New Elephant House, Copenhagen

A Case Study of Digital Design Processes

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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 (SMG) 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.

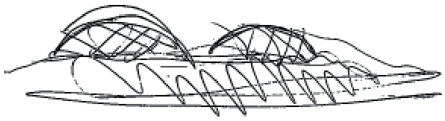
BACKGROUND

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 1, seeks to restore the visual relationship between the zoo and the park and to provide these magnificent animals with a stimulating environment and 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 -12°C 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).

Fig. 1: Visualisation of the Elephant House in the context of the zoo.

Fig. 2: Norman Foster's sketch for the Elephant House.



CANOPY DESIGN STRATEGY

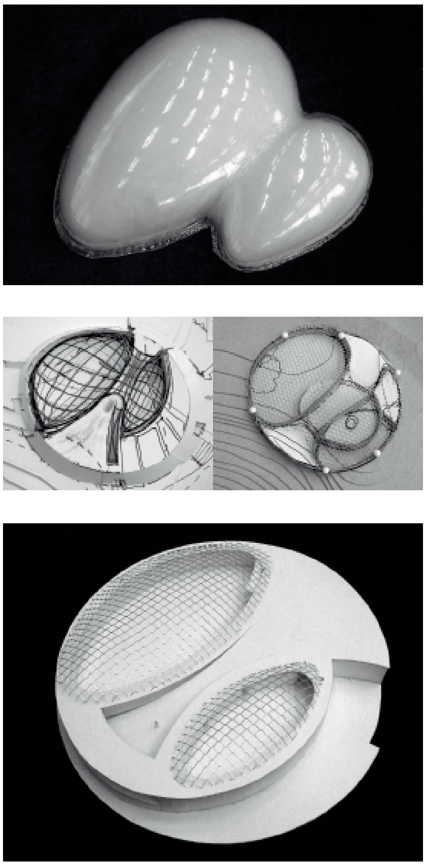
Norman Foster's sketch, shown in Figure 2, suggests two canopy structures, one larger than the other, rising out of the landscape, with the bulk of the building built into the earth. The canopy geometry relates to the internal arrangement of the elephant spaces and relates to the landscape. The domes 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.

Design studies in many media were undertaken by the architects and structural engineers but the physical models were a critical method of design exploration, developing new and creative form concepts. Figure 3 shows several 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 that the design process of these digital sketches needed to be explored through 3D CAD models, not just 2D drawings. CAD was not simply a drafting and rationalisation phase at the end of the project.

Because of the complexities of the proposed geometries, the SMG was brought on to the project to assist with modelling the canopies. The SMG is an internal digital design research consultancy within Foster + Partners that consults in the areas of project workflow, advanced 3D 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 Kestelier 2006). The SMG's strategy outlines three attitudes towards rationalisation: pre-rationalisation, 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 are developed and a more descriptive solution is necessary, digital models become increasingly 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.

Fig. 3: Canopy design concepts.



The digital sketches in Figure 4 demonstrate 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.

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 practice's knowledge about building 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 5, is also commonly referred to as a 'doughnut' 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 several 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 6. Importantly, this repetition minimised the construction cost of the domes. The geometric set-out is also based on arcs, which have another very useful property as they allow for reliable solid and surface offsets, and simplify and resolve 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 the vertical by different amounts. The primary and secondary radii of each torus were driven by the area requirements for each of the two elephant areas, with the herd enclosure to be larger than the bull elephant enclosure. The angle of inclination of each torus was not only driven 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 by the intersect plane. Figure 4 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 modelling phase, shown in Figure 3. 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 is based on these tori; all of the centre lines, 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 of the canopy terminate at a structural ring beam. This ring beam is set out at a torus intersect plane, located parallel to the ground and this plane is common for both tori. Figure 5 illustrates the set out torus and torus intersect plane for the herd canopy.

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 number and complexity 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 customised computer program written by an architectural designer, a member of the SMG, who worked with the design team. Using computer programming as a design tool allowed the design team to define their own digital tools, freeing them from the limited palette of commands available in a standard CAD package. The canopy generation tool was developed as the design progressed. Computer programming was treated like another design tool, as if 'sketching with code'. A similar process was undertaken in a previous project, the Smithsonian Courtyard Enclosure (Peters 2007), and is used by specialised designers in other architectural offices (Becker and Dritsas 2007).

