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Copenhagen Elephant House

A Case Study of Digital Design Processes

Complex Geometry

Computation

Design

Generative

Brady Peters

Foster + Partners

THIS PAPER OUTLINES THE DIGITAL DESIGN PROCESSES INVOLVED IN THE DESIGN AND CONSTRUCTION OF THE NEW ELEPHANT HOUSE AT COPENHAGEN ZOO. Early design concepts for the canopy were tested using physical sketch models. The geometric complexity of these early physical models led to the involvement of the Specialist Modelling Group and the use of the computer to digitally sketch 3D CAD models. After many studies, the complex form of the canopies was rationalised using torus geometry. A computer program was written to generate the canopy glazing and structure. This parametric system was developed to be a design tool, and was developed by an architectural designer working with the team. Through its use the team were able to explore more design options, and alter the design farther along in the design process; however, this generative tool was created largely as a CAD efficiency tool. Another series of computer programs were written to generate and populate a shading system based on environmental analysis. Unlike the computer program that generated the structure and glazing, this program was not developed to make the generation of complex geometric structures more efficient, but developed to explore computational approaches that would have been impossible without the computer. Most of the canopy's design was communicated to fabricator through a geometry method statement, a method that has been proven to be effective in the past. The project completed in June 2008.

Sustainability

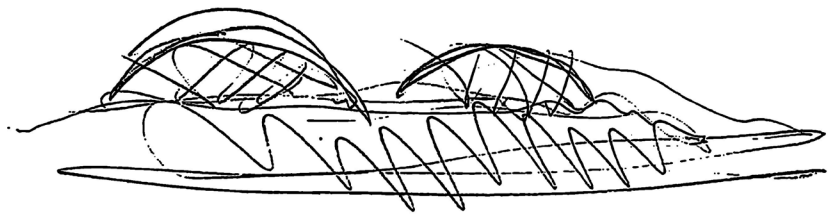
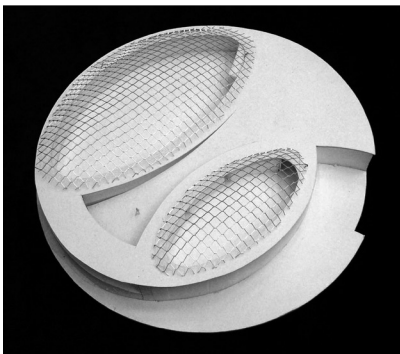
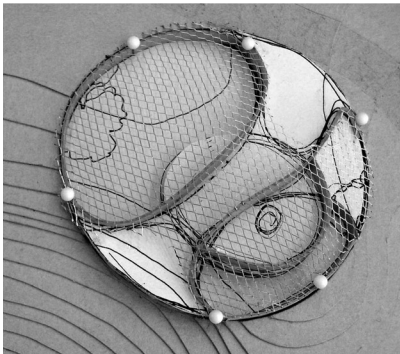
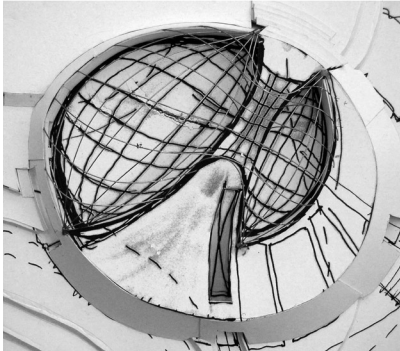


FIGURE 1. (TOP RIGHT) VISUALISATION OF THE ELEPHANT HOUSE IN THE CONTEXT OF THE ZOO.

FIGURE 2. (BOTTOM RIGHT) NORMAN FOSTER'S SKETCH FOR THE ELEPHANT HOUSE.

FIGURE 3. (LEFT) PHYSICAL SKETCH MODELS AT DIFFERENT STAGES OF DESIGN DEVELOPMENT.

