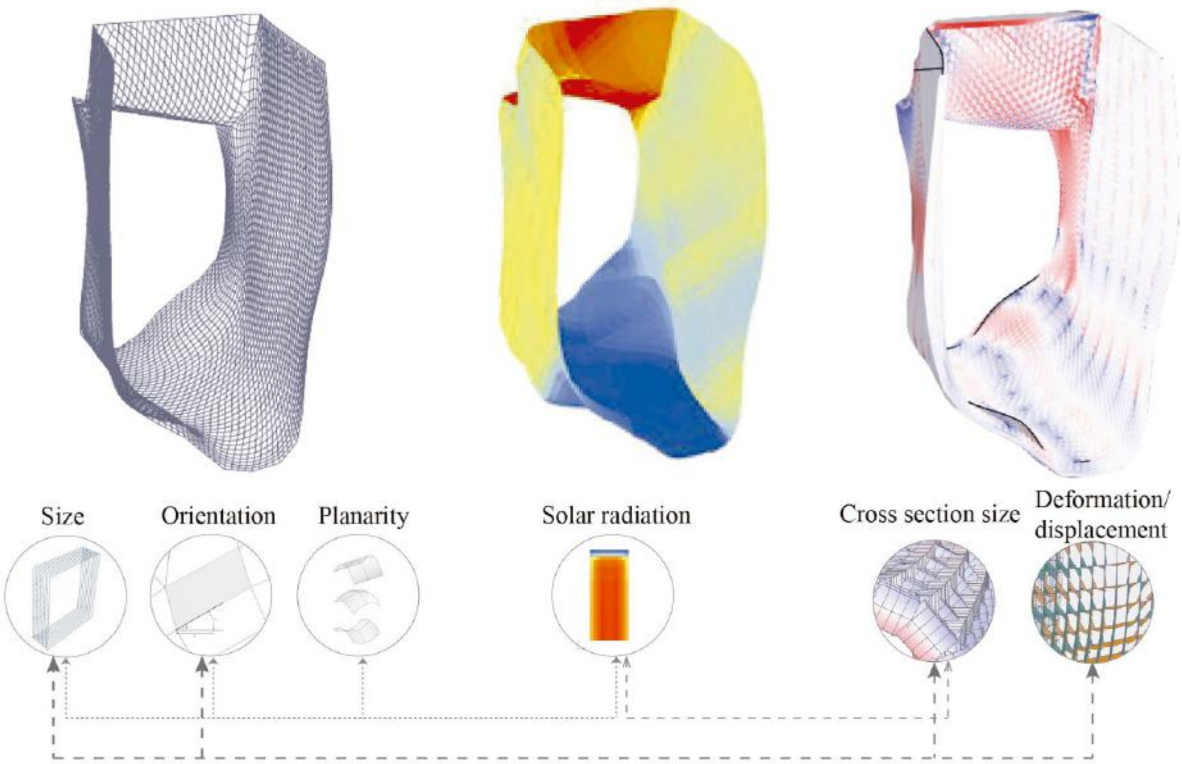


***Figure** 7: Image showing relation between aspects of study for optimization*

The research suggests to initiate that while searching for the best-optimized solution to cut down the cost of design, planarity constraint plays a very big role, but there are other scope of areas also which play a major role in cost factor of the building on a large scale and gets directly affected by each other. (**Figure 7**) For example, the size of the surface panel while in process to make it planar will affect the solar radiation directly (**Figure 19**) and also cross-section size and mass of the curve network because size of panel affects the number of panels which in turn affects the strength of cross-section and lastly the size of the cross-section, now this cross-section size and panel size will also affect the solar radiation received by the building. Similarly, orientation and planarity factors also affect other aspects of optimization.

Now, this web network of interdependent factor requires a process of optimization with some computational tools based on which evolutionary objective optimization can be processed.

4.1. Generative Design Optimization

Generative design has played an important role in modern architecture, by giving the architects and designers an opportunity to explore multiple design options within no time. In this system, the initial parameters are defined to link together under certain geometrical and mathematical rules and expression to form different design options to evaluate the best one out of it. When the initial parameters are changed, the design result change accordingly, making generative design super powerful tool specially in the initial phase of design.**[4] (Figure 8)**

When incorporating cost related to structural components, building energy cost efficiency, production and fabrication cost for a design, developers can minimize the overall cost even further and maximize the building performance. The main objective of optimization is to search for the best solution, according to an objective function as often called fitness function which contain single or multiple objectives. This usually means an optimization which is targeting many objectives, subject to some constraints, and minimizing it until it reaches an optimal solution. This can be expressed as :

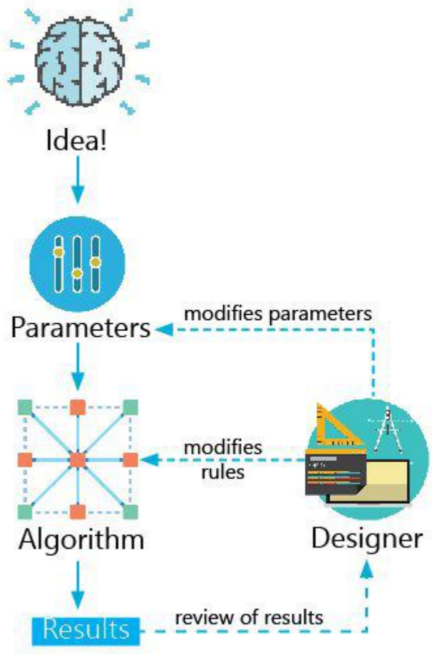


***Figure 8**: Flowchart over parametric process*

$$\begin{cases} \text{min} & (f_1, f_2, \ldots, f_{nf}) \\ \text{subject to} & (c_1, c_2, \ldots, c_{nf}) \end{cases} \qquad \{1\}$$

where *nf* denotes the number of objective functions.

4.2. Multi-objective Optimization

Generally while performing a multiobjective optimization there are results which are conflicting with each other in different degrees and gives many solutions which are not optimal solution for all functions. There are certain ways to solve this problem. One of the ways is to create an objective function like cost which contain a holistic evaluation of all objectives as one. This can be expressed as:

$$\textbf{min}\ (\boldsymbol{f}\,(\boldsymbol{cost}) = C_1 A_s + C_2 V)$$

or

$$\textbf{min}\ (\boldsymbol{f}\,(\boldsymbol{cost}) = C_1 A_s / C_2 V) \qquad \{2\}$$

where $\mathbf{A_s}$ = surface area of panels, **V**= volume of bars, **C**=cost

The expression above when will be minimized through genetic algorithms itself will prioritize different objectives like Geometrical orientation, Cell size, Cost related to building energy, cost of Structural mass to minimize the overall cost of building.

4.2.1 Genetic Algorithms

These are the algorithms which are inspired by Darwinian laws of natural selection. A random population of good solutions for individual objectives are spread and combined to form a better solution for the combined objective. From these solutions forms on other stage are combined further to form better solution taking into account the other objectives as well. This process works in a loop until the exit condition of the loop is satisfied or the number of iterations are over.

Sometimes this process of solution might miss a solution which might be more optimal due to the exit condition being satisfied early or number of iterations getting over before the chance of that solution to come. But to make the loop run for all possible solution will take more calculation time. Because of which some parameters are already set to limit the scope of calculations.As seen in the research by Viktoria henrickson & Maria Hult, Though calculation time for genetic algorithms are higher compared to other optimization techniques. Still, they are good techniques to search a large design space of complex problems, where the designer is not forced to pick a single optimal design but to choose from a final optimized population.**[4] (Figure 9)**

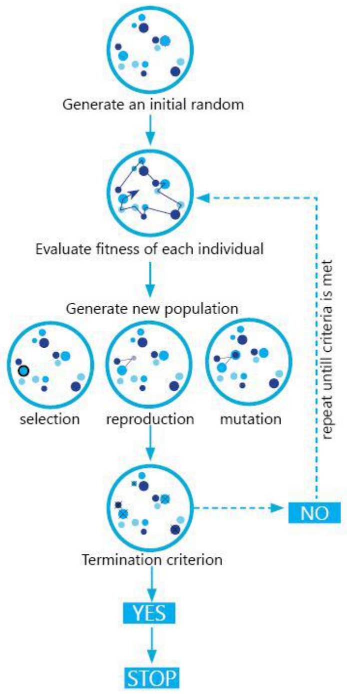


Figure 9: *Flowchart over genetic algorithm process*

4.2.2 Generative Design Tools

To make this tool,certain generative design tools are used which are very popular parametric field of architecture. Some of the most important ones out of them have been described below.

