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Flex Skin: Developing a Material System Based on Interlocking Wooden Panels

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ABSTRACT: This paper summarizes the development process of a performative material system as well as a corresponding digital design tool, potentially to be used in performative building envelopes. The system's basic components are wooden panels that are joined by mechanical interlocking. The triangulation and offset of an immaterial target-surface to both sides defines the components' geometry and distribution within the system. The performative qualities of the system are both on a structural and an environmental level. Changing the size and orientation of the panels, as well as their staggered arrangement, allows to control, within certain limitations, the quantity and quality of incoming daylight. Digital analysis tools help to evaluate the environmental performance of a given configuration during the design phase and create feedback loops that consequently lead to an optimized solution. These modifications have an impact on different levels of the system. A comparative study, based on three different climatic scenarios, demonstrates the system's capacity for adaptation.

1 INTRODUCTION

Over the past few decades, computer-aided design tools have significantly improved. The traditional use of computers as a drafting tool was ousted by computational design approaches (Menges 2017, Monedero 2000). Parametric design is one of the main aspects of computational design. It focuses on the relationships between different constituent parameters of a design problem. A parametric design process starts with exploring the basic properties of the design components and their interactions, which produces information packages that derive the form as an adaptable system (Ahlquist 2011). The term 'material system', on the other hand, refers to an approach in which a building's components and a chosen construction logic act as generative drivers in the design process (Menges 2011).

This paper introduces 'Flex Skin', a performative material system that falls into the category of Interlocking Particle Structures (IPS), the potential of which is currently studied at Aalto University's Chair of Design of Structures. The notion of IPS refers to aggregates or porous agglomerates of interlocking plate-shaped elements. They can also be described as particle systems with structural qualities (Hudert and Kotnik 2017, 2018). *Flex Skin* employs a parametric design approach and can potentially serve as (part of) a building envelope. Building envelopes are at the intersection of interior and exterior environments. They are enclosures that can both provide structural support and control the environmental performance. Moreover, they are critical regarding the external appearance of a building and can also include ventilation and shading systems (Lopez 2017). Building envelopes play an important role regarding the energy consumption of buildings. They are subject of numerous studies that aim at identifying creative solutions to increase the interior comfort and simultaneously attain higher performative efficiency (Lopez 2017).

2 FLEX SKIN

2.1 The System

Flex Skin is a material system with an adaptive and customizable system that provides a tool for covering free-form surfaces and long span structures. It is capable to generate holistic solutions responsive to different architectural and performative aspects of a design problem. *Flex Skin* has a part to whole approach and simultaneously performs on architectural, structural and environmental levels. The goal of the system is to produce a building envelope with specific performative characteristics that is formed in a systemic procedure. *Flex Skin* is constituted of planar wooden components in simple geometries that are grouped and joined through an interlocking process and create an integrated double-layered shell. The staggered arrangement of the panels provides the opportunity for direct natural light in a controlled way and creates a playful pattern of light and shadow inside the shell. *Flex Skin* system is developed in a design research project carried out in three main stages of empirical studies. Each stage develops different aspects of the project and accordingly employ related design and analytical tools.

A computational framework comprising different material characteristics and geometric properties of the system is designed in *Grasshopper* to develop the form of the system. This framework creates a double-layered shell on top of a given surface that is targeted to be covered, we call it the 'basic surface'. Basic surface determines the global form of the shell and is designed in a previous process of form-finding by *RhinoVAULT*. Incorporating the principle of associative geometry, *Flex Skin* reacts to different curvatures of the basic surface by adapting its structural depth accordingly. The emerged double-layered shell is the primitive version of *Flex Skin*. In the next step, structural performance of the shell is analyzed by *RhinoVAULT* and the structure is strengthened in its critical areas. In addition, environmental performance of the shell is analyzed by *Ladybug* in an instance simulated environment and create feedback loops that modify it in real-time (Roudsari, 2013). The modifications have an impact on different levels of the system, ranging from the global architectural form to the size, density, distance, orientation and thickness of the wooden panels. Repetition of the environmental analysis and modification feedback loops lead to an optimized form that consequently generates an environmental responsive design solution (Fotouhi, 2018).

