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User-friendly conceptual design of standardized glass complex shaped façades.

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Abstract

This research study aims to design, apply and optimize a new mechanism that improves curved façades design and construction processes. In this sense, this investigation has the objective of designing an optimization algorithm that: a) is capable of optimizing complex geometric curtain wall paneling so that resulting panels are standardized; b) has a responsive feedback system that visualizes the standardization process and enables users to intervene in this process, permitting an intuitive conceptual design; c) permits the introduction of BIM to the panels and d) is based on broad application strategies so that is a tool applicable as a general working strategy.

The new algorithm has been designed combining physics simulations that act on a conventional CAD system with a polygonal comparative mathematical algorithm. Then it has been applied to Mias Architects' honorable mention proposal for the contest designed for the future Passenger Service Centre at the Kinmen Port in Taiwan. Finally, this application has been compared to the application of two similar existing software tools analyzing numerous parameters such as mesh density, previous programming time, mesh definition and optimization time, panels' standardization time, maximum deviation, molds savings and standardization error margin among others.

The new algorithm stands out because is based on glass production and construction information modeling, permits users to standardize paneling if extra time is dedicated to do so and allows users a detailed edition of the mesh. This research project concludes that the investigation has accomplished the initial objectives and the new algorithm is a useful mechanism for conceptual design processes because of their user-friendly environment and their capacity to incorporate glass construction technical knowledge, which overcomes the existing tools.

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1. Introduction

At present, there are numerous recently built complex shaped facades and roofs with an external paneled surface. When the panels of these surfaces are flat pieces the final surface defined by these pieces does not follow the original design but a faceted approximation of it. This is the case of curtain walls that are composed of glass panels, which are mostly flat because their cost is less [1]. However, there are examples of complex surfaces built using curved pieces such as the Kunthaus that was designed by Peter Cook and constructed in Graz in 2003 [2]. In all these curtain walls, the paneling of their free surfaces results in panels that often vary from each other, being either flat or curved respectively. Therefore, the whole surface has a high level of complexity and a high cost. The assembly process has similar difficulties because each type of panel has to be moved and fixed in a specific way. In consequence, in this kind of surfaces it is essential to standardize panels in order to simplify its construction. Some researchers have developed mechanisms based on iterative approximation systems like Evolute tools [3] which is a plug-in of Rhinoceros 3D to work with surfaces. Based on these mechanisms there are some recent proposals that improve molds efficiency in order to cut down building costs [4]. But resulting panels are not standardized.

Today there are mechanisms based on physics simulations that can solve some optimization problems in run-time such as Kangaroo [5] that are compatible with conventional CAD tools. This system proposes different mechanisms that users can utilize as surface paneling systems. Moreover, Kangaroo permits interaction with users in run-time and eases the introduction of algorithms and the visualization of the results. But none of these approaches is able to perform a complex optimization such as maximizing repetitions of pieces at run-time.

A similar proposal to the optimization mechanism exposed here is the consulting service of Evolute Tools Pro in which this company studies already defined building surfaces and maximizes the repetition of panels [6]. There are other studies that also use iterative processes specifically designed to solve a particular study case [7].

Nomenclature

PBOA Physics Based Optimization Algorithm

2. Research projects

The aforementioned existing software tools, systems and consulting services have weaknesses, which Table 1 shows.

Table 1. Main weaknesses of the existing mechanisms.

	Run-time	Standardization	References
Kangaroo	Yes	No	[5]
Evolute Tools	No	No	[1]
Evolute Tools Pro	No	Yes	[8] [7]

Legend: Run-time: it works in run-time; capacity of standardization, in the case of Grasshopper, it allows users to program new functions using a writing language interface but it breaks the visual logic of Grasshopper and requires programming skills; the application specifically designed for quad meshes is a specific method for a particular case.

None of these existing mechanisms permits users to modify the model while carrying out the optimization process. Kangaroo visualizes the changes in the model in runtime but it is not able to maximize repetition of pieces because it lacks the required predefined functions and its programming does not admit excessively complex processes [9]. Our proposal is PBOA, an algorithm that aims to make this already present standardization processes compatible with real time design.

3. The configuration of this new application

3.1. Mathematical analysis

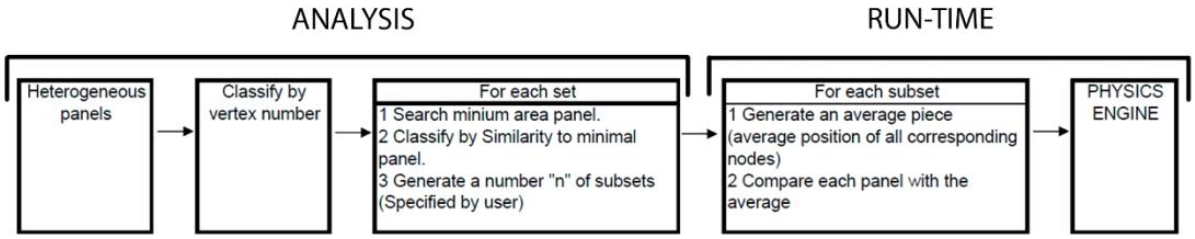

Figure 1. Schematic description of the mathematical analysis.