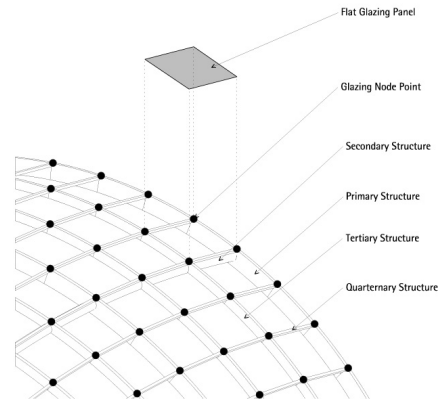
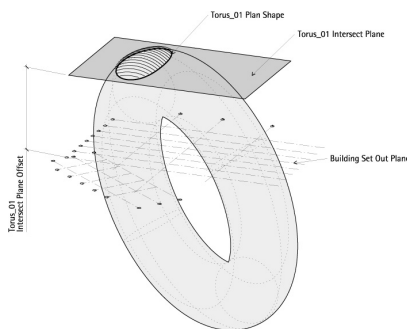
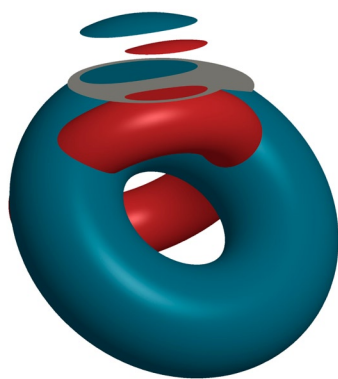
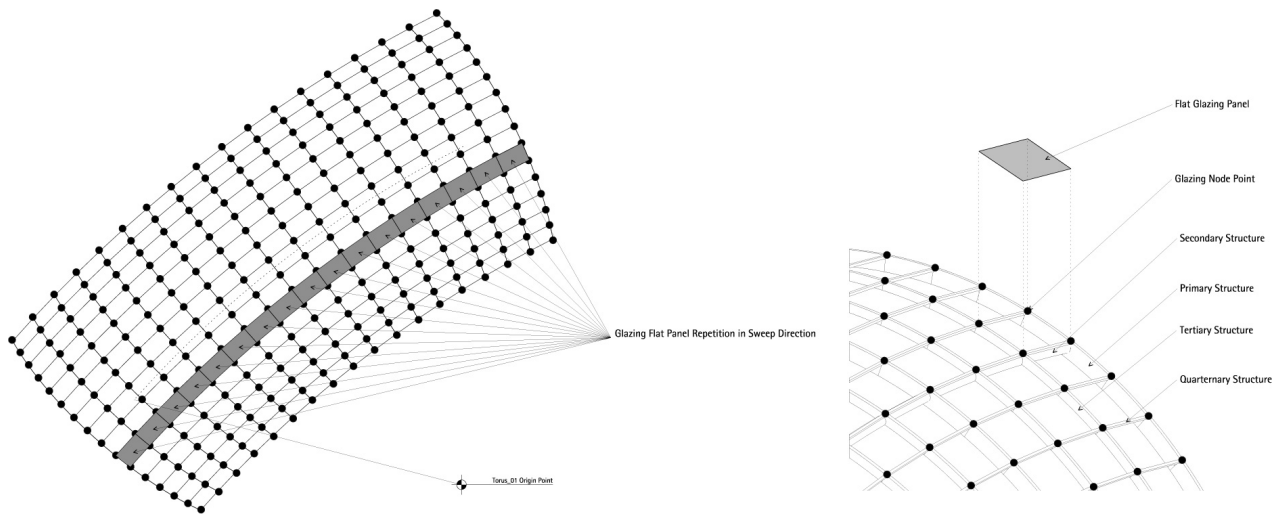
1 Background

Set within a historic royal park, adjacent to the Frederiksberg Palace, Copenhagen Zoo is the largest cultural institution in Denmark, attracting over 1.2 million visitors a year. Among the Zoo's more than 3,000 animals, its group of Indian elephants is perhaps its most popular attraction. Replacing a structure dating from 1914, the new Elephant House, seen in Figure One, seeks to restore the visual relationship between the zoo and the park and to provide these magnificent animals with a stimulating environment, with easily accessible spaces from which to enjoy them.

