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Responsive Façades: Parametric Control of Moveable Tilings

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ABSTRACT

The challenge of developing adaptive, responsive low-energy architecture requires new knowledge about the complex and dynamic interaction between envelope architecture, optimization between competing environmental performance metrics (light, heat and wind indices) and local climate variables. Advances in modeling the geometry of building envelopes and control technologies for adaptive buildings now permit the sophisticated evaluation of alternative envelope configurations for a set of performance criteria. This paper reports on a study of the parametric control of a building envelope based on moveable facade components, acting as a shading device to reduce thermal gain within the building. This is investigated using two alternative tiling strategies, a hexagonal tiling and a pentagonal tiling, considering the component design, support structure and control methods.

Keywords: Responsive envelopes, moveable façade components, parametric modelling, tiling geometry

INTRODUCTION

The built environment is a major consumer of energy and consequently a significant emitter of greenhouse gases (as much as 40%). The field faces unprecedented demands to develop knowledge for reducing energy footprints, exploit renewable sources of energy and establish reliable and accurate performance measures for buildings. To address these demands, a tighter coupling between the design and energy performance of buildings is necessary. Smarter and more energy efficient buildings will be significantly improved by addressing the conceptual hurdles separating the architectural design of building envelopes (the external surfaces of buildings) from the simulation of their environmental performance.

The field of building simulation research has developed tools to calculate the performance requirements (solar gain, daylight penetration, heating and cooling loads, ventilation, water use) of a building (Shaviv, 1999; Malkawi, 2004). Rapid, near real-time visual output from building

simulation models would significantly improve the prediction of performance and enable the optimization of smart, adaptable, net zero energy buildings (Hensen & Augenbroe, 2004). However, current performance models lack the ability to handle envelopes of variable geometry (Kolarevic & Malkawi, 2006) and do not account for local variations in climate conditions (Guan *et al.*, 2007). These classical approaches to improving the efficiency of buildings will benefit from new understanding of the complex interactions between architectural geometry and local climate phenomena.

Advances in building simulation (Malkawi, 2004; Luther & Altomonte, 2007), geometry of envelopes (Pottmann *et al.*, 2007), new construction materials (e.g. responsive glazing) and control technologies for adaptive buildings (Luther, 2000) combined with advances in the field of design space exploration (Woodbury *et al.* 1999; Aish *et al.*, 2005; Datta, 2006; Woodbury, 2010) now permit the sophisticated evaluation of alternative designs for a set of performance criteria.

The challenge of developing adaptive, responsive low-energy architecture requires new knowledge about the complex and dynamic interaction between envelope architecture, optimization between competing environmental performance metrics (light, heat and wind indices) and local climate variables.

PROBLEM STATEMENT

In this paper, we present a comparative study of the parametric control of moveable façade components that make up a responsive building envelope. To motivate the discussion, of a responsive building envelope, we based our study on the façade design of the "pixel" building in Melbourne. The building was designed with the goal of being a carbon neutral office building and to be used as a prototype for sustainable and environmental buildings. The facade is one of the devices used in the building to reduce its environmental impact.

The facade involves a series of 'jumbled' colored and textured panels that act as an aesthetic to the building facade and as a shading device to reduce thermal gain within the building. Each panel has been designed to be positioned and angled in a fixed location that reflects the optimal shading opportunity all year round in the Melbourne climate. Panels are manufactured with different "green" materials that will not only reflect or absorb the sun, but also allow views out from the building with perforation and transparency in the materials. The pixel building is a post-optimized design scheme that is static and fixed with respect to the environmental variables for shading and heat gain. In order to further optimize performance, the problem of component motion with respect to changing conditions needs to be addressed. To address this problem, we develop the façade subdivision scheme from first principles, investigate its responsiveness to environmental conditions and present our findings.