The most difficult part for the run-time calculations is the mathematical analysis of the pieces, which enables PBOA to establish an adequate classification criterion. This classification of pieces is not necessary to be executed continuously but only when a change on the parameters or the geometry produces a significant difference on the state of the mesh. In any case, it is preferable to do it as fast as possible in order to not break the design process. Figure 1 shows this mathematical process, which deals with the identification, analysis and group classification for the panels. This process also generates a pattern based on the average shape of the panels in a group. By doing so, it becomes possible to establish a panel's classification, which permits organizing sets that differ in the number of sides (triangular, square, hexagonal) and classify each of these typologies in subsets following a contour geometric criteria. This fast classification not only allows the system to execute it without cause a significant interruption in the design process, but also allows other derived optimization functions to be executed in runtime using the data obtained from this process.

3.2. Physics simulations

We implemented physics formulas in order to coordinate mathematical analysis with CAD geometry. This principle has been used as a modeling tool previously [10]. The PBOA algorithm applies this simulation on the model's control points, as if it was a molecular dynamics model. First, PBOA uses a spring model [11] to generate bars structures starting from panel nodes.

The PBOA algorithm can establish a direct relationship between the original nodes and the pattern nodes for the analyzed piece, generating actions that tend to join both nodes in one only point. PBOA uses a combination based on Hooke's law and a modified gravity equation that results in (Equation 1) , which is the force between the pattern piece nodes and the studied piece nodes where a is the acceleration of the particle, k an intensity regulator controlled by the user, 0.1 is a factor that reduces the intensity of the force to prevent some undesirable results, d is the distance between the two particles involved, m_i the mass of the particle studied and, in the denominator, the total mass of the system.

$$a = k \times 0.1 \times d \times \frac{m_i}{\sum_{u=1}^{n} m_u} \qquad [1]$$

On the other hand, PBOA can combine this action with other actions also applied on the mesh so that panels not only tend to be equal but also retain different specific geometric properties, such as flatness, orthogonal angles, etc., that users assign. *(1)*

4. Comparative analysis

4.1. Study case

The study case selected for this analysis is part of the Mias Architects' honorable mention proposal for the contest designed for the future Passenger Service Centre at the Kinmen Port in Taiwan [12]. This Passenger Centre [13] will be a building having an area of 45.000 m2 and a 30 m height serving as an international passenger terminal (Figure 2).

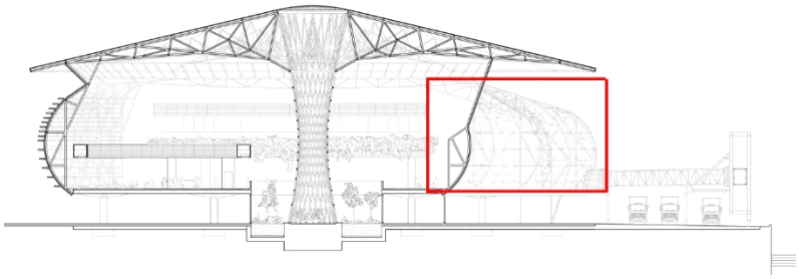

Figure 2. Section drawing of Kinmen Port in Taiwan. Cortesy of Mias Architects. The red rectangle indicates the part of the façade studied in this investigation project.

4.2. Quad mesh tests

PBOA

In the first test, see Table 2, the researchers introduced the original NURB surface in the F-CAD tool and cover it with the initial mesh. After that PBOA automatically generated basic physics based functions in quad meshes, refer to Figure 3. These functions are: 1) the flatness force that keeps the four nodes of each cell on the same plane; 2) the distance force, which keeps mesh nodes separated by a determined distance and 3) an adhesion force that maintains the mesh added to the original NURBS by respecting the user-defined margins. In order to optimize the mesh geometry, a PBOA function that equals tension and length made the lengths of the mesh bars even so those tensions were uniformly distributed. Another function regularized angles so they were all orthogonal. The horizontal aforementioned restrictive guides were several curves so that the mesh followed the original design and its horizontal joints kept their initial horizontality.