Research into the social patterns of elephants, and a desire to bring a sense of light and openness to a building type traditionally characterised as closed, provided two starting points for the design. The tendency for bull elephants in the wild to roam away from the main herd suggested a plan form organised around two separate enclosures. These enclosures are dug into the site, both to minimise the building's impact in the landscape and to optimise its passive thermal performance. Covered with lightweight, glazed domes, these spaces maintain a strong visual connection with the sky and changing patterns of daylight. The elephants can congregate under the glazed domes, or out in the adjacent paddocks. During the winter, temperatures drop to -12C and the elephants cannot go outside for extended periods and so need as much indoor natural light as possible. There are broad, external viewing terraces, and a ramped promenade leads down into an educational space, looking into the enclosures along the way. The main herd enclosure will enable the elephants to sleep together, as they would in the wild. The floors of the enclosures are both heated and covered with a thick layer of sand to maintain the health of the elephants' feet (Foster + Partners, 2003).

2 Canopy Design Strategy

Norman Foster's sketch, shown in figure two, suggests two canopy structures, one larger than the other, rising out of the landscape, with the bulk of the building built into the earth.



The canopy geometry relates to the internal arrangement of the elephant spaces and relates to the landscape. The domes correspond to herd and bull elephant enclosures, and relate to linked outdoor spaces. The canopy structure is arranged so that quadrilateral grid openings are created.

While design studies were done by the team using many mediums, physical models were a critical method of design exploration. Physical models created by the architects and structural engineers were used to develop form concepts in new and creative ways. Figure three shows some of the canopy design concepts that were developed and tested using different form-making techniques; grid shells made from wood, form-found models in metal, sculpted vacuum-form models, net structures, and bendable metal mesh were techniques used to create exciting new formal propositions. In order to begin to resolve the design in terms of the dimensional characteristics of spaces and structures, CAD sketch models were produced. The complex geometry of the canopies meant these digital sketches needed to be explored using 3D CAD models, not just 2D drawings. This was an important part of the design process, and CAD was not left to be a simple drafting and rationalisation phase left until the end of the project.

Because of the complexities of the proposed geometries, the Specialist Modelling Group (SMG) was brought on to the project to assist with modelling the canopies. The Specialist Modelling Group is an internal digital design research consultancy within Foster + Partners headed by Hugh Whitehead. The group consults in the areas of project workflow, advanced three-dimensional modelling techniques, and the creation of custom digital tools. The specialists in this team are a new breed of architectural designer, with a background in design, math, geometry, computing, and analysis (Peters and De Kesteler 2006). The SMG's strategy outlines three attitudes towards rationalisation: pre-rationalised, where the geometric or construction system is established prior to the design process; post-rationalisation, where the rationalisation of the geometry takes place after the design has been fixed; and embedded rationale, where the geometric systems and constructional logic is established as an integrated part of the design process (Whitehead 2004, Fischer 2005).

Design ideas were developed and tested using physical models: form options were studied and notional construction systems were proposed. As design rules began to become developed and a more descriptive solution is necessary, digital models become more useful. The Elephant House canopy geometry was not pre-rationalised or post-rationalised; but, the rationalisation of the geometry, and the concepts underlying the construction system, were allowed to develop with the design. Figure four, one of the digital sketches, demonstrates how the form of the canopies is derived from the torus geometry. Torus geometry is not necessarily derived using computational methods and can be constructed or imagined easily using analog processes.

FIGURE 4. DIGITAL SKETCH MODEL OF TORUS GEOMETRY.

FIGURE 5. TORUS GEOMETRY.

FIGURE 6. PLANAR QUADRILATERAL GLAZING PANELS WITH REPETITION.

