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Optimization of the Panels Used in Free-Form Buildings and Its Impact on Building Cost.

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The described study presents the context of the process of optimization curved panels and the direct impact on reducing high cost, especially in this type of free-form buildings. The main motivation for this study is the avoidance of the traditional style of design where it needs to produce expensive designs because free shapes require a huge amount of specialization, the use of digital technology can overcome the problem of high cost through the production of optimized designs in addition to the ease of implementation of these forms which can be complicated in some cases as the number of freeform buildings that use building information modeling technology has increased recently. The importance of research is shown in guiding designers to optimize curved panels used in free formation during the early design stage so that design solutions can be correctly identified. This paper presents the results of analyzing the types of curved panels by comparing the cost before and after the optimization process, using algorithms for the selected materials (FRP, steel, and aluminum) that aim to reduce the value of curve coordinates while preserving the curve from deformation. In order to further devote attention to methodological frameworks to optimize curved panels besides cost control. the primary goal of the research is innovation at the initial design stage by designers through the use of algorithm-based assistance programs to optimize curved shapes that can produce contemporary project optimization curved panels are less expensive while maintaining the desired curved shape.

Keywords: Free-Forms, Cost control, Optimization, Panel, Algorithms.



1. Introduction

In the manufacture and design of freeform shapes in architecture, one constantly faces design challenges and often high costs [1]. Composite materials also greatly influenced how many forms of engineering systems used in the automobile, medicinal, aerospace, construction, civil and mechanical industries have been developed and studied in recent decades [2]. Therefore, the optimization of the forms of this type of building has become a hot topic since its widespread use. Since then, a lot of curved shape optimization research has been undertaken that has revealed many new optimizations and their direct impact on reducing high cost [3-9]. In parallel, research is being done to build panels that are not only aluminum but it's from different materials such as the height of architectural construction with glass fiber reinforced plastic (GRP) was the era 1960-1972 [10], and lightweight and sustainable wood panels using laminated veneer lumber, where optimization plays a major role in the ability to quickly and accurately assemble curved shapes to maintain the shape of deformation with the help of numerically controlled machines for integrating joints into panels engineering [11]. As higher panel curvature leads to higher cost, the panel optimization method is required to modify curved panels with double curvature into planar panels or single curvature panels. The desired esthetic quality of free-forms and their surface smoothness shall be without damage. According to the breakdown of costs for recent free-form building projects worldwide, the costs for panel construction accounted for between 15 and 20 percent of the total project cost [12]. The study suggests a panel optimization process from different materials for free-form buildings by using a worldwide application that free-form designers can easily use. The study measures the construction cost changes during the panel optimization process by connecting the optimization results with panel construction cost estimates of the free-form building projects. A case analysis on the free-form building projects with different materials is performed to check the applicability of the research findings.

Throughout the analysis, free-form buildings Heydar Aliyev Cultural Center, Weatherhead School and DC New Logic III have cost assessed. Differently from the optimization levels, construction cost control is found for each selected case. In the case study, the most curved parts were chosen for the facades of the free-form projects, and as a result, the optimization was achieved without distorting the shape at about 20.2% of the budget by comparison with the initial cost before optimization process, by choosing the appropriate optimization point for each case while maintaining the continuity of the curved line.

2. Methodology

The five stages of the study were carried out as linear methods to optimizing free-form panels: (1) configuration of the algorithm for optimization analyzes, (2) Script creation which can parametrically monitor panel conversion information, (3) Analysis of continuity and curvature, (4) Optimizing and analyzing panel shape transformation, And (5) preliminary estimates of costs to minimize distortions and save production costs for every range of optimization. Further sophisticated applications can be created in potential studies depending on step-by-step processes see (Figure 1).

3. Material and Software Selection

Grasshopper has been chosen for use in the modeling process which is an algorithm graphical publisher that is closely incorporated with the Rhino 3D modeling instruments for parameter modeling tool for free-form structures., while Microsoft Excel™ is converted by the Para Cloud modeler to a strong parameter modeler. Furthermore, the study assumed the panels are made of Fiberglass Reinforced Polyester (FRP), steel and aluminum as the most popular materials for curved facade panels.

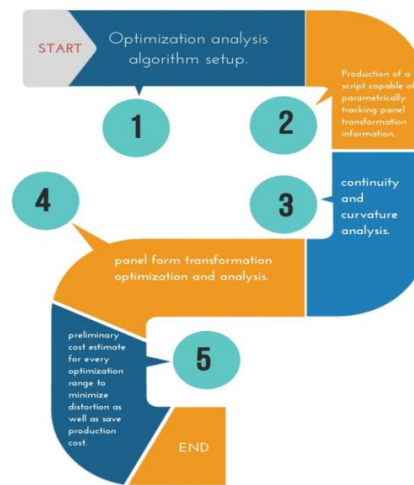





Figure 1: The Study Steps for Optimizing Free-Form Panels.

