Composing the Bits of Surfaces in Architectural Practice

METHODOLOGIES AND CODES FOR GENERATION, RATIONALIZATION, AND ANALYSIS OF NON-STANDARD GEOMETRIES

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Emergent design tools, with enhanced modeling and parametric manipulation capabilities, are encouraging the exploration of new geometric typologies in the field of architecture. Designers are not only finding more opportunities to work with geometries of higher complexities but are also becoming able to manipulate their designs with simple formulations.

After a decade of familiarity with free form modeling tools, architects must now become more aware of the critical relationship between design and construction. When a design is performed without taking the constraints of construction into account the inefficient method of geometric post-rationalization becomes necessary. Thus, the knowledge of the rationale should be applied from the very beginning of the design processes, and digital models should be informed and controlled while being developed.

This paper will present analytical strategies and methods for working with non-standard geometries in a geometrically and parametrically controlled environment. Each method is supported with custom scripts which run in both parametric and non-parametric computer aided design (CAD) platforms. Each script and method is manipulated for the next project and the computational tools created build up a library of surface generation, manipulation, and subdivision tools. This library later becomes a source for office-wide use of surface manipulation.

1. INTRODUCTION

The discrete pieces put together in construction make the building. While represented and perceived as smooth continuous surfaces in CAD platforms, the constructed building envelopes are composed of numerous pieces differing in size, shape, and material.

Design exploration, happens with larger gestures of sketching and modeling. The designer, regardless of the type of creative process he or she is running (analog as sketching or digital as modeling), expresses his or her ideas with outlining and broader abstract lines or forms. Later in the design process, the smaller pieces and components that build the form up are designed and defined. However, the act of construction logically goes vice versa, from part to the whole. Thus, the whole should be designed in awareness of the part, in other words, the part and the whole should be simultaneously designed in the design process. A design process aware of the laws of construction would enable the creation of well-informed design solutions.

1.1. APPROACH

The term computation has been widely used within architectural terminology for last several years. Especially, the efforts and interest in exploring digital technologies as a tool for design and construction has increased the interest of incorporating computational and analytical approaches to design. The digital tools have, without doubt, influenced the designed forms, but now we are in a period in which the tools are also forcing architects to deal with more in-depth analytical design thinking and approaches.

The term post-rationalization implies solving the design-construction problems resulting from uncontrolled geometrical development. Many powerful tools can be developed and used for this kind of effort. However, here, I would like to highlight the explorative and systemizing power of computation, because the complexities we, as designers, are dealing with should be derivative of the constraints of the concepts, site inputs, and limitations of construction, rather than uncontrolled and unintended formal complexities.

A virtually unlimited variety of geometries can be generated with the help of emergent computer aided design tools. Therefore, each has to be bridled to some extend. They have to be evaluated and optimized regarding the limitations of construction technologies. This statement does not aim to propose an adherence to conventional construction methodologies but rather proposes a geometrically well-controlled design process.

1.2. TOOLS AND METHODS

In this paper, I will present several non-standard geometry development and subdivision tools and their evolvement by time. These tools were created in different parametric modeling and scripting environments for different purposes. I will present, compare, and contrast the different approaches in creation and use of surface generation, manipulation, and subdivision tools in different phases of design. I will refer to various large scale projects of Kohn Pedersen Fox Associates New York, including a 680 meter-tall tower and a quarter square kilometer train station roof structure, which were designed for two different sites in China.

I would like to mention a key technical point that I always follow in my studies. One of the most important issues in data transfer between CAD platforms is the reliability and precision of the geometries which occur after the transfer. Transfer of a surface geometry could result in slight deviation in geometric data depending

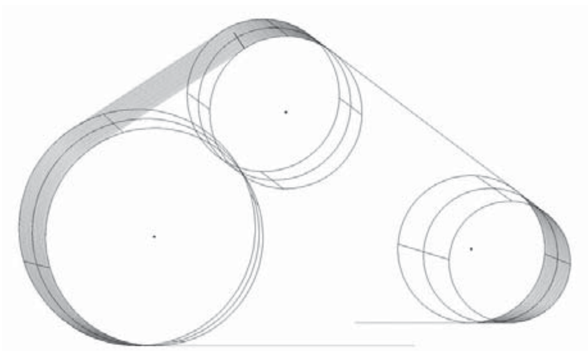


FIGURE 1 The sheared cones in plan-view.