Evolute Tools

In their first test, see Table 2, the authors started using Evolute Tools to both define and optimize the center mesh. This system started with an initial mesh that subdivided and optimized until giving a proposal. This tool based this initial mesh on the control points of the NURBS that defined the skin surface. The researchers subdivided this mesh using the Evolute Tools method called "CatmullClark" until obtaining an adequate mesh. Then the authors optimized that mesh as follows: 1) they assigned a value of 0.1 to the variable "Fairness Springs" in order to make all mesh bar lengths uniform; 2) they assigned a value of 0.5 to the variable "Surface Closeness" to maintain the original surface; 3) they assigned a value of 0.5 to the variable "Curve Closeness" in order to retain the contour shape of the surface skin.

Kangaroo

In the first test, refer to Table 2, at the beginning the researchers had to define a batteries schema in Grasshopper that was capable of developing an adequate process to optimize panels. The resulting process started with a Rhino mesh to which Kangaroo applied different forces in order to optimize the result. The authors introduced a mesh of 24 x 36 panels in Grasshopper as initial data. After defining this mechanism and giving the initial data, it was possible to change mesh values and visualize the effects in run-time with direct feedback. In order to keep the flatness of panels, the authors connected the mesh to the Kangaroo function called "PlanarizeQuads", which permitted the authors to maintain the nodes of several square pieces on the same plane. The function "PullToSurf" was able to keep the mesh following the original surface. The authors tried to make the lengths of the bars even with the function "EqNStrenght", but the authors had to limit the effect of this last function and some bars had different lengths.

4.3. Hexagonal mesh tests

In the second test, see Table 3, the researchers introduced the original NURB surface in the F-CAD tool and cover it with a hexagonal mesh. This mesh was then used to test the optimization processes of PBOA and Evolute tools. The process was not reliable in Kangaroo so it was omitted.

PBOA.

In the first test the application of PBOA was similar to the Quad mesh test. First the authors generated a hexagonal mesh. Then PBOA applied the same flatness, distance and adhesion forces applied to quad meshes because these forces do not distinguish between quads and hexagons. In their second test the researchers repeated their test in order to contrast results with a higher density mesh. Consequently, the flatness of panels improved.

EVOLUTE TOOLS.

In the first test the researchers generated a mesh, for which the authors followed a different procedure than for the quad mesh. First, the authors generated a Rhino square mesh and then they introduced diagonals and horizontal divisions to obtain a triangular mesh that contained the hexagonal mesh for this study case. The authors obtained this hexagonal mesh using the subdivision mechanism called ”Dual WithBoundary”. The authors optimized the mesh by giving the following values to the following options: 1 to ”surfacecloseness”, 1 to ”CurveCloseness”, 0.2 to ”FairnessSprings” and 0.4 to ”BallPacking”. The resulting mesh had a non-standardized uniform distribution of panels with uniform bars lengths. In the second test, see Table 3, the researchers performed a second test with a higher density.

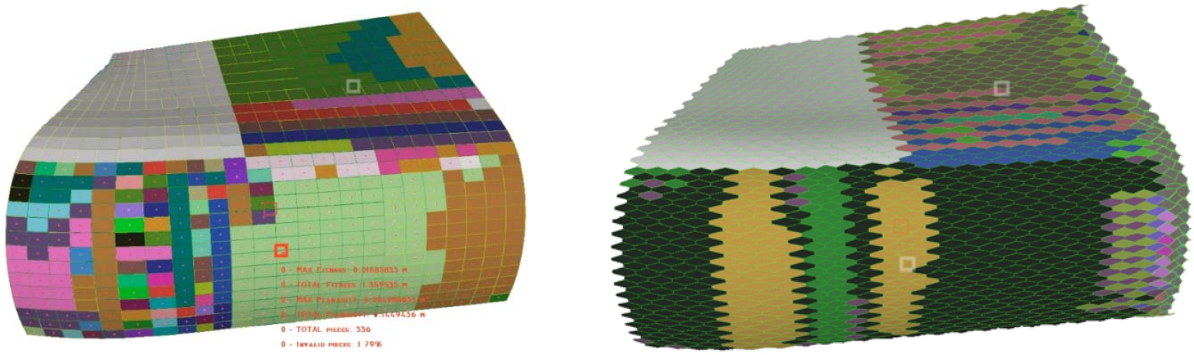

Figure 3. First test using the PBOA algorithm in F-CAD’s tool. with a square mesh left, and an hexagonal mesh, right.

5. Results and discussion

Results in Table 2 prove that the main difference between PBOA and the other two mechanisms is that the new algorithm permits users to standardize paneling if extra time is dedicated to do so and, in consequence, PBOA permits reducing the number of required molds. The results in Table 2 also prove that Evolute Tools and PBOA are better for this case of study because they do not require additional time for a previous programming process; they are quicker generating the mesh and they have a smaller maximum deviation for the panels' flatness.