2.2 Layering of the system

The initial geometric principle of the building envelope is formed in the first stage of design research. The panels are arranged in three main layers, two covering layers and one connecting layer that is interlocking with the covering ones. The arrangement of the panels creates an integrated double-layered shell that has a modular layout and acts both structurally and as an environmental filtration membrane. The panels of the covering layers have triangular geometry and the panels of the connecting layer have tetrahedron geometry that are created within the parametric setting based on the geometry of their neighboring panels in the covering layers. Therefore, every single panel has a unique geometry in terms of shape, size and geometry of its cuts. The formation steps of the structure are shown in the next page (Figure 1). A significant characteristic of the system is that it reacts to various magnitude of curvature at different points of the basic surface. The idea is to create a greater structural height in points with higher curvature, which strengthens the structure in its critical points (Figure 2).

Figure 2. The diagram indicates how *Flex Skin* reacts to various degrees of curvature at different points of its basic surface. a. Basic surface. b. A structure of varying thickness reacting to the curvature of the basic surface. c. A structure of the minimum thickness. d. Minimum structural height at points with minimum curvature. e. Maximum structural height at points with maximum curvature.

Figure 1. Overview of the system

In the next step, the project focuses on form-finding process for the basic surface of the parametric setting. The target is to design a rational surface formed based on mathematical rules that transfers structural loads only through compressive stresses (Rippmann, 2012. Rippmann, 2013). Several alternative surfaces have been created by RhinoVAULT and analyzed from different architectural perspectives. The selected option for developing *Flex Skin* is a dome-shaped surface that in the middle changes its convex from downwards to upwards and shifts to downwards again. This variation creates two adjacent spatial pockets with various heights and a desired spatial diversity. The surface meets the ground in three corners and the length of one of its sides (Figure 3). By applying the parametric setting to the basic surface, the initial version of the *Flex Skin* forms.

Figure 3. Basic surface of *Flex Skin* created by RhinoVAULT; a. plan. b. elevation. c. perspective view

In developing every instance of the system, as it is explained above, the parametric setting is provided with a basic surface that is targeted to be covered and is created by RhinoVAULT. As well the system receives intended values for its different parameters, including the number of constituting panels of the shell, the minimum structural height and factors for converting the curvature of the basic surface to structural height of the shell, as well as the magnitudes for the length and angle of the panels' interlocking joints. These values are specified by the designer based on the preferences, intended size of the panels, properties of the material and other effective factors involving in the specific design application.

3 STRUCTURAL ANALYSIS

The structural analysis of *Flex Skin* is carried out by RhinoVAULT, that calculates and specifies the level of structural stress using color codes on the generated surface. It does not analyze the surface precisely, but gives a rough approximation of its structural behavior. It shows that a high-stress curve along the surface is created where the direction of the surface's convex changes (Figure 4.a). By generating the particle-based material system based on the basic surface, the structural behavior and method of transferring the forces in the structure are changed. Even though the structural analysis for the surface and the particle-based shell do not directly match, the surface analysis gives an initial idea about the high-stress areas of the shell. To reinforce the structure in its high-stress areas, it is suggested to use stronger material with higher tolerance for the shell's panels in its critical areas, as well in the areas the shell meets the ground (Figure 4.b).

Figure 4. *Flex Skin*. a: Structural analysis of the basic surface. b: Structural optimization of the shell. The darker color symbolizes stronger material used for the high stress areas of the envelope.

4 ENVIRONMENTAL ANALYSIS

4.1 Goals of the experiments

The environmental analysis aims to optimize the environmental performance of *Flex Skin* using the real-time feedback loops in *Ladybug* and applying relative modifications to the settings of the system to increase its performance. This process is repeated for couple of times until an optimized performative result is attained. The environmental analysis of the system focuses on the sun path and shadow patterns and aims to control the solar heat and direct sunlight affecting the space covered by the shell. Different configurations of the shell's panels affect the extent of the solar radiation gained by and the light penetrated inside the shell. The setting of the system also allows to adjust the shell partially and apply various values to the mentioned parameters of the shell in its different areas according to the analysis for obtaining a better environmental result.