In order to develop the facade in a parametric manner, the shapes and rules which determine the facade composition are established. This is undertaken using the south façade as this elevation consists of both the jumbled panel facade and the precast panels with the pattern cast into it (Fig.2). The tiling used on the elevations can be termed as Cairo pentagonal tiling a type of polygonal isohedral tiling (Grünbaum & Shephard, 1987).

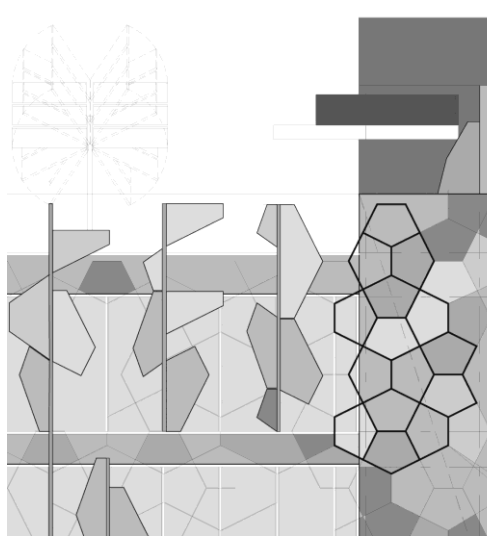Fig.1: The Pixel building, Studio 505. Source – www.australiandesignreview.com

Fig.2: South elevation with Cairo tiling overlayed. Image courtesy of VDM Consulting

RESPONSIVE ENVELOPE SCHEME

First, a subdivision scheme is developed for the dynamic (near real-time) performance optimisation of building envelope geometry using parametric methods. The main features of the parametric tessellation and tiling scheme are:

- Component design: a "carrier-component" (Pitts & Datta, 2009) representation of the envelope;

- Support structure: responsiveness of the carrier and components to performance constraints; and

- Control Method: Modification of the façade model using local and global control parameters.

The responsive envelope scheme presented above is developed using two methods of tiling: a hexagonal tiling and a pentagonal tiling strategy. In each of these methods of tiling, the three aspects of component design, support structure and control method are tested.

HEXAGONAL TILING

In order to do initial testing of the model a simplified tiling was identified; that of hexagonal tiling as the Cairo tiling can be seen as a union of two flattened perpendicular hexagonal tilings. Hexagonal tiling is a regular tiling (Grünbaum & Shephard, 1987) in which three hexagons meet at each vertex. Within the facade, key vertical lines of fixing can also be identified, which then pass through the center of the simplified hexagonal tiling, as shown in Fig.3.

Component Design

The component was mapped out based on a half hexagonal tiling, in order to allow the two halves of the hexagon to rotate independently around the supporting structure. A mid-point to the long side of the shape was given as the origin handle, with a Y Direction point across the face to give the orientation. In order to develop the boundaries of the panel a variable factor was used. This factor was derived from the initial study of the facade, with all the key measurements of a panel being evenly divisible by 300mm. The key dimensions were line01 (panelFACTORx3), line02 and line03 (panel FACTORx4), and line 04 and line 05 (panelFACTORx1) as in Fig.4.

Support Structure

To begin the Facade form, an early problem that was faced was how to create a staggered pattern across a flat surface, which was required in order to achieve the hexagonal tiling. Parametric software can easily define a surface with a point grid across it, containing a given U and V series. However, due to the staged nature of the tiling this is not a desirable method. In order to overcome this issue, the form was set out in a staging process rather than a direct point grid.

The first geometry to define the façade was its width, a simple line across the base, relative to the section of façade covered with the panels. On this base line, points were spread out at 2400mm spacing, giving 8 points. This set of points, which behaves as a single element, becomes the base point for the first collection of vertical façade elements. From this set of points a series of lines is generated covering the three top floors of the façade – Fig.5 (Left). On these lines, a new point is spread evenly across the line at the same specific spacing, 2400mm, as the horizontal base points. Due to the lines being a collection, this new point is replicated on all lines in the collection – Fig.5 (Right). The final point gives the general arrangement of half the façade pattern.