Fig. 4: Digital sketch model of torus geometry.

Fig. 5: Torus geometry.

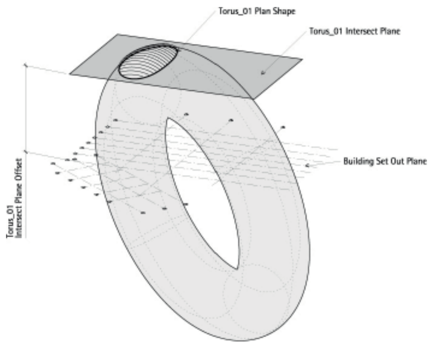
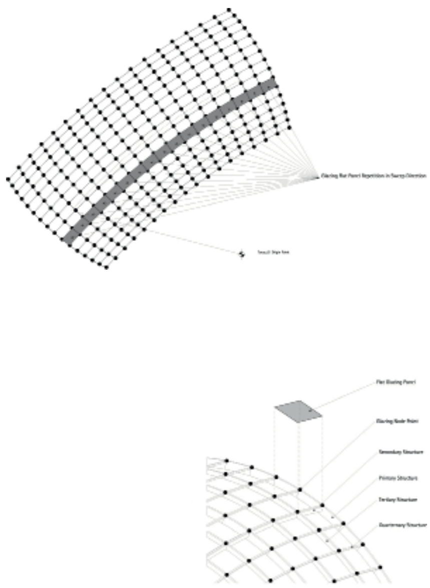


Fig. 6: Planar quadrilateral glazing panels with repetition.



One of the key aspects of a parametric system that makes it useful or useless is the careful creation of appropriate variables (Peters 2007). To generate the Elephant House canopy macro, twenty-six carefully chosen variables were used to control the number of elements, 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: several right-angle lines were also needed as an input. These lines defined a system of coordinates that determined the position of the torus in space and its rotation. The macro generated all of the centre lines, primary, secondary, tertiary, quaternary structural members, glazing components, as well as tables of node points. The generated geometry is shown in Figure 7.

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

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 continue to be made from studying 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 rapid prototyping technology. Studies of landscape options, interior spatial studies and canopy structure options generated by computer programming were all studied using the 3D printer. Figure 8 shows two of many rapid prototype models produced. The process of rapid prototyping works well with the generative process and in this project, it tied in well with the early techniques of physical model making.

Fig. 7: Computer Generated Structure and Torus Geometry.

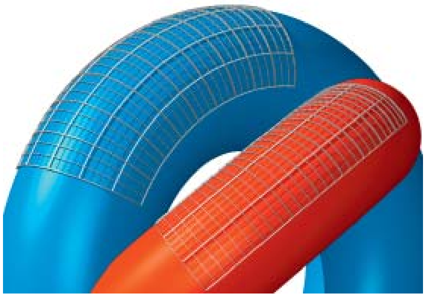
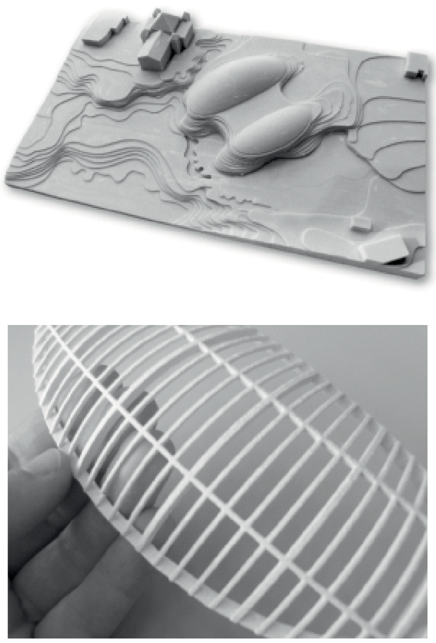


Fig. 8: 3D printed rapid prototype models: landscape study with building massing, above; and canopy structure model, below.