Rhinoceros® is a design tool by Robert McNeel & Associates.**Grasshopper®** is a plugin that integrates with Rhino.It is a visual programming tool that enables a parametric design process that immediately shows the progress and result in Rhino. Grasshopper comprises of sets of components, all of which are actually programming commands to perform certain actions. When these commands are linked together, new commands are generated to perform a new type of task.**[4]**

Octopus, is a tool helps in multi-genetic optimisation. The component generally consists of genes or parameter sliders which changed during the optimization process for the objectives to be satisfied. As stated by Viktoria henrickson & Maria Hult "*The component creates a Pareto front for each generation that enables the user to make trade-offs between the objectives*" **[4]**. It allows user to choose solutions from these generated Pareto front. Hence octopus is used to search for the best results for all objectives to be analysed in this research.

Kangaroo is a Live Physics engine for interactive simulation, form-finding, optimization and constraint solving . A solver weights different goals against each other in an iterative process until the nodes in the structure reaches equilibrium or a minimum energy threshold **[4]**. To optimize the panels in terms of geometry (Planarity, similar panels, etc) with respect to other objectives, kangaroo zombie solver is used with appropriate goals.

Karamba in Grasshopper, enables structural behaviour analysis in real-time. Though it takes a long calculation time for complex geometries .The research will use this plugin to calculate the dimensions of the cross-section, displacement, loads etc and make it an objective to minimize the cost related to the same.

Ladybug is another plugin in grasshopper which will be used to calculate solar radiation received by the building based on the different geometrical and structural constraints like cell orientation, size of the of the panel, planarity of the panel, structural thickness of the framing system etc.

5. Design / Mesh Alternatives from different approaches

Numerous types of meshes can be used and subdivided into smaller elements to be applied to the surface. However the research is limited to types of quadrilateral meshes. There is a wide amount of solutions from which four different types of approaches were selected and studied.The figures below show different approaches and respective meshes obtained for optimization.

5.1 Mesh 'A' approach

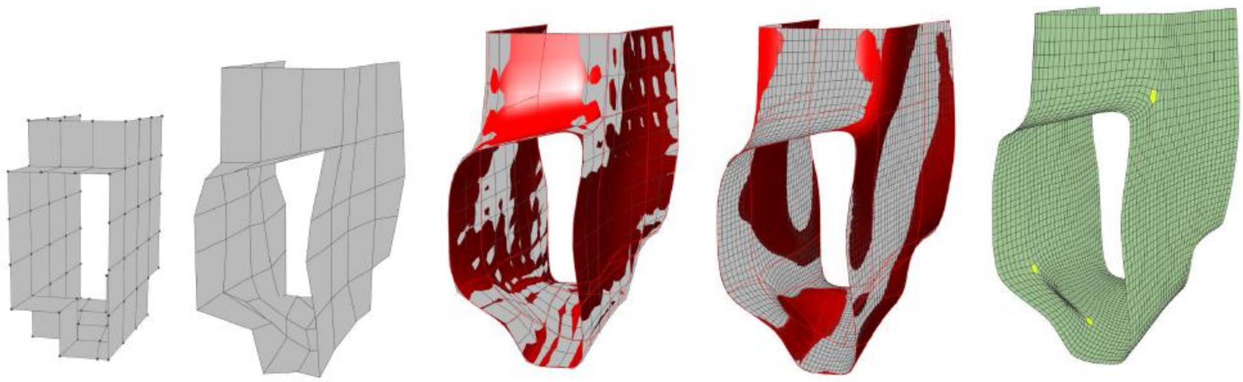


Figure 10*:Quad mesh generated through T-spline method.*

The mesh above **(figure 10),** has been developed by approximating the surface curvature principle lines on a coarse mesh initially and then translating the mesh points close to the actual surface and then further subdividing it by Catmull-clark. This method is helpful while placing strategically singularities, (6 pentagons) which will provide better results while planarizing the quad mesh.

5.2 Mesh 'B' approach

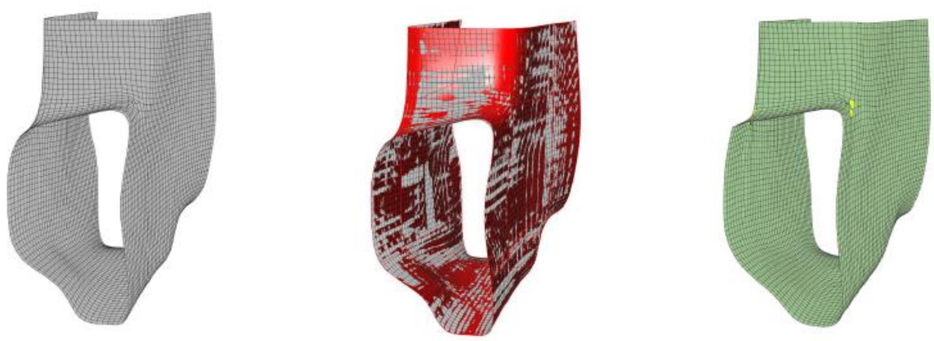


Figure 11*: Quad mesh generated through Rhino*

The mesh above in **figure 11** has been developed by trying a lot of variations on quadriflow on rhino. This mesh also comes out to be smooth with fair amount of surface deviation. The singularities (4 - pentagon) in this mesh approach are well placed and can also be controlled by changing the parameters in the tool in rhino.

5.3 Mesh 'C' approach

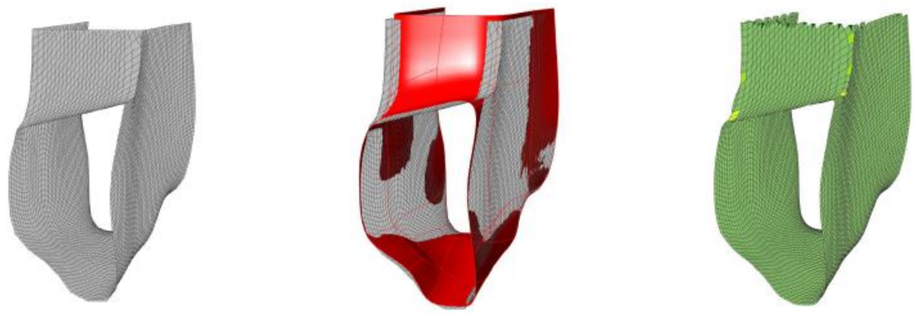


Figure 12: *Quad mesh generated through UV map method*

The third mesh approach **(figure 12)** was followed keeping in mind to be able to control the orientation of the meshes, for which the void surface was mapped with UV points from a flat surface grid in which the rotational angle of the grid lines could be controlled separately.

5.4 Mesh 'D' approach

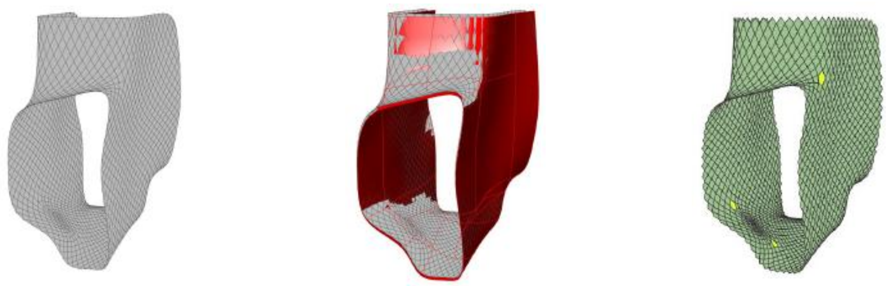


Figure 13: *Quad mesh generated as a diamond grid*

This mesh is diagonal translational of Mesh approach A to create a versatile initial pool of meshes for optimization **(Figure 13)**

6. Geometry Analysis

The initial geometry play a major role in minimizing the cost of the design. In geometrical aspects this paper will be focusing on the surface deviation and cost in relation with just planarity of the surface panels as it majorly affects the cost of the project. The cost for the same can be calculated in various ways but to optimize solutions on different optimization factors and to give them fair weightage, it's important to go in depth to calculate cost of curved panels.**(Figure 14)**

According to Helmut Pottmann for panel cost: "*Let **F** be the given input freeform surface describing the shape of the design. Our goal is to find a collection P = {P1, . . . , Pn} of panels Pi, such that their union approximates F.*

Curved panels are commonly produced using a manufacturing mold M_k. We call the collection $M = \{M_1, . . . , M_m\}$ with $m \leq n$ the mold depot. To specify which mold is used to produce which panel(s), we *define a panel-mold assignment function A : [1, n] → [1, m] that assigns to each panel index the corresponding mold index. The arrangement of panels in world coordinates is established by rigid transformations Ti that align each panel Pi to the reference surface F. Panels produced from the same mold are sub-patches of the mold surface and need not be congruent.*