The second half of the geometry was achieved by offsetting a new single point at 1200mm across (Y Direction) and 1200mm upwards (Z Direction)from the start point of the first half. This new point allows for the first half of the geometry to be copied, while maintaining identical arrangement parameters, and giving a staggered arrangement of points.

From these points, a line can be established to be able to identify the Y Direction in both collections. The reason for this was so that a direction property could be found in response to
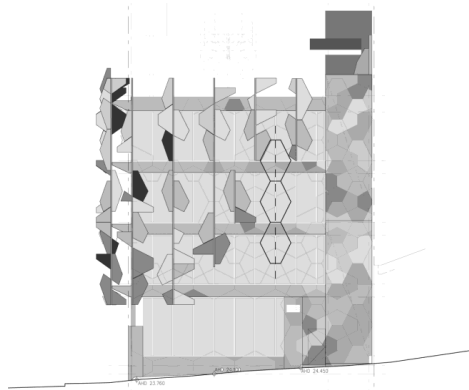
Fig.3: South elevation with Hexagonal tiling overlayed. Image courtesy of VDM Consulting.
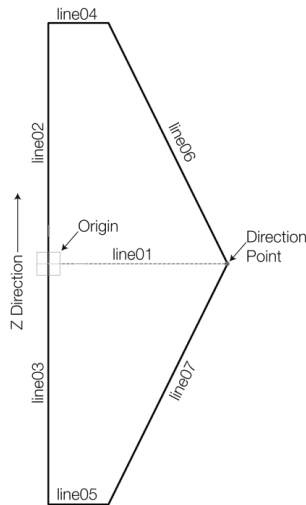

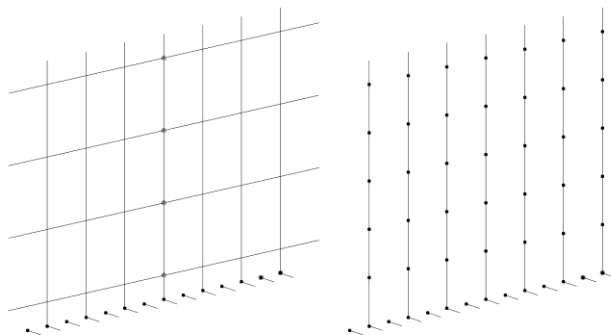Fig.4: The half hexagon tile component and its parametric variables.

Fig.5: Left – Initial supporting lines. Right – First collection of points.

the general environmental orientation, the base coordinate system Y Direction, at each given origin of a panel/component.

The component of the single panel was then generated across each point in both collections, shown in Fig.6. Since the component only covers one direction from the point, the component had to be generated twice to produce both the Y and –Y Directions.

Control Method

The earlier setup of the Panel component required only two inputs; origin and orientation. To be able to change the responsive nature of these panels in the façade, the orientation input needs to be revised. In the initial development of the façade the orientation was based on the environmental orientation, the base coordinate system.

If the panels are able to respond to a point in space, this point can change the orientation of the panels as it moves across the face of the façade. The point behaves as an attractor and can be used to define environmental conditions. A new set of framework was developed within the model to define the path of the attractor, a line, and the attractor itself, a point capable of moving along the line (Fig.7). The extent of the path matched the current framework of the façade.

In order for the panels to now respond to the attractor some further geometry is required to define the direction of the point from any given panel. As the façade is made up of two panels, a direct application of the attractor as the direction point cannot be used, otherwise all panels in the set would point directly at the attractor. A circle was created at the origin of each panel, with the point of the attractor projected onto the circle edge. This formed the individual rotation of one side of each panel set, in this case the right or Y Direction side. Using a coordinate system that originates from the panel origin and defines the upward direction of the façade, Z Direction, a plane could be established to mirror the point on the circle edge (Fig.8). This means that each set of two mirrored panels responds collectively as the attractor point moves (Fig.9).