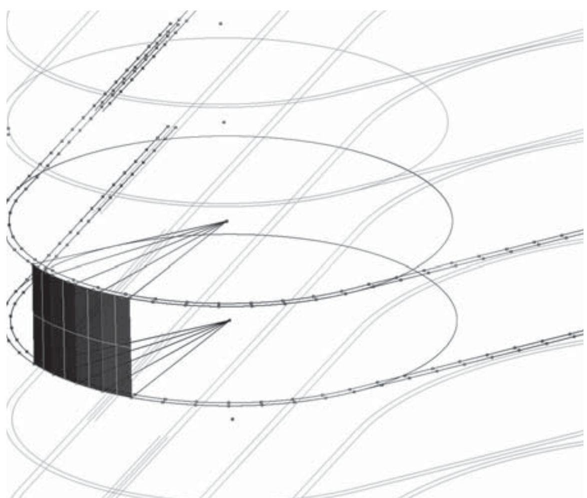


FIGURE 2 Panelling diagram with reference lines.

on the computational approximations of different CAD platforms. A small deviation in the digital model may become a greater problem on the construction scale. Due to these types of considerations, I prefer to transfer only the point data, and regenerate the geometries of higher complexity (lines, curves, surfaces) in the second CAD platform. Such an approach enables a more secure environment, since each point is transferred with their Cartesian coordinate values only, so no other formulation or approximation is used with either of the platforms while exporting and importing the data.

2. CASE STUDIES

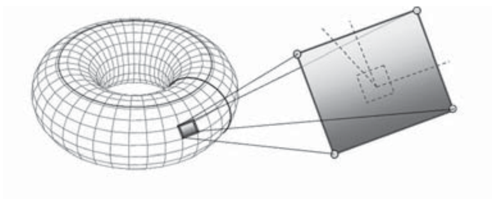
I will present the processes performed with a blend of tools created with RhinoScript, Generative Components (GC) and GC Script, which were used to resolve the geometrical complexities of three different towers. In these projects, the developed tools intended to rationalize and reconstruct the overall form of the building by using rationalized geometries, which were later subdivided into building components regarding the ease of construction and cost balance. The extension of the tool makes automatic preparation of construction documentation possible, through printing the joint location data for each component.

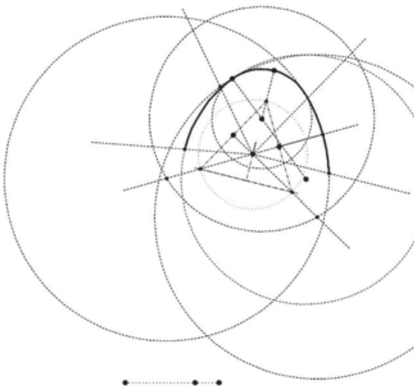
Finally, I will cover the tool chain created for the design and manipulation of the roof of the train station. I will present and compare the different tools developed for different phases of the specific design process, and how creation of these tools was driven by the required actions of design. While the first tool aims at the generation of the complex form in a controlled environment, the second one subdivides the surface in mock-up detail for data transfer for scale models. I will go into detailed geometric and algorithmic explanations for each project.

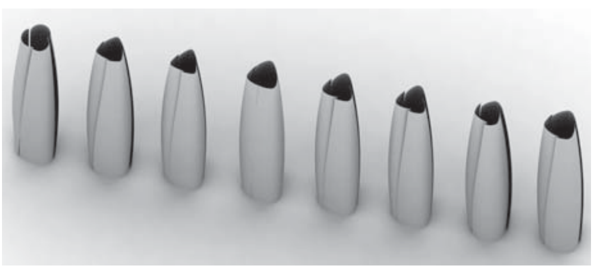
2.1. REVERSE-ENGINEERING THE GEOMETRIC DEPENDENCIES

The main form of CSCEC Tower is generated by three sheared cones, whose bases are centralized on the corners of an underlying triangle (Figure 1). Unlike conventional tower forms, because the cones are tilted outwards, the tower gets wider towards top. A surface wrapping all three sheared cones creates the envelope of the building. A parametric model of the tower was developed by Kyle Steinfeld, who also developed the initial method for paneling the building.