Let $c(M_k)$ be the fabrication cost of mold M_k and $c(M_k, P_i)$ the cost of producing panel P_i using mold M_k (see also Figure 9). The total cost of panel production can then be written as:"

$$\text{cost}(F, \mathcal{P}, \mathcal{M}, A) = \sum_{k=1}^{m} c(M_k) + \sum_{i=1}^{n} c(M_{A(i)}, P_i). \quad \{3\}$$

The cost of mold and the curved panel also depends upon the curvature topology of the panel because of which it is important to classify all non planar panels further to associate them with their respective cost factor. For this paper they have been broadly divided into Cylindrical, Spherical, Cubic, Hyperboloid **(Figure 14)**. After which the expression above can be used for the respective type of panel

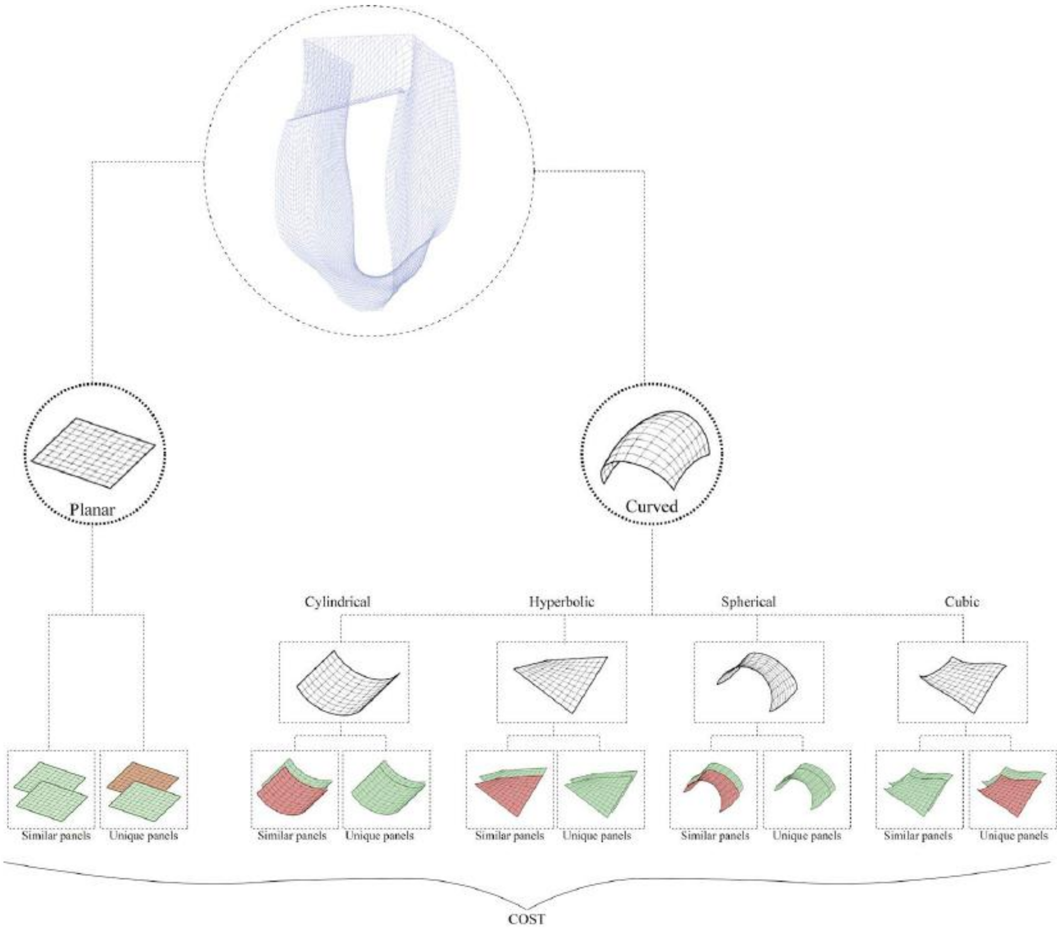
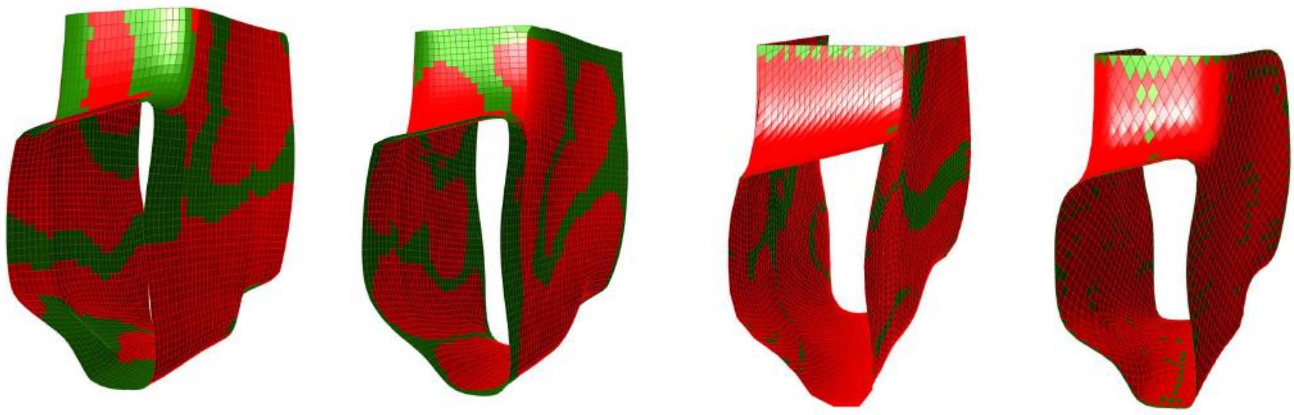


Figure 14: *Classification of panels according to its curvature*

After which the expression above can be used for the respective type of curved panel, unique and common molds. So the total cost of the curved panels can be expressed as :

$$C_T (F_T, P_T, M_T, A_T) = C(F_{Cyl}, P_{Cyl}, M_{Cyl}, A_{Cyl}) + C (F_H, P_H, M_H, A_H) + C (F_S, P_S, M_S, A_S) + C (F_{Cu}, P_{Cu}, M_{Cu}, A_{Cu})$$

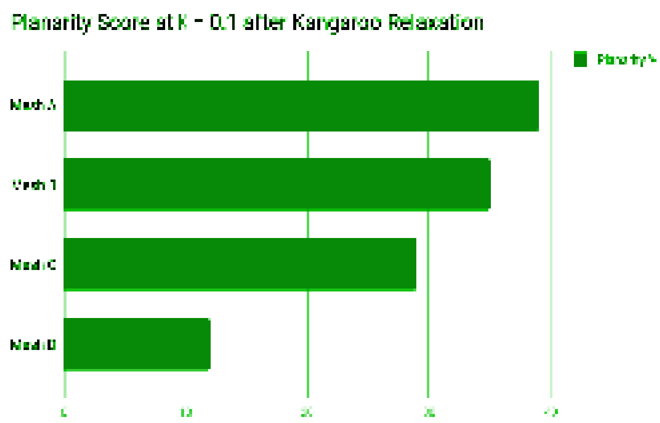
6.1 Mesh evaluation on the basis planar panels



Mesh A Mesh B Mesh C Mesh D

Figure 15: *Evaluation of meshes under planarity constraints*

The four meshes in **figure 15**, have been evaluated above on the basis of planarity to find out and evaluate the cost of planar panels by their area. It can be observed in **graph 1,** that Mesh "A"is the best solution as it has maximum number of planar panels. Further in **table 1,** the cost of planar panels is evaluated for each mesh. These resultant meshes are obtained after relaxing the meshes with kangaroo physics with goal, planarize, maintain the aspect ratio, keep the mesh close to the surface (fairness) and lastly mesh smoothen. Also, to make these meshes comparable, the fairness factor has been purposely kept the same.