While this model is influenced by the environment with the panel orientation changing based on the environmental input, the attractor point, further exploration of the orientation of the panels was desired. With the original design of the facade being one of 'jumbled' panels, the uniformity that exists by the use of an attractor point is in contrast to this. If the orientation of the panels is more random, then the facade will be more varied.

Interactive Hexagonal-Tiling Design Tool

The initial hexagonal tiling patterns presented above were developed utilizing the *Rhinoceros* 3-D freeform modeling tool (McNeel USA, 2012), through the *Grasshopper* generative modeling add-on tool (Davidson, 2012). These tools permitted experimentation with the design of the foundation hexagonal tiling approach but there were limitations in this approach. Limitations included a lack of real-time interactive design support, and no easy way to evaluate the performance (thermal/lighting/wind) criteria of an envelope using this tile design.

To address the limitations of *Rhino3D* and *Grasshopper*, a prototype interactive design tool was developed using the open-source programming language *Processing* (http://processing. org/). The objective of this tool was to provide a 3D interface to the design of a façade using a given geometrical tiling approach, where various parameters of the design could be
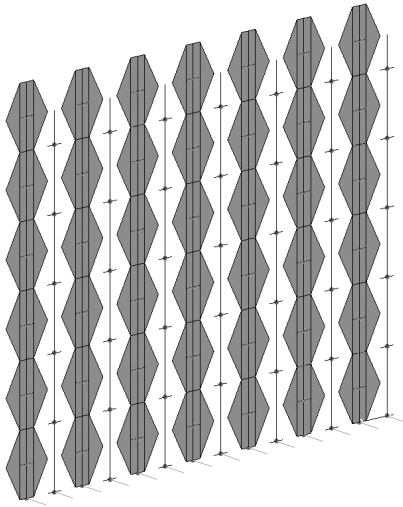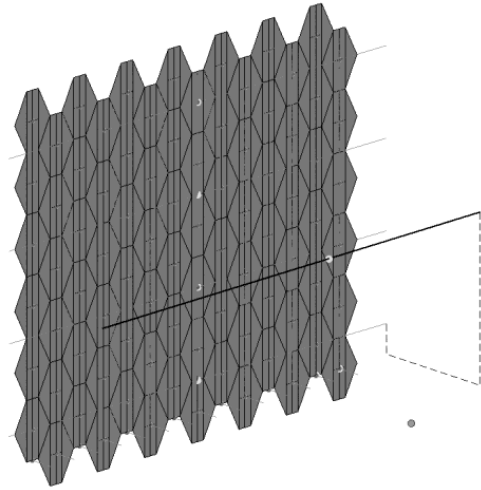
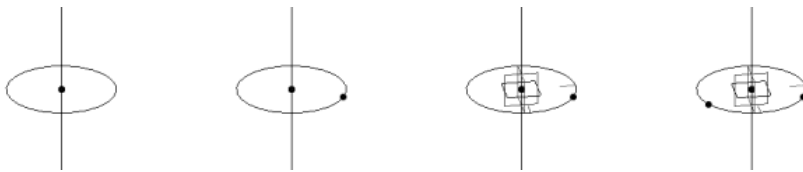Fig.6: First component application.

Fig.7: Attractor framework.

Fig.8:From left to right, addition of the circle, projected point, coordinate system, and mirrored point.
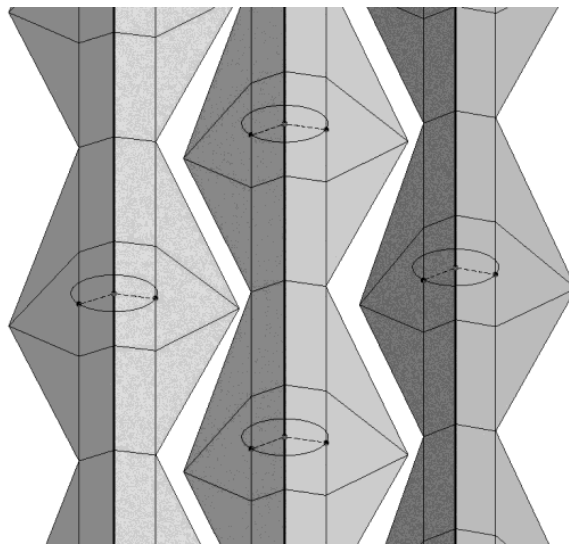
Fig.9: Panels responding to the attractor point