The tower is paneled by both warped and flat panels depending upon the panel position on the surface. To succeed in creating the desired visual qualities, the same number of panels is used in each floor of the building. Thus, since the length of the perimeter line for each slab is increasing from bottom to top, the width of the panels







Top to bottom:

FIGURE 3 Surface curvature properties before (left) and after (right) geometrical rationalization.

FIGURE 4 Torus surface can be panelled with flat panels.

FIGURE 5 An underlying diagram of tangent circles creates a continuous arc composite with smooth transitions.

FIGURE 6 Various towers as a product of parametric model.

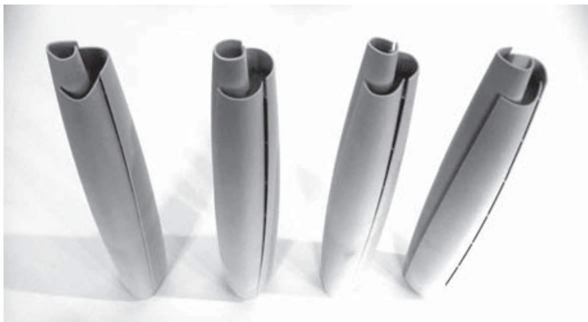


FIGURE 7 3-D prints of White Magnolia Tower variations.

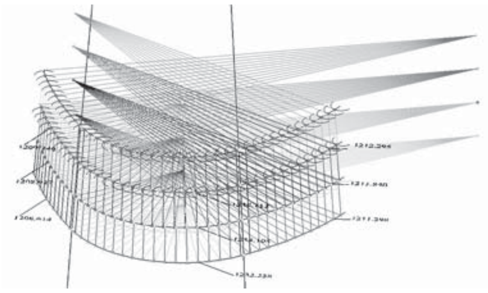


FIGURE 8 Each panel is created in reference to the previous one and local geometrical guides.

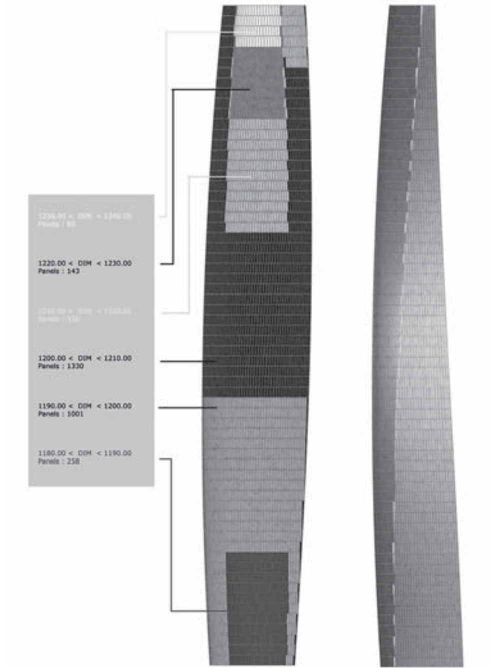


FIGURE 9 Panels grouped and color coded with a 10 mm tolerance in size.

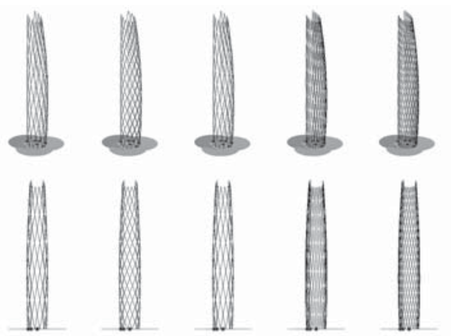


FIGURE 10 Various dia-grid densities achieved by use of parameters.

has to increase by 4 mm on each floor. The envelope of the towers was digitally paneled and the stack joint point data was written to spreadsheets and sent to the construction site.

My role in the project started while the building was already under construction. Due to the misreading of the construction documentations, the concrete slabs were constructed with an offset, which required an update of the stack joint for each panel of the tower. The only source given for the update was a model with the current curtain wall set out point data, a point cloud, and the slab perimeter lines.