Graph 1: *Planarity score after Kangaroo Relaxation*

Stage 1	Mesh A	Mesh B	Mesh C	Mesh D
Number of Planar panels	1511	1654	874	285
Number of Curved panels	2201	2929	4048	1643
Total cost of planar panels	194,568	182,077	88,345	63,644

Table 1: *Cost of panels according to its classification , all cost values have been evaluated in euros*

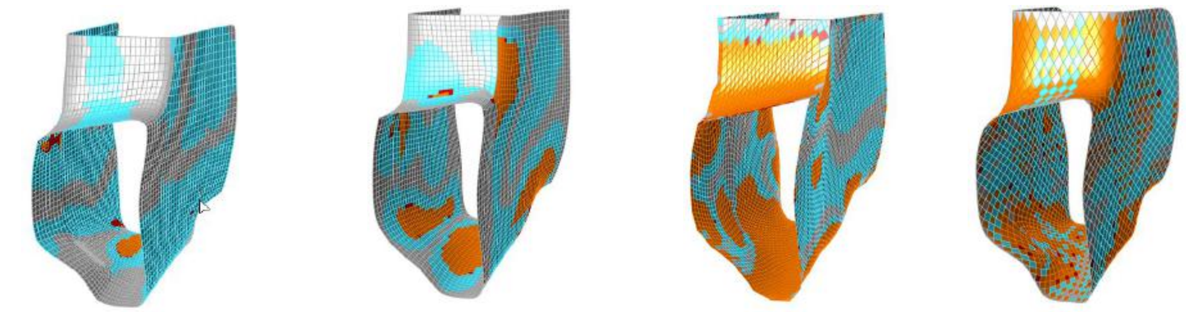
6.2 Mesh evaluation on the basis of curved panel topology

Tol. - 0.1					
Cost factor per mold	0	2	18	24	30
Cost factor per pane	1	2	5	5	5

*

Planar	Cylindrical	Paraboloid	Spherical	Cubic

Mesh A Mesh B Mesh C Mesh D



Mesh A

Tol. - 0.1				
No. of Molds	116	6	2	18
No. of Panels	2023	103	2	73

Mesh B

Tol. - 0.1				
No. of Molds	71	76	0	37
No. of Panels	2111	738	0	80

Mesh C

Tol. - 0.1				
No. of Molds	132	145	0	51
No. of Panels	1895	2100	0	95

Mesh D

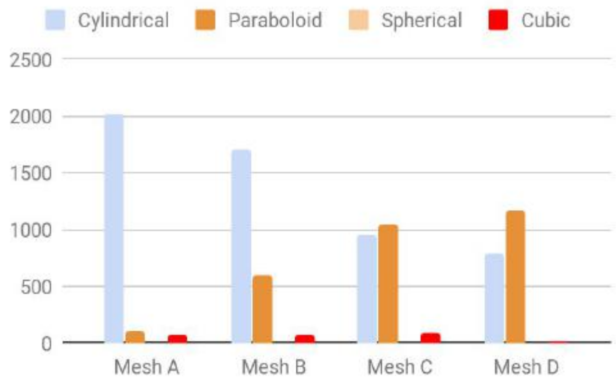
Tol. - 0.1				
No. of Molds	115	310	0	34
No. of Panels	792	1166	0	20

**Table Reference - Helmut Pottmann, "Geometry of architectural freeform structures"*

***Figure 16**: Evaluation on the basis of curved panels topology*

Smart Form Clustering is a tool in grasshopper which is used to classify the curved panels to see which panels are similar and can be produced from the same mold.

Mesh A when classified shows maximum number of cylindrical panels which are comparatively cheaper to parabolic panels. On the other hand Mesh B and Mesh C shows almost equal or more number of parabolic panel.



***Graph 2:** Mesh evaluation according to curved panel topology*

Tolerance - 0.1	Mesh A	Mesh B	Mesh C	Mesh D
Cost of Curved Panels	782,866	1,190,200	2,008,400	3,579,800
Cost of all panels **(Planar + Curved)**	977,435	1,372,300	2,096,700	3,643,500

***Table 2:** Cost of panels according to its classification, all cost values have been evaluated in euros*

By comparing the meshes and their cost Mesh A shows the lowest value amongst all the meshes in terms of cost. The cost of the Mesh D is the highest where the panels are diagrid, it's due to the same principle because Mesh A follows the principal curvature of the surface the most and Mesh the least.

6. Environmental Analysis

To analyze the building context and the energy required, a solar radiation study is conducted. Solar radiation is the energy received by the Sun during the daytime. Depending on the location this might be high or low and their impacts might differ. The context in our study is Dubai, United Arab Emirates which receives very high radiation throughout the day making it necessary to reduce it to reduce the cooling load on the building. A solar radiation tool enables to map and analyze the effects of the sun over a geographic area for specific time periods.

Two main indicators are analyzed during the study -

- The total radiation falling on the building in KWh, This is computed by ladybug through the mass addition of results at each of the test points in KWh/m^2 multiplied by area of face that the test point represents.
- The total radiation per sq.m of the building in KWh/m^2 which is computed by dividing the total radiation by the total area analysed by ladybug.

6.1 Analysis of solar radiation according to orientation.

The maximum amount of solar radiation depends upon the location of country according to the equator line. Countries that lie above the equator have solar radiation maximum at the south while countries that lie below have maximum towards the north. **(Figure 17)**

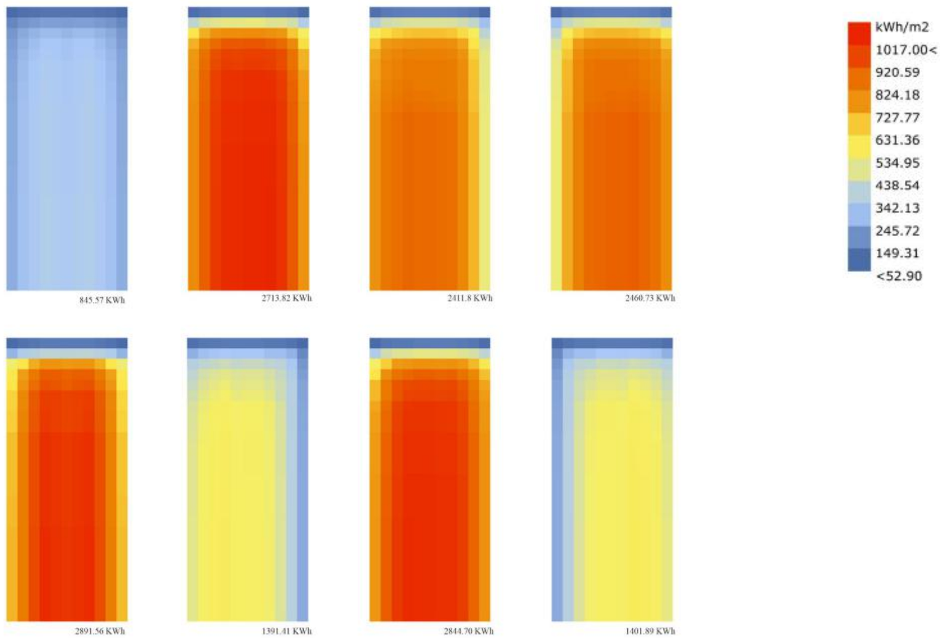


Figure 17: *Solar radiation according to its orientation*

From the above figure it can be summarised that the best glazing orientations would be the ones facing the North, north-west and north-east directions, while the worst performing would the ones facing the South direction especially the ones oriented towards the south-west and south-east directions.

6.2 Analysis of solar radiation in relation to angle between face and xy plane

In general scenarios windows are generally constructed keeping the angle between the face and the ground at 90 degrees. However methods of constructing windows at angles between 30° and 150° are also feasible. **(Figure 18)**

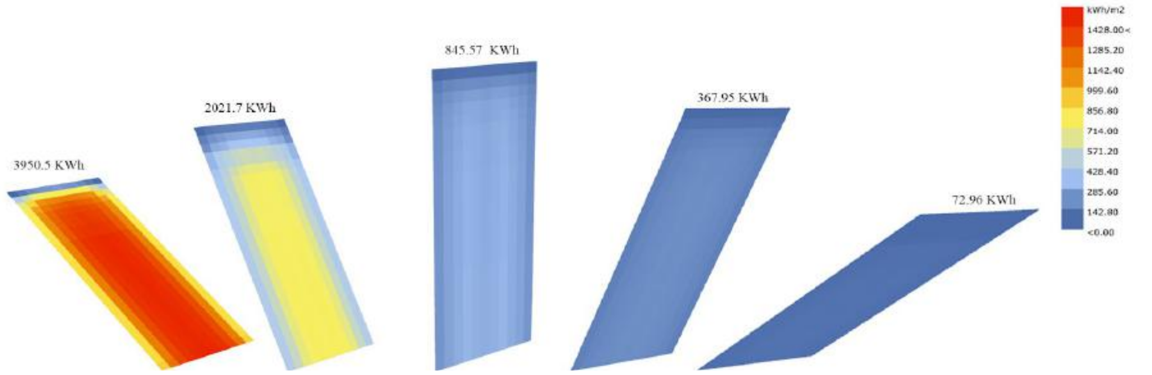


Figure 18: *Solar radiation in relation to an angle between face and xy plane*

6.3 Analysis of solar radiation on different types of panels.

As observed from the geometric analysis, the glass panels are not always planar and hence it was important to analyze the total radiation per sq.m from the panels.**(Figure 19)**