4. Case Projects

The three case projects this study referred to for inducing free-form surfaces. The second line of (Table 1) indicates the surfaces modeled for the optimization test. The surfaces intended to reflect the biggest curved portions of each case project the red circles in the case projects.

The model for each surface of free form is a 100 m² area with an error margin of ± 5 m² so that that the curvature range of each case project can well be reflected. The free-form surfaces were scheduled for a quadrangle that was commonly used in previous free-form building projects.

Table 1. Test Optimization Subjects of the Panel.

	Selected Projects	Materials	(The surface modeled for test)	Panel Type
Case 1	 Heydar Aliyev Cultural Center (2012) [13]	Fibreglass Reinforced Polyester (FRP)	Area: 103.8 m ²	Planar 5
				Single Curvature 9
				Double Curvature 86
Case 2	 Weatherhead School (2002)[14]	steel	Area : 99.7 m ²	Planar 3
				Single Curvature 9
				Double Curvature 88
Case 3	 DC New Logic III (2019)[15]	Aluminum	Area : 104.4 m ²	Planar0
				Single Curvature 62
				Double Curvature 38

The three test surfaces were then tested with Grasshopper. The number of panels should be restricted to 100 in each situation. The highest curvature of aluminum, FRP and steel panels that can be produced using MPF processes is 30 cm. The panels whose curvature surpassed the value were therefore divided into smaller parts to half the size of the panel above see (Figure 2).

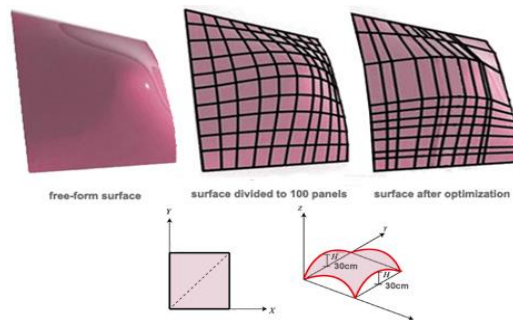


Figure 2: Divide Curved Panels.

The study created, as shown in (Figure 3), a panel optimization algorithm. Panel Arc height, from P1 to P2, was divided into 30 cm parts and curved to six different points was optimized.

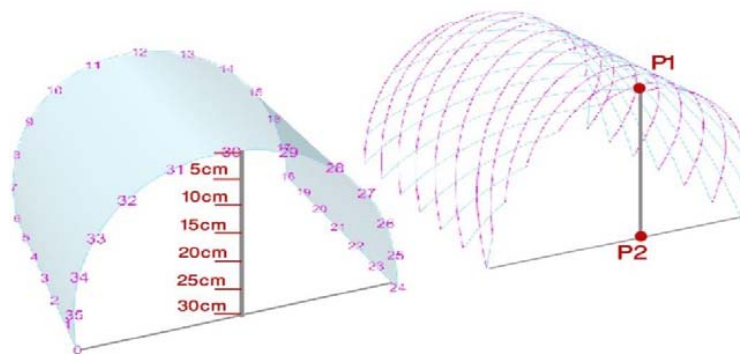


Figure 3: The Process Determines The Circular Parts Of Each Surface.

This study developed the continuous transformation process of the curved surfaces as shown in (Figure 4). The method is chosen as the circled parts of each surface that demonstrate the conversion of the surfaces from double curvature panels through the optimization method to single curvature and planar panels. The study also created scripts using Grasshopper's mark curve start & end feature to measure the quality level of keeping curved surfaces. Coordinate points are extracted, identified as optimization points, and used to maintain the original plan (coordinate points).

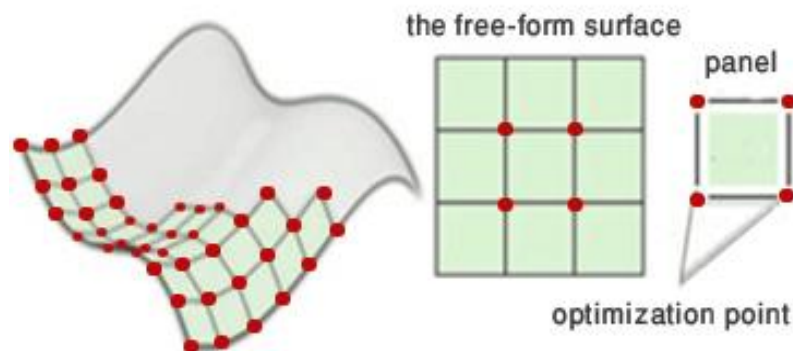


Figure 4: The Process Determines The Circular Parts Of Each Surface.