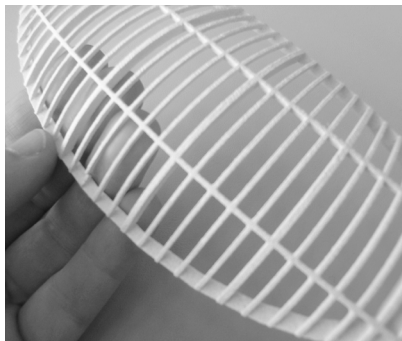
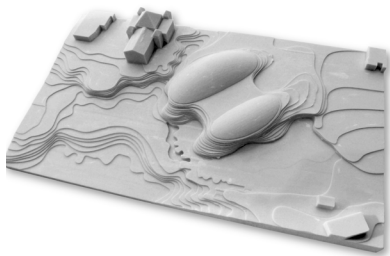
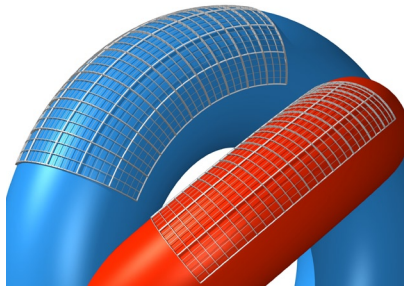


FIGURE 7. COMPUTER GENERATED STRUCTURE AND TORUS GEOMETRY.

FIGURE 8. 3D PRINTED RAPID PROTOTYPE MODELS: LANDSCAPE STUDY WITH BUILDING MASSING, AND CANOPY STRUCTURE MODEL.

FIGURE 9. LEAVES FROM LOCAL PLANTS.

3 The Torus—A Design Strategy for Rationalising Complex Geometry

Foster + Partners has designed a number of buildings based on toroidal geometry and each has extended the office's knowledge of how to build doubly curved structures. The sculptural forms of the American Air Museum, Gateshead Sage Music Centre, Canary Wharf Station, and the Great Glasshouse are all developed from toroidal geometry.

The torus is a surface of revolution, generated by revolving a circle about an axis; this axis of rotation being coplanar with the circle, and generally, but not necessarily, outside of itself. The torus form, figure five, is also commonly referred to as a 'donut' or a 'tyre'. When the smooth surface of the torus is modified into a discrete surface, this creates a surface with a series of planar faces that can be manufactured in a convenient way (Pottman, 2007). These panels have a number of very useful properties: the panels are planar and align with each other along their edges; the panels are quadrilateral, not triangular; and there exists a repetition of similar panels in the direction of rotation, as shown in figure six. This repetition was important as construction cost of the domes had to be minimised. This geometric set-out is also based on arcs, another very useful property as this allows for reliable solid and surface offsets and simplifies and resolves many complex issues of design and production (Whitehead 2003).

Both canopy structures of the Elephant House are based on torus geometry. Each canopy is based on a different torus; these two tori have different radii and are inclined from vertical by different amounts. The primary and secondary radii of each torus were driven by the area requirements in each of the two elephant areas, with the herd enclosure being larger than the bull elephant enclosure. The angle of inclination of each torus was driven not only by the form of the space created between the two enclosure areas but also by the form of the intersection created when the torus is cut with the intersect plane. Figure four shows both of the tori cut with the intersect plane. By inclining the torus away from the vertical and cutting with a horizontal plane, an irregular form is created that was similar to the irregular forms created in the sketch modeling phase, see figure three. This strategy also allowed the design team to adjust the form and size of the viewing and exhibition spaces that sit in between the elephant enclosures.

The set out for the structural and glazing systems are based on these tori; all of the centerlines, beams, and glazing elements are oriented according to the mathematical logic of the torus. All of the architectural elements for each ring of the torus can be generated once, and then copy/rotated around the torus. The structure and glazing and glazing of the canopy are terminated at a structural ring beam. This ring beam is set out at a torus intersect plane, located parallel to the ground. This plane is common for both tori. The set out torus and torus intersect plane for the herd canopy is shown in figure five.

4 Generative Design Process for Structure and Glazing

As with physical models, design ideas in digital models are often first developed in a manual fashion. However, as the geometric rules and construction details become established a parametric model can then be considered. Because of the complexity and number of configurations to be studied, it became clear that it would be quicker to develop a parametric model to explore further design options. The parametric model was developed through the writing of a custom computer program. The computer program was written by an architectural designer, a member of the SMG, who was working with the design team. Computer programming as a design tool allowed the design team to define to define their own digital tools, freeing them from the limited palette of commands available in the standard CAD package. The canopy generation tool was developed as the design progressed. Computer programming was treated like another design tool, like "sketching with code." A similar process was undertaken in a previous project, the Smithsonian Courtyard Enclosure (Peters 2007), and is used by other specialised designers in other architectural offices (Becker and Dritsas 2007).