I first developed a RhinoScript, which sorted and grouped all the points according to their height values in the Cartesian coordinate system. This enabled me to classify all the points as a specific stack joint of each panel in each floor. To update the point data according to the new construction each point had to be translated on an axis, which is the projection of the *normal* of the surface to a horizontal plane at that specific point. While this guideline was fairly easy to determine in the flat portions of the surface as a perpendicular to the floor slab perimeter line, the points on the curved surfaces had to be analyzed according to the central spine of the sheared cones. A horizontal cut at the level of any floor slab creates a circular section and the center of that specific circle can be used as a reference for the curtain wall stack joint points on the curved surfaces on that floor. A line drawn from this center point to any of the stack joint point creates the guideline, which is the translation axis for the points on the curved portions of the tower (Figure 2).

After determining all the translation axes the points were moved on these axes depending on the offset data sent from the site. This represented the new lower corner stack point for panels. All offset points were then used to define the top stack joint for each panel. Here I would like to highlight the complexities that are embedded in such a fairly simple geometrical construction. Since each panel has a different orientation in all three axis of the Cartesian coordinate system, the top points of the panels also have to be determined by local geometrical properties. To do so, the local translation axis lines were translated to the upper floors and extended centrically

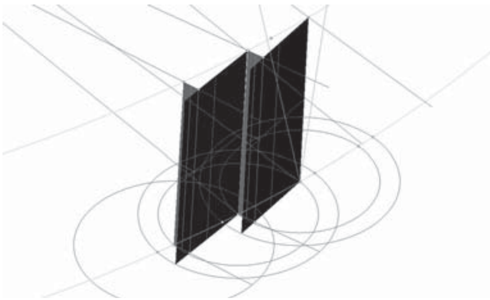


FIGURE 11 Two consecutive panels and the reference geometries used to locate them in the Cartesian coordinate system. Smaller panels fill the shingle gaps.

to hit the slab perimeter line. The intersection gives the necessary top stack joint point data.

The four points representing the four stack joint locations for each panel are computed after the creation of a set of guide geometries, and the finalized data, which is the nodal coordinate values, is written to spreadsheets. For a better understanding and clarification of construction documentation, the values were color coded depending on the floor height. Spreadsheets are then sent to the site to be used as construction documents. All the algorithms are developed in RhinoScript.

This study can be defined as reverse engineering, in which I worked on finding the origins of the developed geometry. While not presenting explorative efforts in design, these techniques and methods created a knowledge base to be applied to the following processes.

2.2. GEOMETRIC RECONSTRUCTION AND RATIONALIZATION

White Magnolia Tower is a 65 storey free-from building. In the original design, which was modeled by non-uniform rational b-spline (NURBS) modeling techniques, three double curved surfaces wrap the tower. The form of the building is inspired by the white magnolia flower. The configuration of the three continuous surfaces intends to imitate the petals. The form represents deviating curvature degrees (Figure 3), thus it becomes impossible to panelize the tower by the use of flat panels only. However, a limited budget required the use of flat panels instead of bent ones, which required a geometric rationalization process before the paneling studies. Here, I will explain the re-modeling of the tower with fully parametric dependencies, which also required a geometrical reconstruction.

The reconstruction studies of White Magnolia Tower developed around the idea of the generation and use of parametrically controlled torus patches, since a torus or a torus patch (which is a cutout from the surface of a torus); can be built by the use of flat panels (Figure 4).

A set of parametrically controlled circles, which are constructed with tangential dependencies are used to produce a layout for arctangents, which are later combined into a composite curve and define the slab perimeter of the building (Figure 5). The composite curves representing the slab perimeter lines are then trimmed from both ends. While trimming, two guide lines creating a “V” shape are used and the section of the composite curve that remains in between the two arms of the “V” determines the actual surface line. Each time this pair of lines is transferred to the next floor, they are rotated a certain amount, thus the consecutive floor slab perimeters represent slightly shifted start and end points,