ENVIRONMENTAL PERFORMANCE AND COMPUTATION

The environmental performance of the elephant areas was a key aspect of the design of the project and included concerns for occupant comfort, which contributed to the definitive measure of environmental performance. The environmental analysis was carried out by environmental consultants at Buro Happold. In order to achieve the desired performance, especially in the summer, it was necessary to introduce solar control into the canopy enclosures. This meant a reduction of energy input into the space to maintain a comfortable temperature. It was also critical to manage airflow in the space. Solar control was accomplished through the introduction of variable openings in the glass canopy. It was important to maximise the transparency of the glass to introduce natural light into the elephant enclosures and allow visitors to see through the glass from the above without undue reflection.

The final solar control strategy was to silk-screen a fritted pattern onto the glass to create shade and avoid the use of additional coatings. Fritted glass, also known as enamelled glass involves applying a layer of ceramic coating to the glass surface of toughened or heat-strengthened glass, which is then baked on during the manufacturing process. Solar control is achieved by shading 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 frit densities, and the number of panels of each particular 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 standardised micro-dot frit pattern was considered unsuitable for this project because it would produce an even lighting level internally. While suitable for an art gallery or office, it was not appropriate for the elephant enclosure in which areas of light and 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. Three leaf forms from plant species selected by the landscape architect,

Fig. 9: Leaves from local plants.

illustrated in Figure 9, were used as inspiration for the design of a frit pattern for the Elephant House canopies. Additionally, this pattern suited the large landscaping component of the project, both because the building is itself buried in the landscape and also because the outdoor elephant areas and associated visitor areas extend into the park and zoo.

A computer program was written to create frit patterns from the leaf forms based on the shape of the glazed panels 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. Account was taken for areas where leaf shapes overlapped and 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 10 shows one step in this process of placing leaf shapes into the base glazing shape.

When the desired degree of fritting was achieved, based on the percentage of solar shading required, the finished pattern was finally output by the computer program. Examples of these frit patterns are seen in Figure 11. Though it would have been quite easy to create different fritting patterns for each panel on the canopy through this computerised process, because of the costs associated with silk-screening and enamelling the panels, ultimately only four panel types were 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 frit algorithm was a design exercise that generated a performance-based complex pattern that emerged from the computational rules set by the designer. While the canopy needs all panels in the population to achieve the correct performance, the different density of panels created localised areas of greater and lesser degrees of shading. This would not have been possible to consider without computational tools. Figure 12 shows the installed fritted panels of glazing.

Once the fritting patterns were generated, the distribution of them onto the canopy structure needed to be established. This required a new strategy, and another customised 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 were the 'tree' areas and the areas in between with density decreased are the openings in this forest of 'trees'. This design strategy also allowed the many operable panels in the canopy structure to be located in the clear areas between 'tree zones'. The opening panels were then both literally and metaphorically openings in the '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 input into the computer program. The freedom to explore multiple iterations and multiple algorithmic approaches was important to gain an optimum result in this case. This iterative approach would have been impossible without the help of the computational tools. Figure 13 shows a distribution pattern of frit patterns on the Elephant House canopies.

CONSTRUCTION AND COMMUNICATION

As with many projects undertaken by the SMG at Foster + Partners, the design is communicated to the fabricator not through a digital model, but through a document called a Geometry Method Statement. This statement assures that reliable simple geometric rules are reliably transferred between different CAD systems; fabricators are required to build their own models on their own CAD systems following the Geometry Method Statement.

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 centre lines for the structural elements in the canopies is shown in Figure 14.

Fig. 10: Computer Program to Create Leaf Pattern.

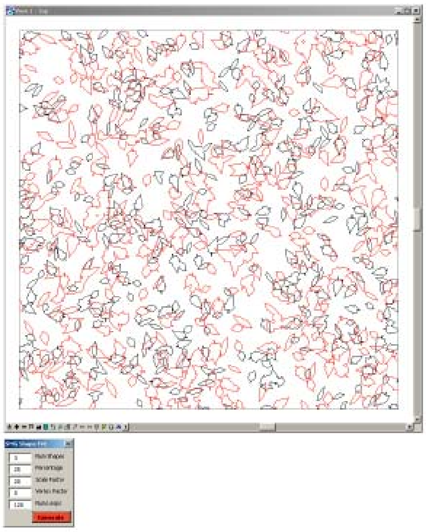


Fig. 11: Four varying percentages of frit pattern, from left to right: 60; 45; 30; 15.