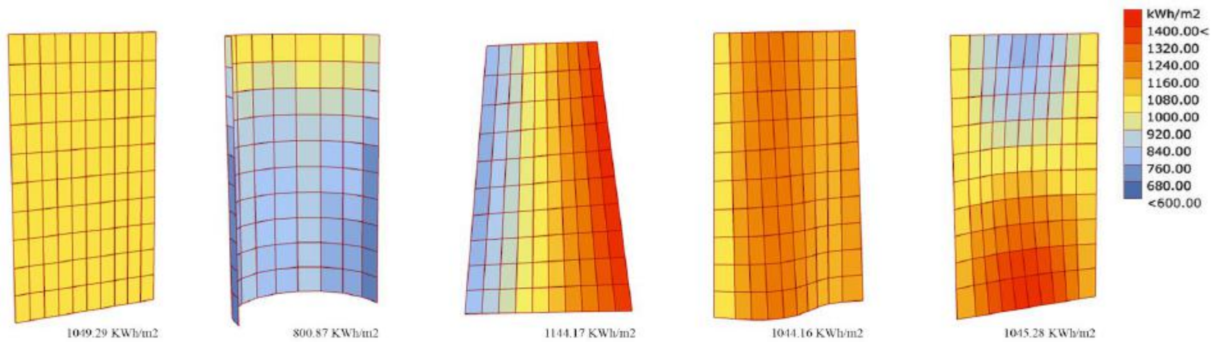
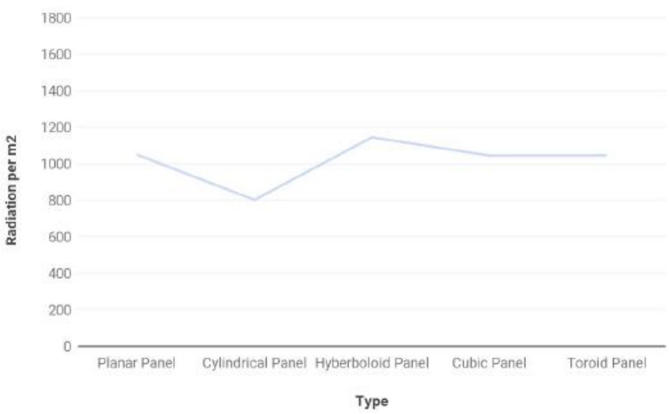


Figure 19: *Solar radiation according to panels classification*

From the above figure it can be observed that radiation depends on the orientation of the sub panels towards the sun and hence the cylindrical panels curved inwards absorb the least amount of radiation per sqm followed by the planar panels as it has least orientation of more the 90° compared to the other panels. **(Graph 3)**



Graph 3: *Solar radiation according to panel classification*

6.4 Analysis of solar radiation of different types of meshes.

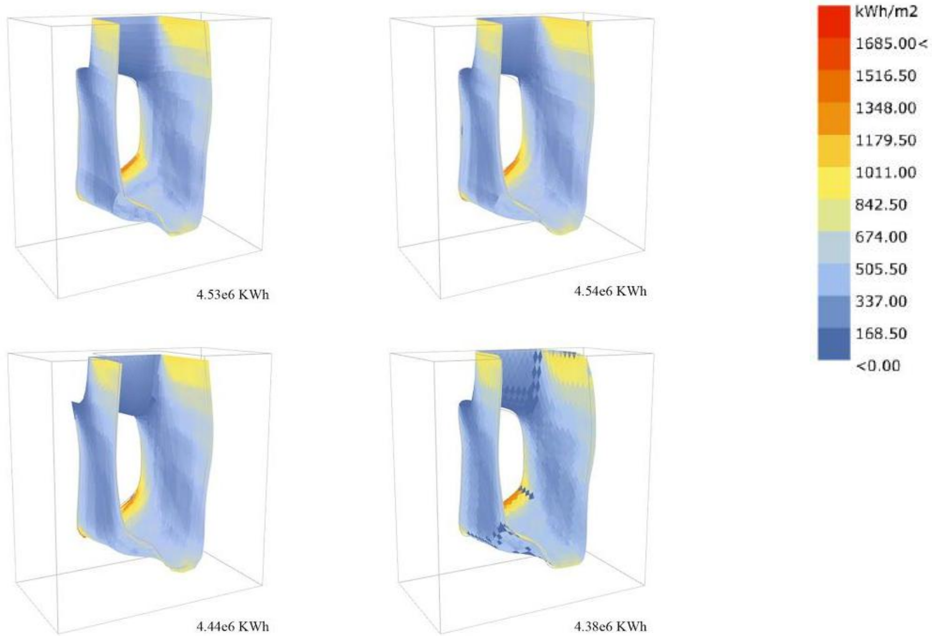


Figure 20: *Solar radiation applied to mesh alternatives*

6.5 Analysis of solar radiation of different types of meshes with shade of 1.2m.

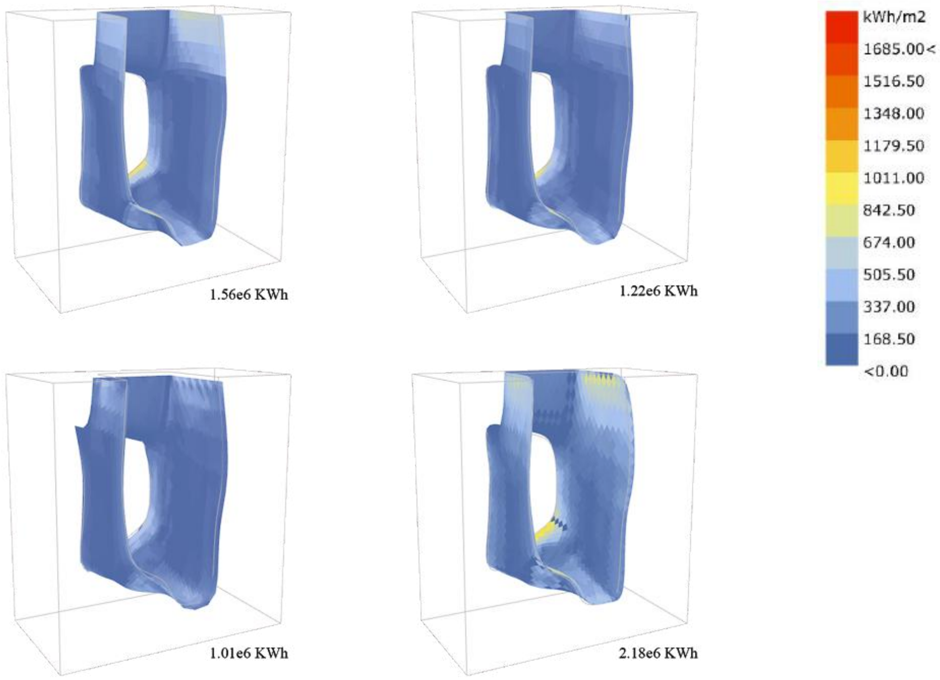


Figure 21: *Solar radiation with shade of 1.20m*

6.5 Method for Calculating of cost due to radiation

Energy through glazing,

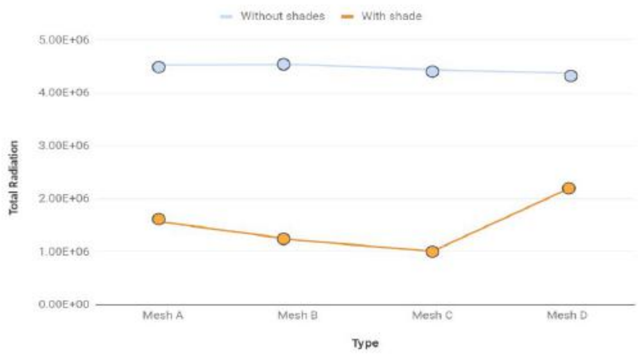
$$E = \underbrace{\text{Solar factor}}_{0.4} * \text{Radiation } (\text{KWh}/\text{m}^2) * \text{Window Area } (\text{m}^2)$$

Hence Cost,

$$€ = \frac{\text{E (energy through glazing)}}{\underbrace{\text{System performance}}_{3}} * \underbrace{\text{Cost of electricity}}_{\substack{\text{4 cents} \\ \text{Cost of electricity per KWh in} \\ \text{Dubai}}} * 20$$