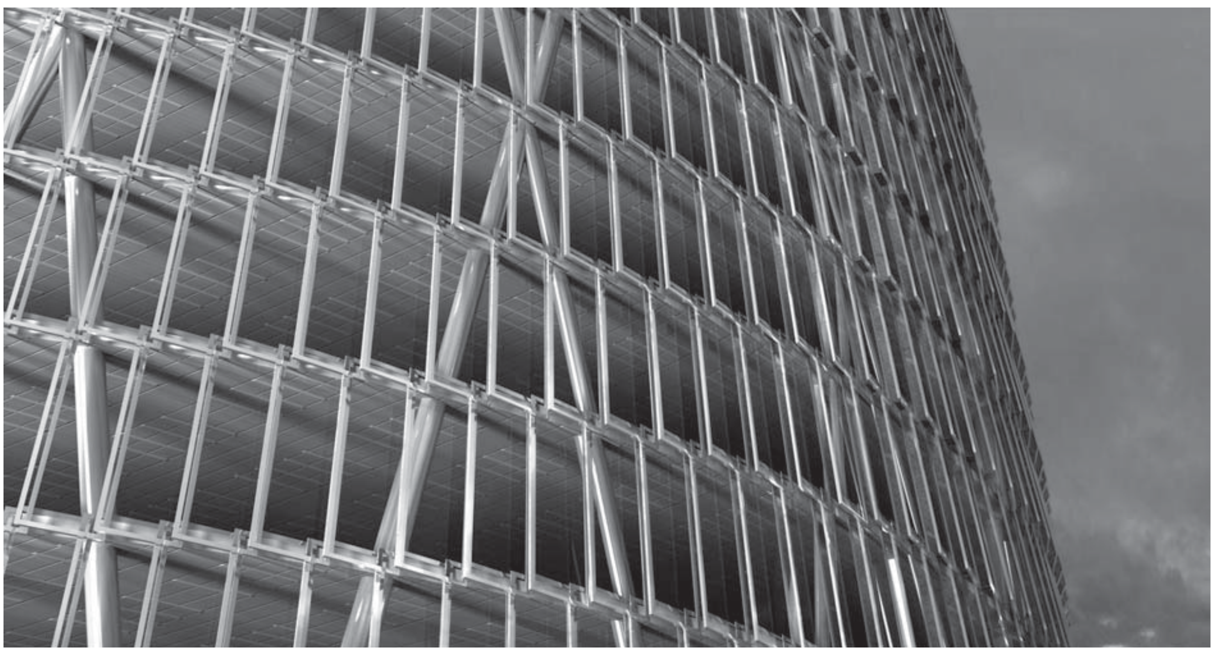


FIGURE 12 Final configuration of the shingle panels on the building surface.

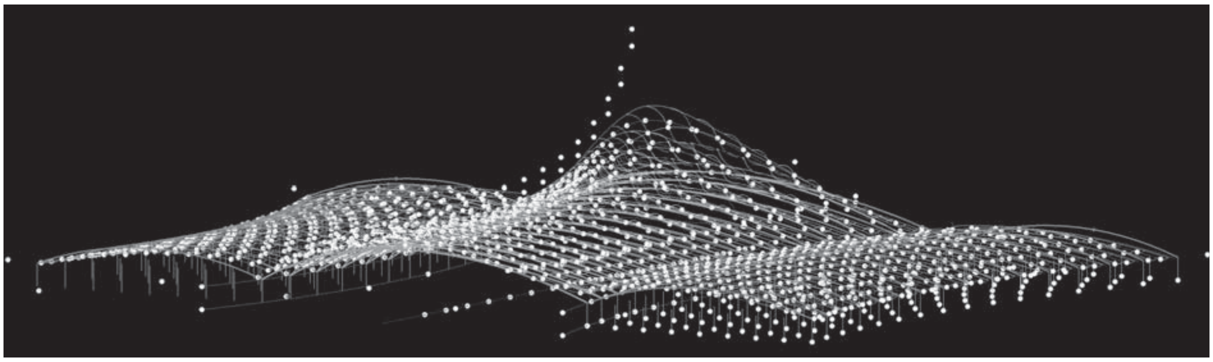


FIGURE 13 Fully parametric generative components model being dynamically updated by geometric drivers.

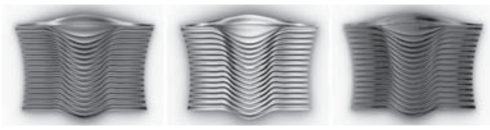


FIGURE 14 Overall form analyzed for solar exposure. Results for annual, June and December, exposures displayed.

which finally creates a twisted cut of the surface, while the complexity of the surface remains the same.