In each panel is four edges differ in height. The study created a Grasshopper Script, allowing automatic measurement in the optimization of the maximum location value and the height value of all four edges of each panel see (Figure 5).

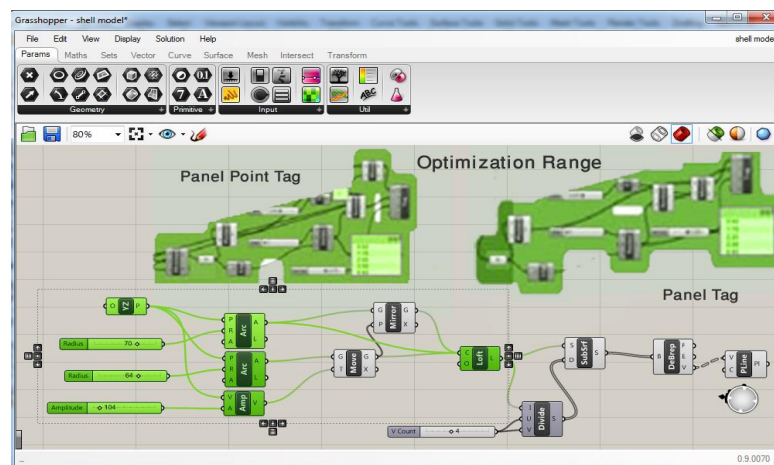


Figure 5: Panel Optimization Grasshopper Script.

5. Panel Optimization Analysis

Developable surfaces were commonly used as part of these methodologies owing to their geometric efficacy in distributing bent panels over planar substrates. A surface that can be developed is the material that can be applied without deformation to a plane (i.e. bending or compression). The use of developable surfaces is suitable for sheet metal panels which can be deformed to developable or almost developable shapes at reasonable expenses [16].

(Figure 6) is the graphic representation of data in (Table 2). It shows a decrease of double curvature panels at each optimization point of the cases and an increase in single curvature and planar panels. The issues with the optimization results are evaluated by test results of Curvature Analysis in (Table 3).