One of the key aspects of a parametric system that makes it useful or useless is the careful creation of appropriate variables (Peters 2007). For the Elephant House canopy generation macro, 26 carefully chosen variables were used to control the number of ele-

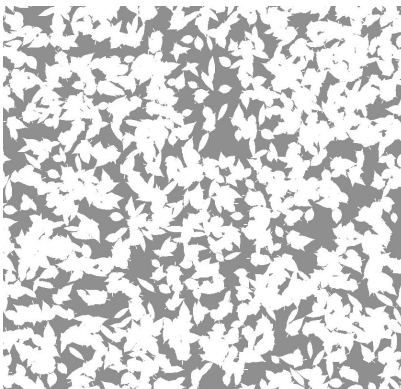
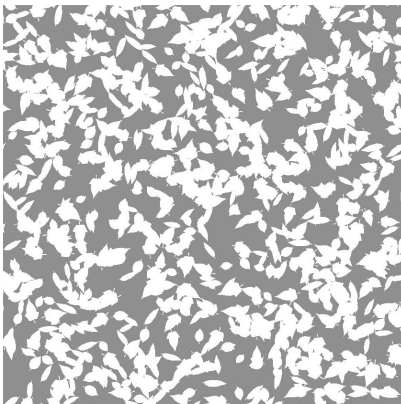
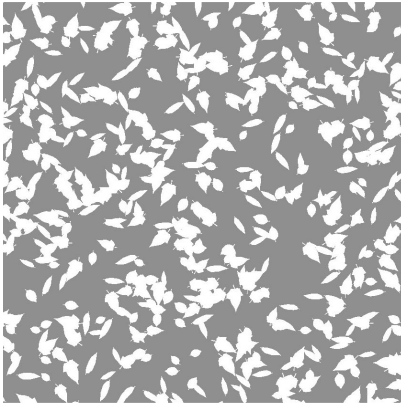
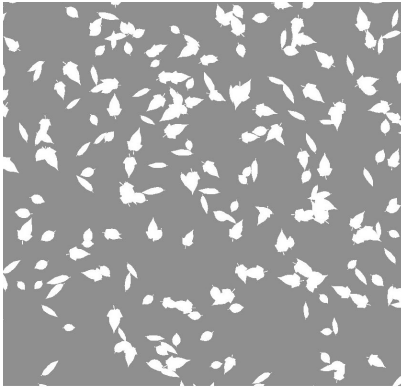
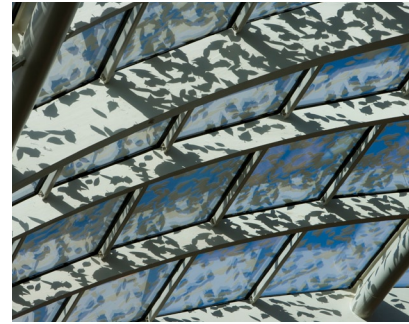
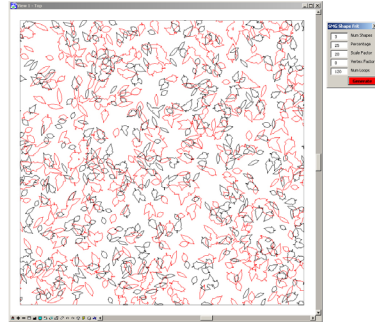


FIGURE 10. COMPUTER PROGRAM TO CREATE LEAF PATTERN.

FIGURE 11. 15%, 30%, 45%, AND 60% DENSITY FRIT PATTERNS.



ments, the size, spacing, and type of the structural members, the different structural offsets, the primary and secondary radii of the torus, and how much of the structure was to be created. In addition to these numeric variables, input geometry was also required: a couple of right-angle lines were also needed as an input. These lines defined a coordinate system which determined the torus' position in space and its rotation. The macro generated all of the centrelines, primary, secondary, tertiary, quaternary structural members, glazing components, as well as tables of node points. The generated geometry is shown in figure seven.