modified and the resultant façade displayed. In the first version of this tool, hexagonal-tiling was implemented and (initially) two control parameters supported: number of tiles in the X/Y dimensions; and the 'kink' angle of the individual tile. Screenshots of this initial prototype are shown in Fig.10.

It is intended that this tool provide an interface to additional performance modeling tools, which would measure a given façade's performance such as: shading, thermal and wind properties. The base tool has been designed to be flexible and additional tiling approaches to be added later – such as Pentagonal tiling, presented in the following section.

PENTAGONAL TILING

Returning to the original shape grammar, it was identified that the Cairo tile was used to define the facade pattern. In order to simplify the initial model a hexagonal tiling was used, utilizing data lists a pentagonal tiling can be achieved and provide greater control of the individual tiles.

Component Design

The geometry of the pentagons that make up the Cairo tiling can be extracted from our initial hexagonal tiling. This also provides a starting point from which to develop the underlying surfaces that support the actual tiles. The overall facade pattern can be made up of vertical collections of pentagons, with four differently orientated sets of pentagons in each collection.

Support Structure

The first step was to establish the surface geometry of a single vertical set of tiles, beginning with the bottom pentagon from the hexagonal collection. A horizontal line was created based on the width of the tile unit, 1.2m. From the start and end points of this line, two vertical lines were created with an initial length of 14.4m. This length input was drawn from a variable allowing it to be changed later, but in order to ensure that there was an even division of the surface, regardless of length, the variable was based on the number of units multiplied by the height of the tile. Between the two vertical lines a base surface could now be generated.

The base surface was then subdivided using its U and V parameters. In the case of the U, the vertical aspect, it was divided by one as this surface was only going to carry a single vertical set of tiles. The V subdivision was produced by taking the facade height input and dividing it by the tile height property, which always produces an even division because of the facade height inputs underlying rules as discussed above.

With the first supporting surface established, three more are required and can be achieved by offsetting the first. Moving in a clockwise direction the offsetting can be undertaken by adjusting the start point of the baseline from 0, 0, 0 to:

- -0.6, 0, 0.6 (left)

- 0, 0, 0 (top)

- 0.6, 0, 0.6 (right)

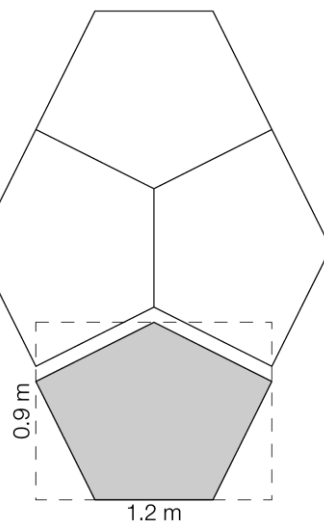Fig.10: Prototype design tool implemented in *Processing*.

Fig.11: Panels with pentagonal tiling configuration.

The top tile uses the same starting point as the bottom tile, but its surface height is calculated by combining the facade height input and the tile height to allow for one extra tile to be generated. As with the hexagonal system a position count is used, but it is based on each set of four tiled pentagons, so all four of these surfaces receive the same position count input. The surfaces are then subdivided by the U and V parameters, with the U being 1 and the V being based on the facade height divided by the tile height (Fig.12). As in the hexagonal model the facade height input is based on the tile dimension so that a clean tile division always occurs.