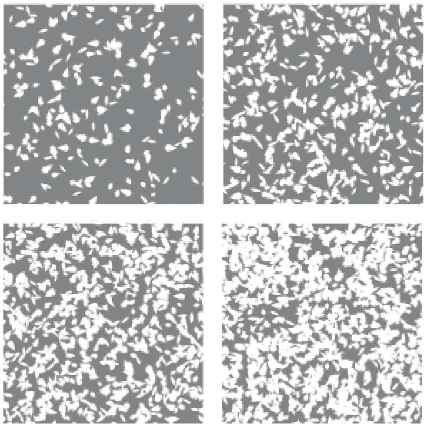


Fig. 12: Leaves from local plants.

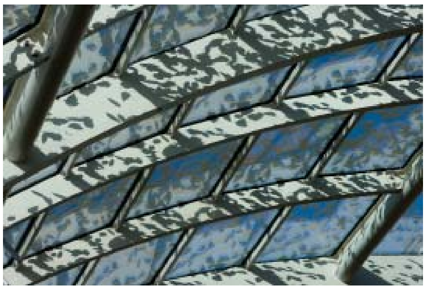
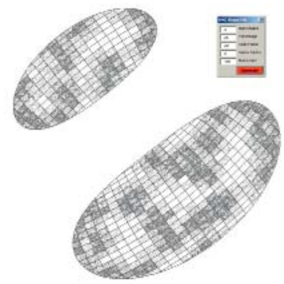


Fig. 13: Frit distribution pattern.



The geometry method statement was the basis and precondition for the digital model of the fabricator, Waagner-Biro. Werner Braun from Waagner-Biro feels that this is the best way to communicate complex geometric ideas. The fabricator constructed a digital 3D CAD model from the Geometry Method Statement using ACAD 2005 with mechanical desktop. The detailed model included structure, glass, gutters, and flashing and 2D drawings were automatically generated from the 3D model. The fabrication of more than 655 structural components was manually made from the 2D drawings (Braun and Korbell 2008). Therefore, in this project the drawing creation was digitally automated, but the fabrication was not.

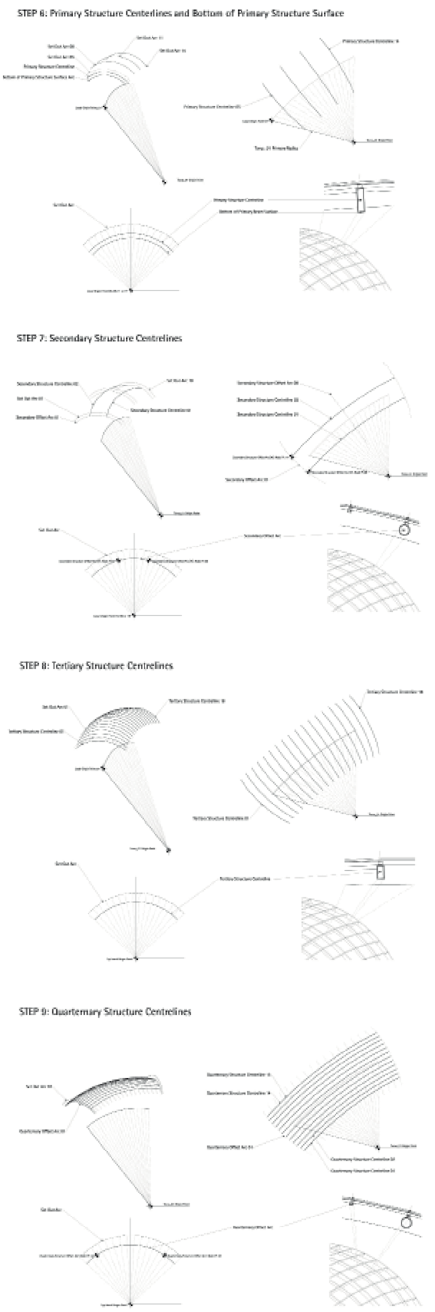


Fig. 14: Definition of centre line geometry in the Geometry Method Statement.

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 lead 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 architectural 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 a series of parametric tools that generated a complex shading pattern based on natural leaf forms. A series of drawings – the geometry method statement – was then used to communicate the complex ideas to the fabricator. The project was completed in June 2008.

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