In this project, the creation of the parametric model and the use computer programming to generate the canopy structure and glazing was not a method to generate new and unprecedented modes of expression, but to create many variations could be created and tested. The use of computation in part of the design process was seen as a way to more efficiently generate the canopy structure and glazing.

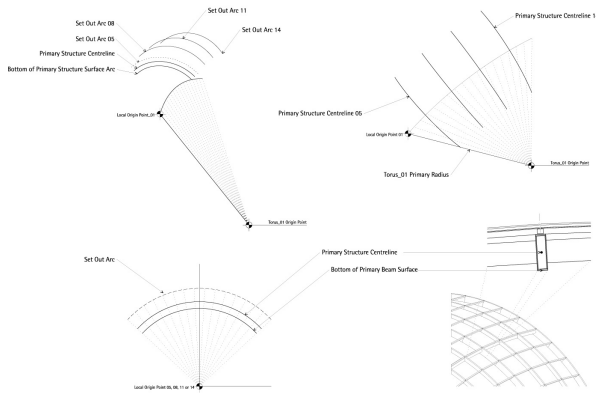
Study models were a key part of the design process of this project, and rapid prototyping technology closes the loop in a digital design process by recognizing the fact that key decisions are still made from the study of physical models. As the structure of the canopies was developed digitally, rapid prototyping was an obvious way to test the developed designs. The period of development of the canopy design corresponded with the adoption of 3D printing processes in the office. Many different aspects of the design were tested using the rapid prototyping technology. Landscape options, also generated using computer programming techniques, interior spatial studies, and canopy structure options were all studied using the 3d printer. Figure eight shows two of many rapid prototype models produced. The process of rapid prototyping works well with the generative process and in this project, tied in well with the early techniques of physical model making.

5 Environmental Performance and Computation

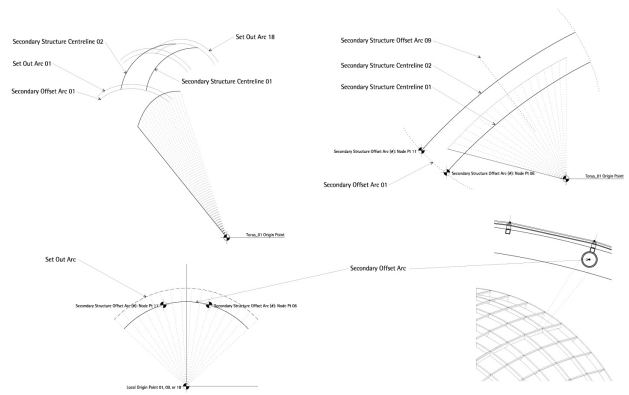
The environmental performance of the elephant areas was a key aspect of the design of the project. Occupant comfort was a key driver in the design of the elephant enclosure and helped to define the measure of environmental performance. The environmental analysis was carried out by environmental consultants at Buro Happold. In order to achieve the desired environmental performance, especially in the summer, it was necessary to introduce solar control for the canopy enclosures. Solar control was necessary to reduce the energy input into the space to maintain a comfortable temperature. It was also critical to manage airflow in the space. This was accomplished through the introduction of variable openings in the glass canopy. It was important to maximise the transparency of the glass, so that there would be more natural light within the elephant enclosures and so that the visitor could look through the glass from the outside with experiencing large amounts of reflection.

The solar control strategy that was decided upon was to silk-screen a fritting pattern onto the glass; no coatings were used on the glass other than the fritting. Amongst architects, enamelled glass is often called 'fritted glass'. Enamelling involves applying a layer of ceramic coating to the glass surface and then baking it into the glass during the manufacture of toughened or heat-strengthened glass. Solar control is achieved by the shading