6.6 Comparison of radiation between shaded and non- shaded mesh.

As seen from the **(Graph 4)**, there is a good reduction in radiation with shades, However the more number of mesh faces , more is the reduction in radiation compared to Mesh C with less number of faces, Rotating the shading device also helps considerably with Mesh C a considerable decrease compared to the other meshes. However it is also to be noted that adding shading devices also increases the cost factor during construction.**(Table 3)**



Graph 4: *Comparison between shaded and non-shaded mesh*

	Mesh A	Mesh B	Mesh C	Mesh D
Total Radiation Without Shades	4.53E+06	4.54E+06	4.44E+06	4.38E+06
Total Radiation With Shades	1.56E+06	1.22E+06	1.01E+06	2.18E+06
Percentage Change	65	73	77	50
Cost Without shades	724,512	725,648	711,104	700,912
Cost With shades	250,304	195,104	162,368	348,560
Percentage Savings	65.45	73.11	77.17	50.27

Table 3: *Comparison of cost and savings between shaded and non-shaded mesh*

7. Structural Analysis

The following study will analyze the structural performance of the freeform building facade and will provide an approach to a structural optimization on the basis of cost. In order to evaluate the structure, this analysis sets multiple objectives subjected to constraints based on total mass weight (ribs cross section), displacement and utilization. These aspects will be considered while analyzing each design alternative to achieve the most suitable solution.

7.1 Building analysis considerations

7.1.1 Optimization objectives

- **Min(*mtot*):** Minimize total mass of structure
- **Min(*dmax*):** Minimize displacement
- **Max(*u*):** Maximize utilization

7.1.2 Hard Constraints

- Maximum utilization must not exceed 1 (100%) for the ribs
- Maximum displacement should not exceed: δmax= *Lspan*/350

7.1.3 Optimization variables

- Cross section height and width

7.2 Parameters

This study is analyzed in Karamba, (add-on to Grasshopper), in which are considered the following inputs:

- Supports
- Curtain Wall ribs
- Glass panels
- Loads: gravity, self weight (beams, glass panels), wind load.

7.2.1 Support

To find the support points for all alternatives of meshes, the building void is intersected by 20 planes which represents the slabs of the building. The closests points from the mesh to the intersection points of the slabs, are the supports which will be chosen parametrically for each grid orientation of each type of mesh (See **figure 22**)

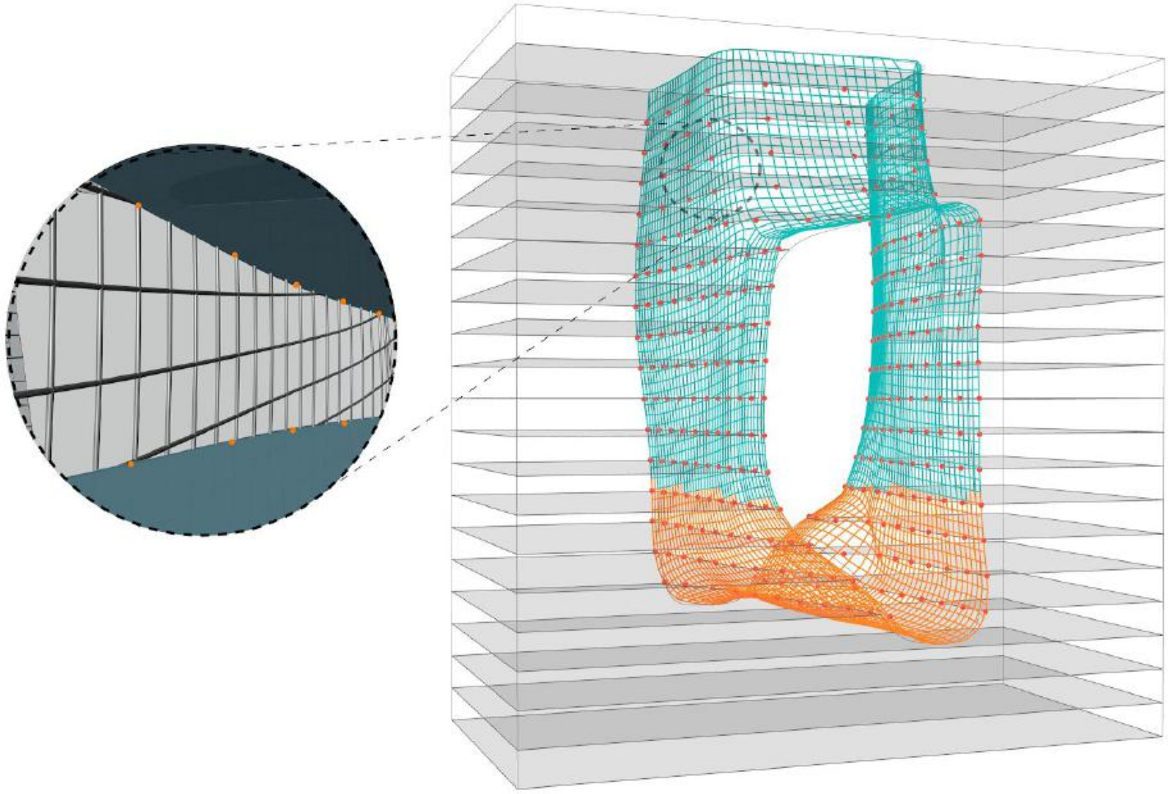


Figure 22: *Support points for each type of grid orientation*

7.1.2 Loads

For this analysis, self weight is conditioned by the loads of the ribs, glass panels and gravity. Due to computational limitations, wind load is not taken into account in this analysis **(Figure 23)**

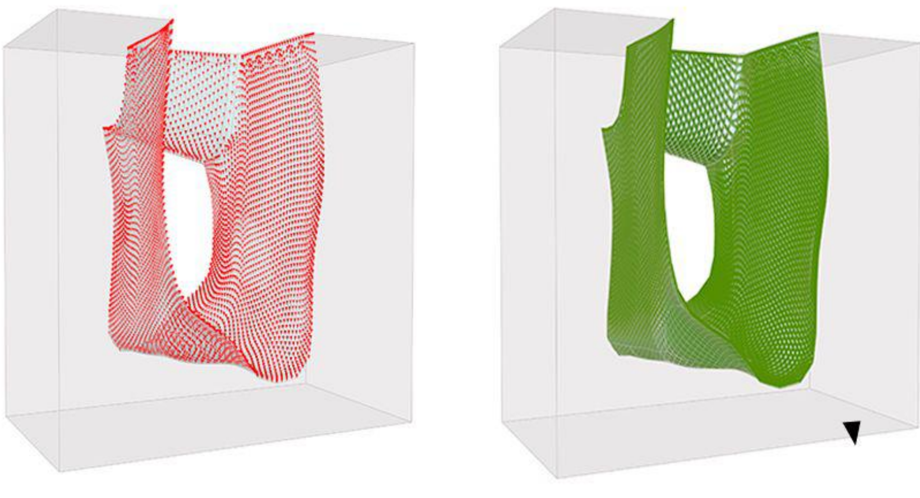


Figure 23: *From left to right, load from glass panels, load from curtain wall ribs and gravity*

7.1.2 Cross Sections

In order to calculate the dimensions of cross sections for upper and lower ribs, two different types of families are chosen for each case.The height of the ribs is the same for each type of family while the thickness and width vary. In order to reduce the total mass of steel in the structure, the **figure 24** below, shows the different dimensions for cross sections, which are analyzed in Karamba Optimize Cross Section component, to keep stresses and deflections below maximum values

1st cross section family

Subset for upper ribs
(L<3.5m)

- 250x150x10.0
- 250x100x12.5
- 250x150x12.0
- 250x150x12.5
- 250x150x16.0

2nd cross section family

Subset for lower ribs
(3.5m<L<5m)