The curve that defines the vertical curvature of the building is a parametrically controlled vertical arc. The vertical arc is used as a rail for the slab perimeter line, and the parameters adjusting the composite arctangents define the deviation of the curvature. The manipulation of both the vertical arc and the composite slab perimeter curve defines the overall form of the building, controlling the amount of tapering and the maximum width in the middle of the building. The resulting geometry is rather complex since it is composed of three different torus patches depending on the three arc segments of the composite curve, but the transition is perfectly smooth since the composite curve was initially developed with tangential transitions of underlying circles (Figure 3).

Each of these processes was developed in Bentley's Generative Components. The model I generated is driven by both global variables, which are numeric inputs, and the associative dependencies between the underlying geometries, which dynamically update in connection to any change in a geometric member. This parametric model was used to generate variations of the tower, all of which are the members of the same design family (Figure 6). The generated geometries were evaluated in terms of ease and cost of construction and the proximity of the final form to the initial one. Three dimensional prints were used to compare and contrast the different visual qualities of the different towers (Figure 7).

Later in the process I transferred the point data to RhinoScript, to work on creating an automated system for paneling the building. I then regenerated the curves representing the slab perimeter lines. Once they were reconstructed, I worked on development of a scripted routine, which would automate the panelling process all through the building. The panelling happens to be a linear process computationally, thus, each panel is placed following the previous one. The first panel can be fixed to any of the top or bottom floor slab perimeter lines. But, in the same floor, the place of the first panel affects the other end, since the panels at that end would need to be cut to meet the trim line of the surface.

The panel placement works as follows: The start point of the slab perimeter line acts as a center of a circle, whose radius is equal to the desired panel width. Once drawn, this circle intersects the slab perimeter line at a point, which determines the second point for the panel. The next panel is created by using this second point of the first panel. So it becomes the center or the second intersecting circle, which will determine the second point of the second panel. And the routine keeps creating the panels until it reaches the end of the slab floor perimeter line, and then the next floor is processed (Figure 8).

While translating the points, in this case to the lower floor, a similar type of approach is taken to the one of CSCEC Tower. Similar to the situation of the points on flat and curved surfaces of CSCEC Tower, the location

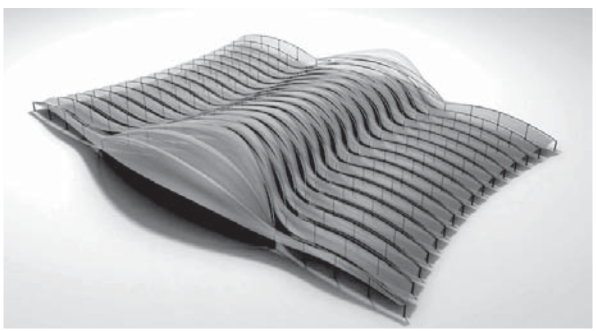


FIGURE 15 Final design of the train station.

of each point has to be determined here as the arc piece they stand on. This helps in creating a reference according to the center of the specific arc piece to translate the points to lower floors with straight lines.

Once all the panels are created, they are classified depending on size and color- coded for a quick representation of the number of panel types. While determining the groups, a tolerance of 10 mm is used, this can be neglected for the curtain wall frames. Ultimately with this methodology the tower can be panelized by using six different types (Figure 9).

2.3. COST-EFFECTIVE PANELING

Z3 Tower is conceived with a diagrid structure and represents similar geometric qualities to White Magnolia tower. In the parametric model we developed, a subdivision factor over the surface of the building updates the nodes for the diagrid, and the manipulation of the factor enables the production of various densities (Figure 10).

The underlying diagrid structure implies the use of parallelogram (diamond) shaped panels, which was also the original design intent. However, a quick study we made by conventional 3D modeling techniques in RhinoScript revealed the inefficiency of the use of parallelogram shaped panels. In this part of the study we subdivided one of the diagrid cells, which spanned twelve floors, into discrete panel pieces. In the next step we explored potential subdivisions that would use trapezoidal panels instead of parallelogram shaped ones. Several pattern studies, including graphical ones were developed for evaluations. The final conclusion for Z3 Tower was to use shingled panels, which would reduce the cost of paneling by enabling us to use panels of the same size on most of the portions of the building.

In a shingle system, the consecutive two panels overlap a certain amount and an additional smaller panel, perpendicular to both panels, fills the gap between them (Figure 11). So the variation in size can be embedded into the smaller filling panels, instead of the main ones. This would also reduce the cost since the parametric changes are applied to smaller window fixtures and no customization is needed for larger ones. Thus, the same panel can be used for a specific floor level and can even be used in the upper and lower flows as long as the surface deviation is under the tolerant limits, as in the case of White Magnolia Tower.