When the component is applied to the supporting surface a pentagon is generated in each of the polygons which results in too many pentagons that overlap. Using the data lists the excess tiles can be culled, leaving the desired pattern. The cull function uses a true false pattern which allows for the desired tiles to be maintained, removing the overlap and producing the Cairo tile (Fig.13).
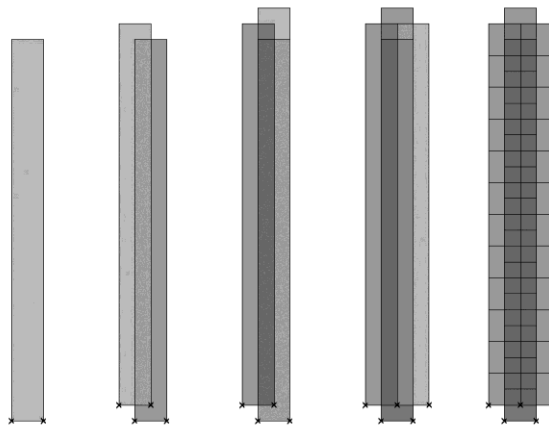
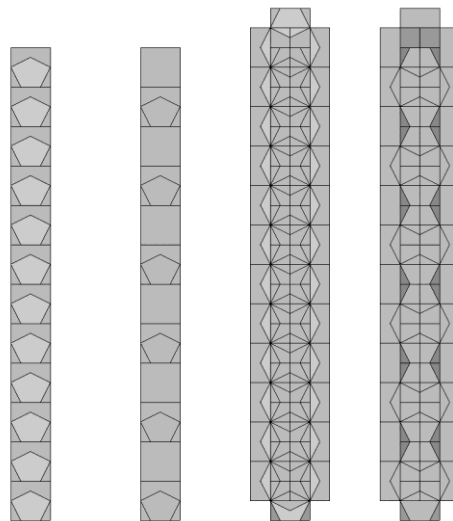Fig.12: Offsetting of the supporting surfaces and subdivision.

Fig.13: Culling of the pentagons to produce the Cairo tiling.

With one vertical section complete, offset sections are now required which will allow for a complete facade to be produced. A position count variable is used to achieve this, which influences all four pentagons in a set, so only the Z attribute of the baseline needs adjusting. A simple subtraction of the existing Z value by the tile height is built in, which results in the baseline being offset downwards, with the position count adjusting the sideways offset.

Control Method

With the facade tiling established, the rotation of the individual tiles can now be undertaken. The first step in this process is to set an axis for rotation. Two attributes are taken from the existing geometry of the underlying surface of each set; that of the center point of the base
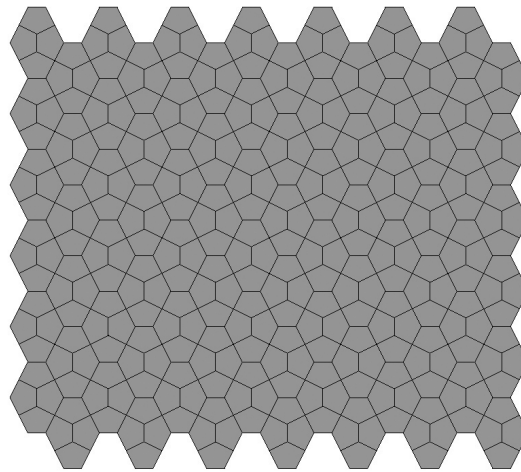
Fig.14: Complete north façade using the Cairo tiling.

horizontal line and the depth of the component. The depth of the component is divided by two to provide the offset distance from the center point, and a line is drawn from this vertically defining the axis of rotation.