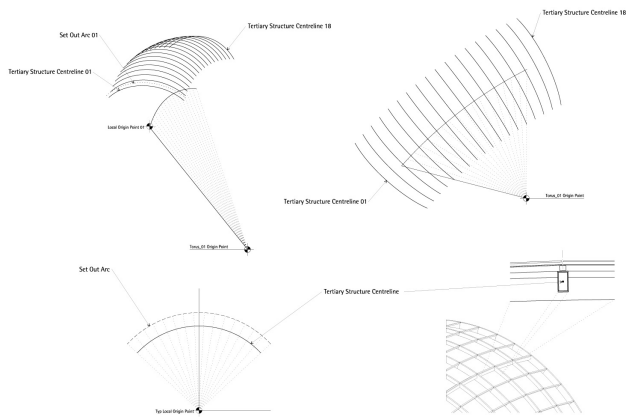
STEP 6: Primary Structure Centrelines and Bottom of Primary Structure Surface



STEP 7: Secondary Structure Centrelines



STEP 8: Tertiary Structure Centrelines



STEP 9: Quarternary Structure Centrelines

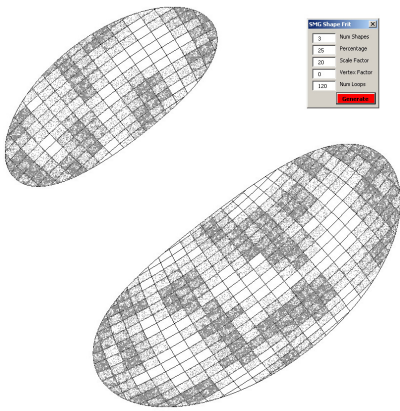
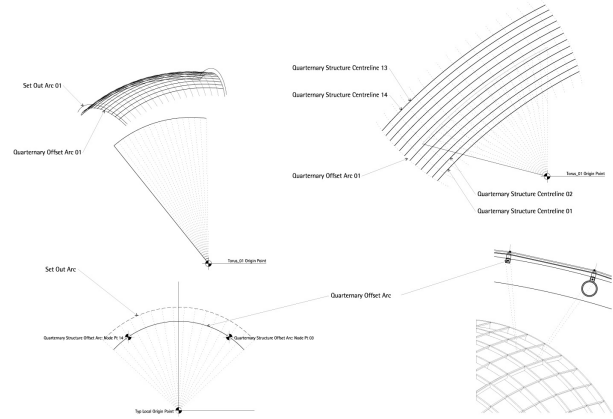


FIGURE 12. GLAZING PANELS WITH LEAF-INSPIRED FRIT PATTERN.

FIGURE 13. FRIT DISTRIBUTION PATTERN.

FIGURE 14. DEFINITION OF CENTRELINE GEOMETRY IN THE GEOMETRY METHOD STATEMENT.

FIGURE 15. ELEPHANT HOUSE CANOPY COMPLETED.

from the pattern. The solar control effect depends on the different ratios of transparent to opaque areas (Balkow 1999).

The environmental consultants established the amount of solar control that was needed to achieve the desired environmental performance. They defined fritting densities, and the number of panels of each particular fritting density. However, the set out of these different densities of frit panels was not pre-determined. Different configurations of the placement of these panels were studied through the development of many design options. A more standard micro-dot frit pattern was considered unsuitable for this project because it would produce an even lighting level internally; this would be suitable for an art gallery or office, but not for the elephant enclosure where areas of light/dark contrast were considered an advantage. As the elephant's natural habitat is at the edge of the forest, a leaf pattern was seen as an appropriate starting point for the frit design. The landscape component of the project is a large part of the project, both because the building is itself buried in the landscape, but also because the outdoor elephant areas and associated visitor areas extend well into the park and zoo. Three leaf forms from the plant species selected by the landscape architect, see figure nine, were used as inspiration for the design of a fritting pattern for the Elephant House canopies.

A computer program was written to create fritting patterns from the leaf forms. The computer program used as input: the base shape of the glazing panel and the outline forms of the different leaf shapes. The computer program then iteratively, and randomly, placed these leaf forms into the base glazing area. Overlapping areas where leaf shapes were placed on top of each other and the condition when leaves were placed outside of the base glazing shape were taken into account. The area of fritting was calculated for each iteration. Leaves could be randomly rotated, scaled, and even randomly form-changed,



though the topology would stay the same. Figure ten shows a step in this process of placing leaf shapes into the base glazing shape.