4.2 Setup of the experiment

The environmental analysis examines the effect of different parameters involved in formation of the shell. The selected parameters are tested in different conditions. Comparing the result helps to select the best condition for optimizing the system. Based on the structural characteristics of the shell, three parameters are selected to be examined in this experiment (Figure 5):

1. Distance of Panels - This parameter specifies the distance of covering layers, which defines the structural height of the shell. In the analysis three rates are tested, the default case with 'd' structural height, and two test cases with ' $1.25 \times d$ ' and ' $0.75 \times d$ '.
2. Size of Panels - The panels are reduced in size in the early steps of the formation process. The size reduction rate is adjustable and affects the transparency of the shell. In the analysis two rates of 70% as the default rate and 85% as the test rate are examined.
3. Angle of Panels - This parameter determines the orientation of the panels in covering layers towards south direction. The analysis includes five conditions. The default case with no orientation towards south, and each of four case studies with $\pm 10^\circ$ rotational angle towards south in their upper and lower (outer and inner) covering layers.

Figure 5. Three parameters involved in the parametric setting of the system selected for the environmental analysis, a. Distance, b. Size, c. Angle of the covering panels.

The analysis calculates the solar radiation gained by the panels of the shell and by the ground covered by the shell separately. The calculation of solar heat on the ground level simultaneously is an indicator for providing shadow by the shell. The studies are carried out for a shell with same setting in three cities of Helsinki, Lisbon and Singapore. Helsinki is selected as an example of Nordic climate, Singapore is selected as an example of tropical climate and Lisbon as a city in north hemisphere with about an average latitude between the two other ones. The studies of environmental performance of the shell in each city tries to optimize its setting for the specific environmental conditions of that city, while the comparative studies of three cities shows the flexibility of the setting of the system to be adapted to and optimized for different environmental conditions. The analysis is designed in two steps that are explained in the next part.

There are two points good to mention. First, the priority of this optimization is the interior comfort of the occupants of the space. Therefore, the evaluations on the ground level is considered more important than the evaluations of the envelope's panels, because it is closer to the conditions the occupants may experience. Second, the mindset of the studies is for optimizing the interior comfort. In case of the pavilion, because it is a semi-open space, this may raise a question about the importance of the environmental optimization. However, the matter of focus in this project is the general method of optimization, not the specific case study. This method can be used for other instances like building envelopes made by *Flex Skin* system in the future.

4.3 Result and conclusion

4.3.1 Environmental Analysis Part 1

In the first part eight cases with different settings are generated to examine the effect of different values used by different parameters of the system. The results of the evaluations are summarized in Table 1. The evaluations are carried out for a summer representative day and a winter representative day in each of the cities. Different aspects of the environment in different climatic conditions may have different levels of importance in the decision-making and optimization process. Helsinki has medium summers and cold winters. The evaluations show that the lowest solar radiation in summer is gained by the Case 001-1, Case 010 and Case 100-1. It is expected by creating a new case combining the features from above cases in a new setting, probably we generate a sell that has minimum solar radiation gained in summer time. In addition, Case 000 and Case 100-4 gain maximum solar radiation in winter; thus, if we combine features from those cases probably we generate a shell with maximum solar radiation gained in winter time.

Table 1. Solar radiation gained by the shell and the ground it covers in a summer and a winter representative day in three cities of Helsinki, Lisbon and Singapore for eight different cases.

			Solar Radiation Gain %							
			Case 000	Case 001-1	Case 001-2	Case 010	Case 100-1	Case 100-2	Case 100-3	Case 100-4
Helsinki	Midsummer	Ground	100	91	96	84	98	104	102	108
		Panels	100	76	81	93	104	97	99	89
	Midwinter	Ground	100	89	98	86	96	99	100	103
		Panels	100	75	86	90	109	100	100	83
Lisbon	Midsummer	Ground	100	92	101	79	100	103	102	106
		Panels	100	83	83	95	100	97	98	94
	Midwinter	Ground	100	85	95	86	92	98	98	107
		Panels	100	67	78	85	112	95	98	74
Singapore	Midsummer	Ground	100	91	101	79	113	113	113	113
		Panels	100	82	82	94	94	98	98	100
	Midwinter	Ground	100	90	98	82	98	102	101	106
		Panels	100	78	81	93	101	97	98	91

Similar evaluations are carried out for the cities of Lisbon and Singapore. Lisbon has a Subtropical-Mediterranean climate with warm summers and short-mild winters. Its environmental optimization targets to moderate the conditions of the shell in summer time. The evaluations show that the minimum solar radiation is gained by the Case 001-1 and Case 010; therefore, combination of the features from those cases in a new setting, probably generates a new shell with minimum solar radiation gained in summer. Singapore has a tropical climate with no true distinct seasons. The evaluations show that the best performative objectives are gained by the Case 001-1 and Case 010; therefore, it is expected by combining the features from those cases in a new setting, a shell with decreased solar radiation in the whole year around is created.