- 450x250x8.0
- 450x250x10.0
- 450x250x12.0
- 450x250x12.5
- 450x250x16.0

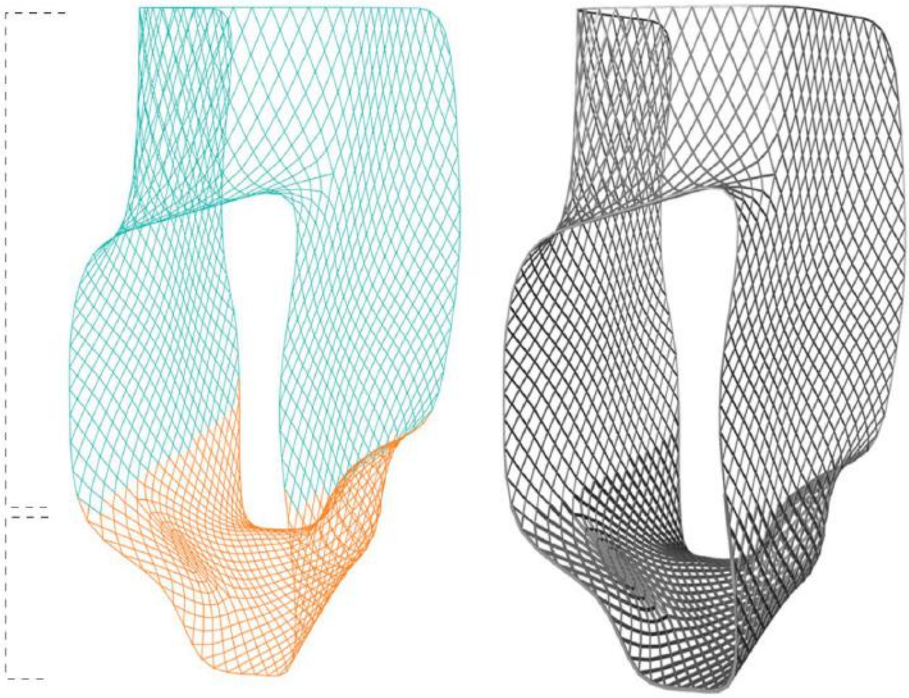


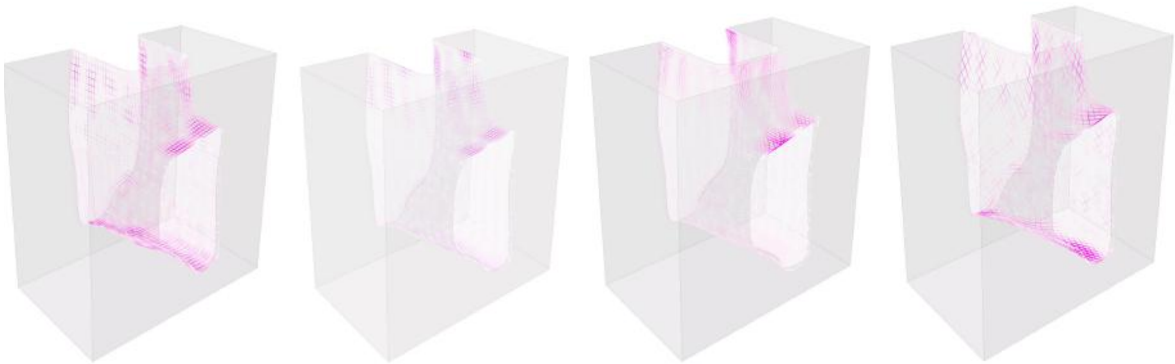
Figure 24: *Cross section families applied to upper and lower ribs*

7.3 **Displacement**

To analyze the displacement of the structure under loads, the following formula for steel structures is applied:

$$\boldsymbol{\delta}\mathbf{max} = Lspan/150 \qquad \{4\}$$

As it is shown in **Table 4** and **Graph 5,** the maximum value for displacement for each type of mesh, is set previously in Karamba; after calculation it is shown how the displacement in most of the meshes is located in the lower ribs, and the bridge, where the span of ribs are greater. In this case Mesh “A’ has the lowest value.



Mesh A
Quadriflow Mesh

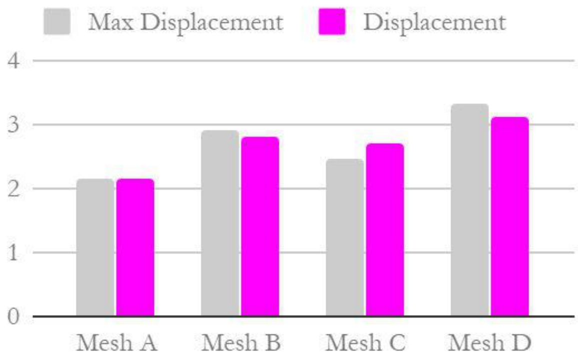
Mesh B
T-Spline final

Mesh C
Uv Map 30

Mesh D
Mesh 30 UV Map

Design Alternatives	Max Displacement-input (cm)	Displacement (cm)
Mesh A	2.16	2.15
Mesh B	2.92	2.82
Mesh C	2.48	2.7
Mesh D	3.32	3.11

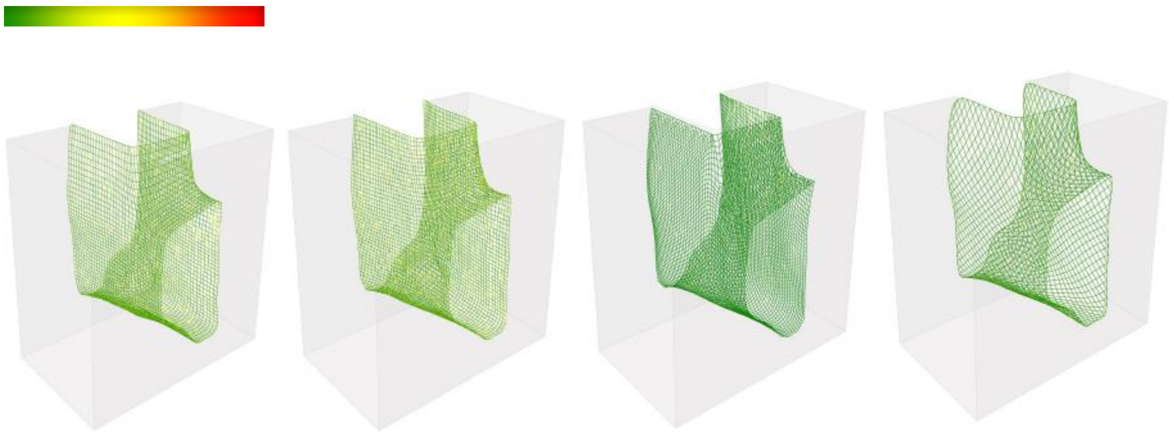
Table 4: *Deviation of the displacement output value from the input parameter value*



Graph 5: *Deviation of the displacement output value from the input parameter value*

7.4 Utilization

Utilization should not exceed 1(100%), for any bar on the structure considering all load cases, as it is shown in **Table 5** and **Graph 6,** Although utilization is evenly distributed, no bars are fully utilized



Mesh A
Quadriflow Mesh

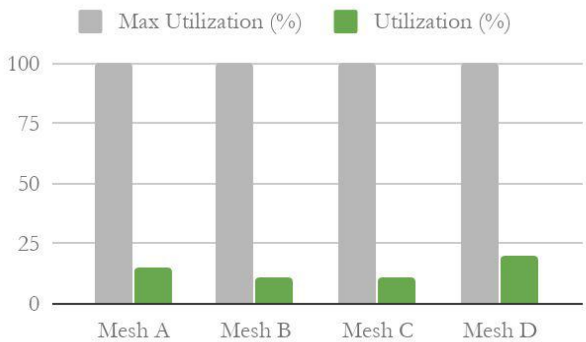
Mesh B
T-Spline final

Mesh C
Uv Map 30

Mesh D
Diamond

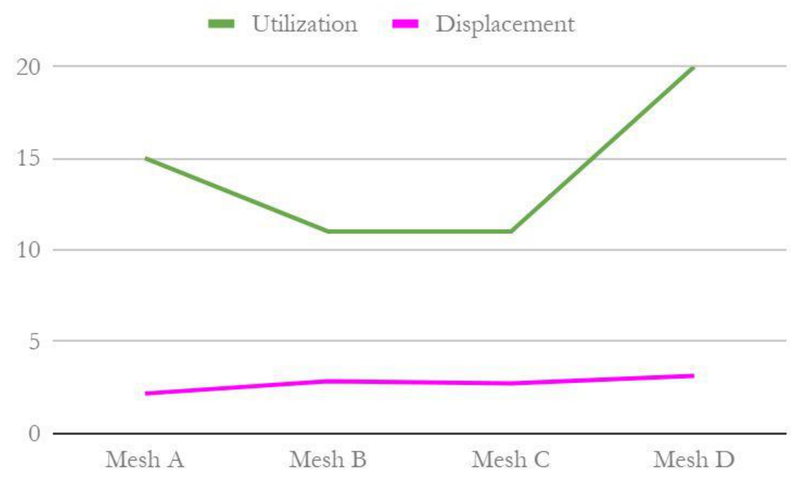
	Max Utilization (%)	Utilization (%)
Mesh A	100	15
Mesh B	100	11
Mesh C	100	11
Mesh D	100	20