Due to performance considerations and the one directional logic of computation, I preferred to use RhinoScript while developing the panels for Z3 Tower. While the scripted routine lays-out the panels in a similar process to that of White Magnolia Tower, the placed panels are then rotated a certain amount around the vertical axis where they touch the slab edge. This angle can vary and is open to manipulation depending on some external parameters or mathematical drivers. Further investigation can be explored with environmental and computational fluid dynamics analyses, thus the shingle angle can be manipulated according to either solar orientation or the prevailing winds.

The panel surfaces are then rotated on the lateral axis, and extended to create the shingle effect above the lower panes (Figure 12). This vertical shingling helps in rain water drainage. Considering the total height of the building exceeds half a kilometer, the accumulated rain water from the top to the bottom of the building creates a big problem. This is avoided by partially keeping most of the rainwater out of the draining system and simply letting it go down the surface of the building.

2.4. INVISIBLE COMPONENTS

The knowledge gained from the previous three towers, and the motivations those studies created in the office enabled me and my colleagues in our other office overseas to collaborate on a project beginning from the very early stages of the design process. The train station project thus represents a different character and work flow compared to the three tower projects. At the very beginning of the design process, we received a conceptual non-parametric CAD model that presented the design intentions for the train station. The 500 meter long platforms lying between the fifteen train-tracks aligned on an east-west axis are sheltered with large canopies to act as a rain screen, while the tracks themselves are left open on top to let the sunlight into the platforms. The canopies begin to raise and respond to the north and south in the middle of the station which act as entrances and exits. While the conceptual approach intends to create an organic and fluid form, the limits of regular modeling techniques did not reveal these intentions.

With references from the non-parametric CAD model, a basic parametric model was built in Generative Components to explore different formal organizations (Figure 13). Unlike the initial model, the canopies were designed and modeled as responsive parts of a global surface, thus any manipulation on the global form dynamically updates the form of each canopy. We generated several models with certain parameters and analyzed and evaluated them in terms of environmental performance and visual quality (Figure 14).

In the Generative Components environment, the canopies were designed with an “S” curve in section, which enabled us to control the reflection from and penetration to the station of sunrays, as well as the water drainage. The surfaces were generated as a derivative of various configurations of discrete “S” curves, which were parametrically controlled. While driving the design, these curves, as components, remain invisible. The layout and organization of the "S" curves were defined with global rule-sets, and the final design configuration (Figure 15) was a result of these rule-sets, rather than a "hand-crafted" geometry.

The behavior and ranges of adaptation for the "S" curves were defined before-hand, thus the geometry was already being developed under certain constraints. In other words, the design was informed and restricted by certain limitations, thus it was pre-rationalized with embedded intelligence in the parametric model. The underlying structural scheme was developed simultaneously with the surface generation. We were in constant conversation with structural engineers and updated our models according to their input.

A 1/400 scale model, approximately two meters long was built in China, using digitally transferred information. This was also a rehearsal of the real construction since all the structural members and surface pieces were created and prepared for prototyping. The model, when ready, gave us ideas about the configuration of the ribs supporting the canopies and the qualities of the double curved surfaces we were working with.

3. CONCLUSION

The projects I cover in this paper demonstrate different strategies developed for subdividing complex-geometry surfaces. Pointing out the problems of geometric post-rationalization, this paper highlights the importance of incorporating the information related to construction limitations into the design processes.

This paper presents parametric modeling not as a solution tool for design but as a new area of inquiry for it, since every design problem now demands custom approaches, analyses and applications in the parametric modeling environment.

In the contemporary course, architecture stands as a product of hybrid processes, in which traditional analogue and developing digital design methods merge with methods developed by coding. Giving references to real large scale projects, this paper represents how concepts of architectural design can overlap with principles of scripting and how design processes can be supported with digitally generated tools.

Today, an architect capable of customizing his or her tools through digital means would be able to express and realize the design's intentions more solidly in the digital environment. A complete set of both analog and digital skills would put the architect to the position of the "master builder" as a "digital craftsmen," in which all the aspects of design are determined by the designing hand and mind.

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