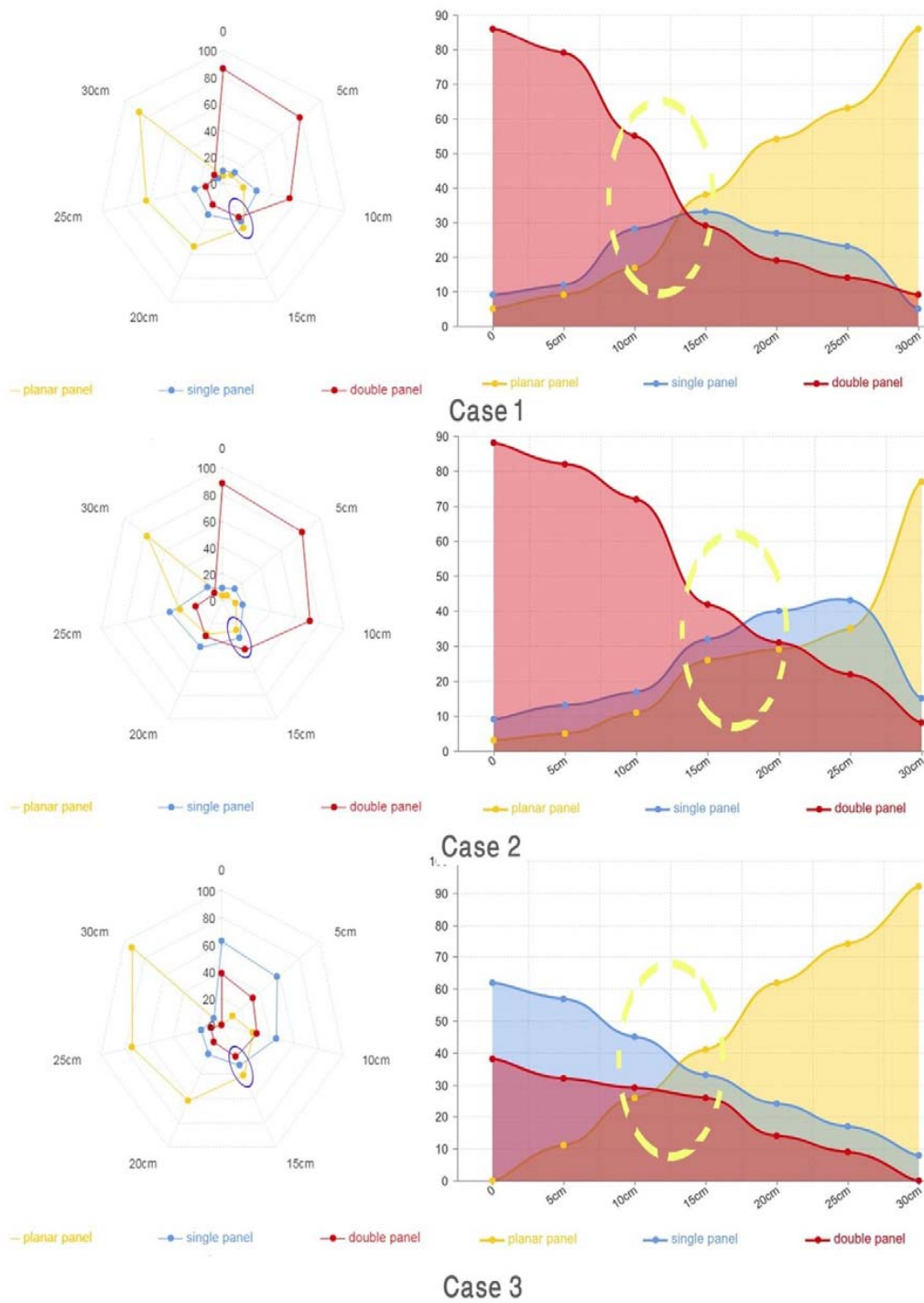


Figure 6: Change Panel Types Graphical Presentation.

Table 2. After Optimization Test, the variation of the panel types.

case (1)								
1		0	5cm	10cm	15cm	20cm	25cm	30cm
2	planar panel	5	9 ▲	17 ▲	38 ▲	54 ▲	63 ▲	86 ▲
3	single panel	9	12 ▲	28 ▲	33 ▲	27 ▲	23 ▲	5 ▼
4	double panel	86	79 ▼	55 ▼	29 ▼	19 ▼	14 ▼	9 ▼

case (2)								
1		0	5cm	10cm	15cm	20cm	25cm	30cm
2	planar panel	3	5 ▲	11 ▲	26 ▲	29 ▲	35 ▲	77 ▲
3	single panel	9	13 ▲	17 ▲	32 ▲	40 ▲	43 ▲	15 ▲
4	double panel	88	82 ▼	72 ▼	42 ▼	31 ▼	22 ▼	8 ▼

case (3)								
1		0	5cm	10cm	15cm	20cm	25cm	30cm
2	planar panel	0	11 ▲	26 ▲	41 ▲	62 ▲	74 ▲	92 ▲
3	single panel	62	57 ▲	45 ▲	33 ▲	24 ▲	17 ▲	8 ▲
4	double panel	38	32 ▼	29 ▼	26 ▼	14 ▼	9 ▼	0 ▼

Table 3. Test results of Curvature Analysis.

Optimization point	0	5cm	10cm	15cm	20cm	25cm	30cm
Case 1							
Case 2							
Case 3							

The area change for each panel type's with the procedure of panel optimization at 6 optimization points and cost comparison of the manufacturing of the panel together. To calculate the cost rate in (Table 4) multiply each area of panel types by cost rate then the values are collected for each panel type used in each case study to obtain production cost rate. The same method was followed in the second and third cases by using different values of the Cost Rate between the kinds of the panel materials for each case as illustrated in (Table 5).

Table 4. Free-Form Facade Panels Costs Rate.