When the desired area of fritting was reached, based on the percentage of solar shading required, the computer program would output the finished pattern. An example of these frit patterns is seen in figure eleven. It would have been computationally quite easy to create different fritting patterns for each panel on the canopy; however, because of the costs associated with the silk-screening and enamelling of the panels, ultimately only four panel types could be generated.

The algorithm for this computer program is relatively simple. Once the code is written, it is not complicated for the computer to calculate the results; however, it would have been very difficult, perhaps even impossible, to achieve these results without computational tools. So, unlike the use of computer programming for the generation of the structure and glazing, where the computer was used to simply make an already possible task faster and more efficient, the development of this fritting algorithm was a design exercise that generated a performance-based complex pattern that emerged from the computational rules set by the designer. While canopy needs all panels in the population to achieve the correct performance, the different density panels create localised areas of greater and lesser degrees of shading. This would not have been possible to consider without computational tools. Figure twelve shows the installed fritted glazing panels.

Once the fritting patterns were generated, the distribution of these fritted panels onto the canopy structure needed to be established. This required a new strategy, and another custom computer macro. Inspired by a forest canopy, a design strategy was developed to bunch the panels into tree zones with decreasing density from the centre. The leaf shape and distribution of frit density is a representation of the tree canopy, where clusters of increased frit density are the “tree” areas and the areas in between with decreased frit density are the openings in this forest of “trees”. This design strategy also allowed the many controllable opening panels in the canopy structure to be located in the clear areas between the tree zones. The opening panels then were both literally and metaphorically openings in this “tree canopy”. In order to find a solution for the placement for the exact number of each type of panel a computational approach was again taken. The glazing panels, the location of the operable windows, the number of tree zones, and the number of panel types were needed as input into the computer program. The freedom to explore multiple iterations and multiple algorithmic approaches was important to optimisation in this case. This iterative approach would have been impossible without the help of the computational tools. Figure thirteen shows a distribution pattern of frit patterns on the Elephant House canopies.

6 Construction and Communication

As with many projects done by the SMG at Foster + Partners, the design is communicated to the fabricator not through a digital model, but through a document called the *Geometry Method Statement*. The geometry method statement assures reliable data transfer between different CAD systems as fabricators are required to build their own models on their own CAD systems following the rules set out by the geometry method statement. This document describes the design in terms of simple geometric rules that allow the design to be communicated. This deliberate educational strategy assures the fabricator has a full understanding of the geometric complexities of the project. A sample diagram showing the generation of the centrelines for the structural elements in the canopies is shown in figure fourteen.

The geometry method statement was the basis and precondition for the fabricator’s (Waagner-Biro) digital model. Werner Braun from Waagner-Biro feels that this is the best way to communicate the complex geometric ideas. The fabricator constructed a digital 3D CAD model from the geometry method statement. This model was constructed using ACAD 2005 with mechanical desktop. The model was very detailed including structure, glass, gutters, and flashing. 2D drawings were automatically generated from this 3D model. The fabrication of the over 655 structural components was done manually from the 2D

drawings (Braun and Korbell 2008). In this project the drawing creation was digitally automated, but the fabrication was not.

7 Conclusion

Early design concepts for the canopy were tested using physical sketch models. The geometric complexity of these early physical models led to the involvement of the Specialist Modelling Group and the use of the computer to digitally sketch 3D CAD models. Rapid prototyping closed the digital design loop by bringing the design decision making process back to a physical representation of the building. While early form studies were sketched with 3D CAD software, this led to a rationalisation of the geometry due to fabrication constraints. The rationalisation process was embedded as part of the design process. A toroidal geometry solution was chosen for its formal properties, flat panel quadrilateral glazing solution, and arc-based structure. This structural and glazing strategy was explored with a computer-programming-based parametric model. This parametric system was developed to be a design tool, and was developed by an architectural designer working with the team. It allowed for the rapid generation of many different options and the exploration of different designs. The solar shading strategy was driven by environmental performance criteria. Algorithmic design principles were used to create series of parametric tools that generated a complex shading pattern based on natural leaf forms. A series of drawings, the geometry method statement, were then used to communicate the complex ideas to the fabricator. The project completed in June 2008.

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