The data list can now be used to establish a collection of random values to rotate the tiles with, producing the' jumbled' pattern. In order to minimize the duplication of parts a pseudo random generator was developed that could provide the rotation information to all four sets of pentagons within a vertical set. The first step was to use the list data of the component applications and measure each of the four sets of pentagons. This measurement occurs after the cull, so only counts the visible pentagons. This list data is added together to give the total amount of random numbers required. This count is then fed into the random number generator along with a seed input and range of values. The seed input is influenced by the position count, so that each vertical collection will receive a different seed input. The range of values is treated as the minimum and maximum rotational angle in degrees and is adjustable, so that this can be tuned.

The list of values now needs to be split in order to give the rotation information back to each set of pentagons individually; this is done in a series of steps. The whole list is fed into a split function along with the first of the measured lists which results in two lists being produced, one contains a list of the same length as the measured list and the other contains the remaining values. This process is repeated twice more, producing four lists of rotational inputs that match the size of the original pentagon counts (Fig.15). These lists can then be input to the rotational tool, generating a randomly rotated collection of pentagons.

RESULTS

This paper reports on a comparative study of two responsive envelope models based on a computational simulation of their properties. The façade schemes investigated alternate tiling strategies, component design, support structure and control methods. The results of these tests are presented here.

The outcomes of the responsive exploration were a flexible facade geometry based on tiling and tessellation. This was undertaken using two tiling patterns, regular hexagonal tiling and isohedral pentagonal tiling, which create an order and rhythm within the facade. In order to achieve the desired pattern, the underlying geometry becomes more critical than the tile itself and allows for control of the tiles both individually and as a group. This control can be very strict and focused, taking advantage of attractor points representing environmental characteristics, as in the hexagonal tiling. While each tile is orientated in relation to the attractor point, they cannot be individually adjusted as they behave in a set, which limits the flexibility. The control can also be based on stochastic models, as in the pentagonal tiling. The stochastic control of the facade allows for the pattern and rhythm of the tiling to be explored within set parameters and achieve unexpected results. The use of the data lists not only allows for the creation of the 'jumbled' façade pattern, but also allows for rotational information to be feed individually into the model, allowing for specific orientations to be achieved in order to find a balance between the 'jumbled' aesthetic and the environmental benefits (Hanafin *et al.*, 2011a, 2011b; Hanafin & Datta, 2012).

The study is limited in terms of its focus on the geometric and control aspects of the representation scheme. Further analysis of the methods incorporating material constraints, structural and load considerations and automated control using networked sensors are currently under investigation.
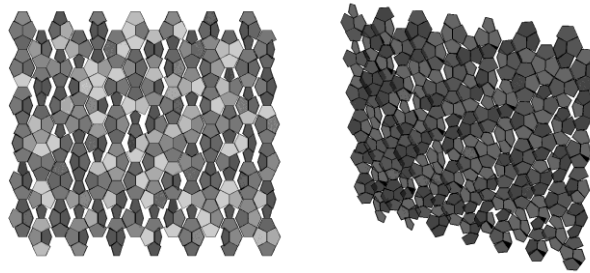

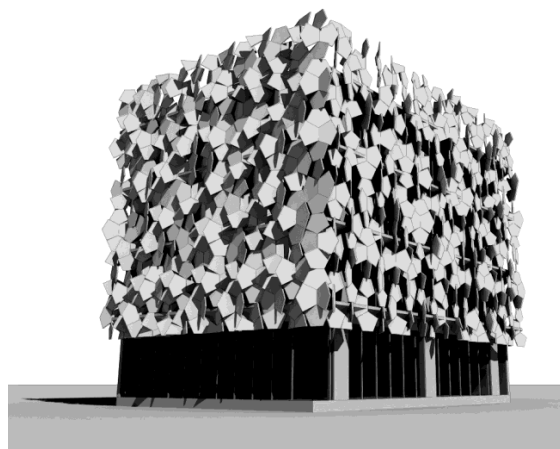Fig.15: Panel rotation based on stochastic data list.

Fig.16: Cairo tile façade visualisation.

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