Table 5: *Deviation of the utilization output value from the input parameter value*



Graph 6: *Deviation of the utilization output value from the input parameter value*

Results of displacement and utilization are translated to cost of mass per ton of steel, the table below shows that according to these constraints, the lowest value for cost is Mesh “A”



Graph 6: *Comparison between utilization values and displacement values*

Design Alternatives		Cost (euro)	Displacement (cm)	Utilization (%)
1	Mesh A	262657,00	2.15	15%
2	Mesh B	314366,00	2.82	11%
3	Mesh C	333744,00	2.7	11%
4	Mesh D	173926,00	3.11	20%

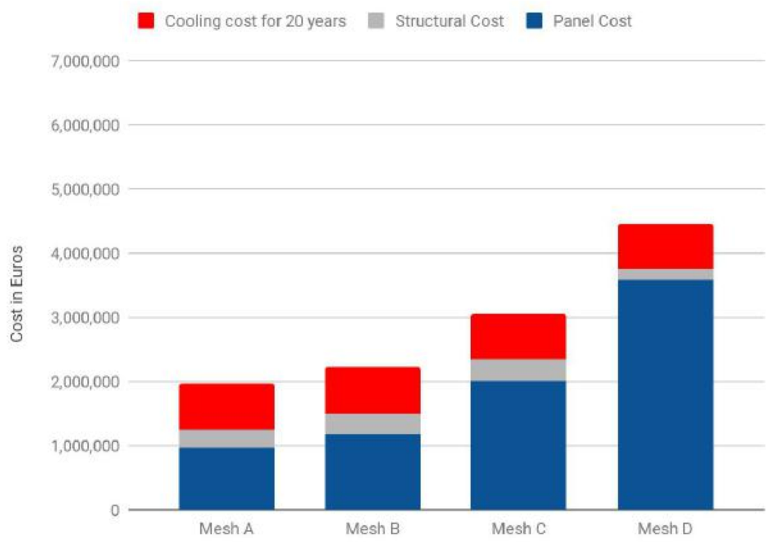
Table 7: *Total cost per ton according to displacement and utilization constraints*

8. Multi objective optimization comparing results and costs.

From the above analysis of specific individual methodologies, Cost of total structure is calculated which is summarised in the below table (**Table 8**):

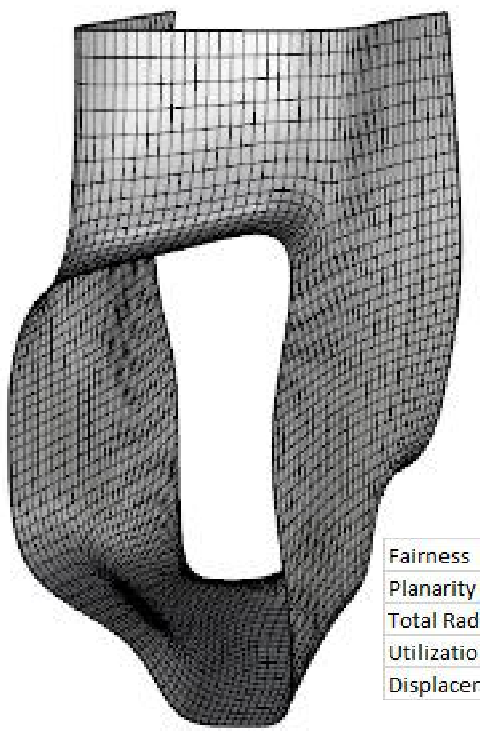
Optimization aspects	Mesh A	Mesh B	Mesh C	Mesh D
Panel cost	977,435	1,190,200	2,008,400	3,579,800
Structural Cost	262,657	314,365	333,743	173,95
Cooling cost for 20 years	724,512	725,648	711,104	700,192
Total	1,964,604	2,230,213	3,053,247	4,279,992

Table 8: *Total cost of individual analysis*



Graph 7: *Cooling as an operating cost while structure and panels are initial cost*

Mesh “A” selected



Fairness	0.1
Planarity	38%
Total Radiation	4.53 e6
Utilization	15%
Displacement	2.15cm

Figure 25: *Mesh A with various fitness parameters*

Looking at the table and the graphs (**Table 8, Graph 7**), though the different meshes perform better in terms of cost in individual analysis. Example: Mesh A in terms of panelling cost, Mesh D in terms of structure and Mesh C in terms of cost of cooling. The panelling costs always outweigh the cost of structural cost and cooling cost and in turn helps lower the total cost of analysis.Hence we can summarise that with the present technology, it is beneficial to have most number of planar panels to lower down the cost of construction of the facade.

The same results can also be observed when trying to optimize the meshes in terms of cost with fitness parameters of planarity, displacement and utilisation. The evolutionary solver however results in cost that is slightly better than that observed with the individual analysis. However, this cost difference is due to better planarity factor of 5% compared to the one seen with the individual analysis.

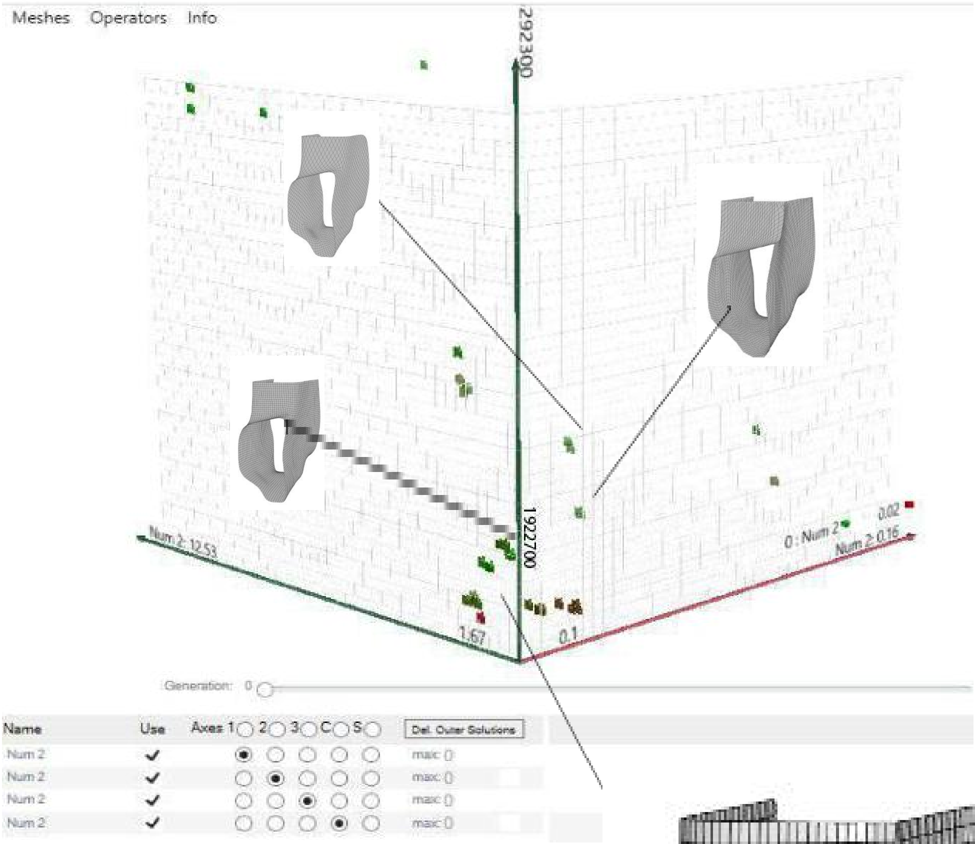


Figure 25: *Evolutionary solver results*

	Mesh
Panel Cost	966,570
Structural Cost	255,242
Cooling cost for 20 years	720,960
Total	1,942,772

Table 9: *Cost break-up from results of evolutionary solver*

Fairness	0.1
Planarity	43%
Total Radiation	4.50 e6
Utilization	15%
Displacement	2.15

Figure 26: *Mesh chosen by evolutionary solver with various fitness parameters*

9. Conclusion & Future Works:

- Planarity check to minimize the overall cost is still the dominating factor over other factors in terms of cost. This factor alone can win the other two factors in the study.
- Though the results in the two approaches are close to each other and belong to the same family. In the near future with upcoming new techniques to build curved panels the cost for same might lower down. That time this type of tool can prove to be more useful.
- Research on strategies to reduce cost of curved panels.
- Applying algorithm on a sinclastic or anticlastic surface.
- More factors for analysis like Thermal comfort, Daylighting can be incorporated to increase operating costs in the building

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List of figures

[Figure 4] https://www.zaha-hadid.com/architecture/opus/