Table 2. Results of the quad mesh tests.

Edition	**Units**	**Test1**		
		PBOA	Kangaroo	Evolute
Study case name		Q1a	Q1b	Q1c
1. Mesh density	Pieces	23x30	23x30	23x30
2. Programming time	Minutes	0	40	0
3. Meshing time	Minutes	15	25	15
4. Standardization time	Minutes	15	N/A	N/A
Optimization	**Units**			
		PBOA	Kangaroo	Evolute
5. Maximum deviation	cm	0.00	1.70	0.70
6. Molds per panel	None	241/690	690/690	690/690
7. Molds' savings	%	65.00	0.00	0.00
8. Standardization error	cm	2.00	N/A	N/A

Legend: 1) number of panels in one direction multiplied by the number of panels in the other direction; 2) Time spent to program the mechanism to solve the study case; 3) time spent for the definition and optimization of the mesh; 4) time required for the standardization of the pieces; 5) maximum deviation of the panels' flatness (m); 6) number of molds divided by total number of pieces; 7) saving of molds in percentage and 8) length of the standardization error margin.

Table 3. Results of the hexagonal mesh tests. Legend: See table 2.

Edition	**Units**	**Test1**	
		PBOA	Evolute
Study case name		H1a	H1b
1. Mesh density	Pieces	24X53	25X53
2. Programming time	Minutes	0	0
3. Meshing time	Minutes	25	30
4. Standardization time	Minutes	35	N/A

Optimization	**Units**		
		PBOA	Evolute
5. Maximum deviation	cm	0.7	1.2
6. Molds per panel	None	954/1272	1325/1325
7. Molds' savings	%	25	0
8. Standardization error	cm	2,25	N/A

The previously proved PBOA capacity for standardization permits a reduction of the glass surface economical and environmental impacts during the production, transport, assembly, maintenance and disassembly phases [14]. For example, only with the production of the glass panels molds standardization carries a 65% savings in rectangular meshes and a 25% savings in hexagonal meshes, refer to Table 2 and 3. Considering that these molds cost from 1500 to 3000 Euro [15], for a curtain wall similar to that in this study case but with double curved panels, between 838 Euro/m2 and 1192 Euro/m2 could be saved in rectangular and hexagonal meshes respectively, refer to Table 4, because of standardization.

Table 4. Table about the reduction of the economic and environmental impacts due to PBOA standardization of paneling.

Study case	Mold economic impact		Mold environmental impact Material consumption		Energy consumption		CO2 emissions	
Name	Cost (Euro)	Saving	Steel (kg)	Saving (kg/m2)	MJ	Saving (MJ/m2)	kg CO2	Saving (kg CO2/m2)
Q2b, Q2c	1552500	-	200100	-	20390	-	1463	-
Q2a	886500	838	114260	108	11643	11	835	1

The combination of all additional PBOA advantages results in a very useful mechanism for the conceptual design phase. This occurs because PBOA run-time feedback and intuitive functions define a user-friendly environment; furthermore, due to its accuracy and the fact that PBOA is based on glass production and construction information modeling, which avoid conflicts between conceptual design and technical solutions and permits the inclusion of environmental criteria since the inception of the project.

This mechanism still has several shortcomings, which the authors are aware of and currently resolving. For example, systems such as Evolute Tools, are more powerful to use with simple curvature surfaces and panels. On the other hand, in general, physics simulation systems still have important challenges in order to facilitate the control and precision of results that need to be addressed.

6. Conclusions

The main innovation of this research project is the development of an algorithm capable of standardizing the paneling of a complex shaped curtain wall combining any geometric condition with the direct edition of the mesh and with run-time feedback. These capabilities result in a useful mechanism for conceptual design processes because of their user-friendly environment and their capacity to incorporate glass construction technical knowledge. This useful novelty for the design and construction of complex shaped glass skins is different from the existing tools.

The authors have developed this new algorithm starting with F-CAD software, which corroborates conclusions from previous research projects such as that F-CAD “is a base to develop software tools for prefabricated façades composed of different materials” [16].

This investigation project has also found new research paths to follow. For example, the PBOA algorism enables improvements in sustainability due to the standardization of glass panels and PBOA prepares specific functions for the production and construction of glass surfaces. In this sense, the authors are working in order to incorporate a sustainability assessment for their new mechanism, which will operate in run-time and will intuitively give the economic, environ- mental and social impacts of a design to users. Therefore, their PBOA mechanism is ready to incorporate the Integrated Value Model for Sustainable Assessment (MIVES) [17]. The authors and the glass industry are also finishing an application that automatically prepares the required information to produce the mold necessary for each glass panel type.

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