Division		Planar	Single Curvature	Double Curvature
Heydar Aliyev Cultural Center (2012) (Fiberglass Reinforced Polyester)	Contract Price	\$ 201	\$ 301	\$ 482
	Cost Rate	1	1.5	2.4
Weatherhead School (2002) (Steel)	Contract Price	\$ 232	\$ 441	\$ 626
	Cost Rate	1	1.9	2.7
DC New Logic III (2019) (Aluminum)	Contract Price	\$ 178	\$ 196	\$ 392
	Cost Rate	1	1.1	2.2

Table 5. Each Optimization Point Cost Estimated Panel Types.

case (1)

Division	0	5cm	10cm	15cm	20cm	25cm	30cm
planar m ²	2.26	4.55	7.68	17.17	41.61	52.09	85.15
single m ²	13.84	18.94	39.34	55.53	41.52	35.84	7.68
double m ²	87.70	80.5	56.08	29.57	19.37	14.27	9.17
total m ²	103.8	103.5	103.1	102.8	102.5	102.2	102
production cost rate	233.5	226.1	201.2	171.4	150.3	140.0	118.6

case (2)

Division	0	5cm	10cm	15cm	20cm	25cm	30cm
planar m ²	3.72	6.72	13.64	32.24	35.96	43.4	95.48
single m ²	18.75	20.82	22.28	29.71	35.14	34.2	6.08
double m ²	77.23	71.96	63.18	36.85	27.20	19.30	7
total m ²	99.7	99.5	99.1	98.8	98.3	96.9	96.4
production cost rate	247.8	201.0	226.5	188.1	176.1	160.4	125.9

case (3)

Division	0	5cm	10cm	15cm	20cm	25cm	30cm
planar m ²	0	10.65	29.29	41.89	63.31	74.85	102.3
single m ²	71.8	66	52.11	38.21	27.79	19.63	0.14
double m ²	32.6	27.45	22.30	23.30	12	7.72	0
total m ²	104.4	104.1	103.7	103.4	103.1	102.2	102.5
production cost rate	149.7	142.8	135	134.4	119.9	113.1	102.5

6. Results

Changes in panel types were examined at each facade and the cost of production was assessed during the process of optimization of the panel with the three facades. Where we notice after the improvement process, the biggest decrease was in the first case, which is Fiberglass Reinforced Polyester (FRP) material; the rate fell by 26.5 percent from 233.5 to 171.4. And then the second case that used steel material, the rate fell by 23.9 percent from 247.3 to 188.1. The least is the third case, which used Aluminum material, it decreasing by 10.2 percent from 149.7 to 134.4, whereas the low-cost average decreased by 20.2 percent. A model designed with the utmost optimization against deformation was obtained see in (Figure 7).

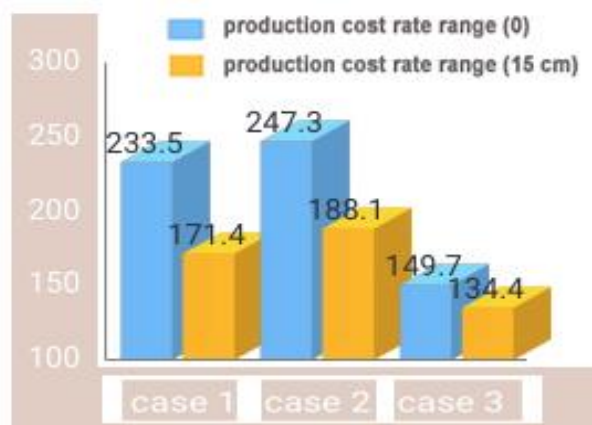


Figure 7: Low-Cost Projects after Process Optimization.

7. Conclusion

In conclusion, the design and manufacturing approach developed by algorithms in this work has become a guide for designers to focus on architecture and make design decisions. It changes the traditional design methodology in such a way that reduces the design complexity for the designer which is optimized by the algorithm resides in the potential of creating a wide range of solutions quickly and effortlessly, developing various approaches to design and gives more flexibility for the designers to focus on the more important issue in the context of architecture and the built environment design.

A structure of free-form building is a sloping, deformed building of design. The buildings outer facades include the panels with very complicated curvature. While the panels display impressive building forms in the urban environment, so the forming of the panels is extremely complex in reality. The higher the curvature of the panels, the higher the cost, For this, the designer must take into account optimization process by reducing the height of the curvature during the early design stages so as not to affect the interface functions without prejudice to the aesthetics of the curved shapes and preventing them from deformation. If this method can be related to the cost estimate of panel construction, cost variation can be observed by panel curvature change so that a feasible array of panel curvatures can be defined that fulfill both the construction cost limit and the free-form model purpose.

Throughout the analysis, free-form buildings Heydar Aliyev Cultural Center, Weatherhead School and DC New Logic III, Were cost assessed. Differently from the optimization levels, construction cost control is found for each selected case. In the case study, the most curved parts were chosen for the facades of the free-form projects, and as a result, the optimization was achieved without distorting the shape at about 20.2% of the budget by comparison with the initial cost before optimization process, by choosing the appropriate optimization point for each case while maintaining the continuity of the curved line.

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