4.3.2 Environmental analysis part 2

This analysis can examine the assumptions of the environmental analysis part 1, which suggests generating a new case study, Case 111, with new settings for each of the three cities to attain a better environmental performance; the new cases are analyzed by *Ladybug*. The result of the analysis and their comparison with the cases from analysis part 1 is summarized in Table 2.

Helsinki – Referring to the function of a pavilion as a semi-open space, which is expected to be used more during the summer time in Helsinki, the optimization targets the summer time, while in case of a closed shell developed for a building envelope, the preferences may change and optimization targets the winter time. Based on the analysis in part 1, the setting for optimizing the shell for summer and creating the Case 111 for Helsinki combines the features from Case 001-1, Case 010 and Case 100-1. It means that the Case 111 uses ‘1.25 x d’ as distance of its covering layers, panel size of ‘85% x a’ and angle of +10° in both upper and lower covering layers (Figure 6). The result clearly shows that the new case has a lower level of solar radiation in summer compared to all the other cases and confirms the assumptions from analysis part 1.

Lisbon - Based on the analysis in part 1, the setting for creating the Case 111 for Lisbon combines the features from Case 001-1 and Case 010. It means that the new case uses ‘1.25 x d’ as the distance of its covering layers and the panel size of ‘85% x a’. The result show that the new case has a significant lower level of solar radiation gained in summer compared to all the other cases and confirms the assumptions from analysis part 1.

Singapore - Based on the analysis in part 1, the setting for creating Case 111 for Singapore is exactly similar to the case of Lisbon. The result of the analysis also shows that the new case has a significant lower solar radiation gained in summer compared to all the other cases and confirms the assumptions from analysis part 1.

Table 2. Solar radiation gained by the shell and the ground under it in a summer and a winter representative days in Helsinki, Lisbon and Singapore for four case studies with better environmental performances.

			Solar Radiation Gain %				
			Case 000	Case 001-1	Case 010	Case 100-1	Case 111
Helsinki	Midsummer	Ground	100	91	84	98	76
		Panels	100	76	93	104	127
	Midwinter	Ground	100	89	86	96	80
		Panels	100	75	90	109	136
Lisbon	Midsummer	Ground	100	92	79	-	66
		Panels	100	83	95	-	132
	Midwinter	Ground	100	85	86	-	81
		Panels	100	67	85	-	111
Singapore	Midsummer	Ground	100	91	79	-	78
		Panels	100	82	94	-	129
	Midwinter	Ground	100	90	82	-	80
		Panels	100	78	93	-	125

It is important to mention that because of the high level of complexity in the analysis, in all the cases above the analysis are carried out by *Ladybug* on case studies that model plane panels instead of volume panels with relative thickness. Therefore, it is expected that the real result of the analysis and modifications of the system are better than the result attained by these analyses.

Figure 6. *Flex Skin* optimized for the structural and environmental performance in Helsinki in summer time. a. south view. b. A physical model shows the shadow pattern formed under the shell

5 CONCLUSION AND OUTLOOK

This paper introduces the material system *Flex Skin* as well as the development process behind it. Moreover, it elaborates on the system's capacities and limitations. The dynamic-relational set-up behind the system allows for the optimization of its performance during the design process. Studies of its environmental performance demonstrate its flexibility and adaptability to different climatic conditions. As part of a (comparative) optimization study, an iteration of the system was placed in three different climate zones within the northern hemisphere during summer. In each of these cases, the optimization steps towards a decreased solar radiation on the ground below the system were similar. Future studies could investigate the potential performative qualities of the system regarding wind-flow and noise-cancellation. More importantly, future investigations should also develop and evaluate different strategies and materials for weatherproofing.

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