Geometry, Form and Complexity

Is geometry the essence of form, or just a convenient means of description? At the level of philosophy or of science this is a question that could be debated without ever reaching a conclusion, while to most architects the question would be almost rhetorical. However in the digital age, where computers are increasingly used in design, fabrication and construction to explore the art of the possible, the answer is no longer clear cut. This is because the approaches to design are as much a matter of style as the resulting form. The choice of medium for design exploration and the materials and methods used for construction to a large extent determine what will be the most effective means of description.

Historically, the use of geometry and mathematics to describe built form provided a common basis for communication between the processes of design, fabrication and assembly. This meant that the theories of proportion and harmony and also the precision required to coordinate delivery by large numbers of people under a legal contract, could both be specified within the same system. The implication was that the application of rationale would not compromise creativity or the creation of a beautiful form. This is now being challenged by the use of digital technology to produce free-form buildings which, by transcending the limitations of Euclidean geometry, can deliver an aesthetic that appears more organic but which can also achieve higher levels of performance.

Ultimately the creation of form is about the resolution of forces – some physical and some metaphysical. While engineers may use form-finding techniques to deploy material in a way that minimises stress, architects will explore the trade-off between considerations that are much harder to quantify or balance. In terms of aesthetics there can be no absolute measure and the author Chris Abel compared the works of Foster and Gehry by concluding that 'without Gehry heat there can be no appreciation of Foster cool – and vice versa'. The appeal of a building may lie in the delight of experiencing habitable sculpture in which the exterior celebrates the play of light across curved metal panels, while the interior uses digitally fabricated timber to provide superb acoustics, yet the complex structure that supports it is never seen. On the other hand the honest expression of structure and detailing can be seen as symbolic of an intellectual rigour that permeates the whole design, so that the complex qualities of form and space can be de-coded in terms of an underlying simplicity, which makes it possible.

Accepting the constraints of a limited palette of surfaces that can be described in terms of simple projections of lines and arcs has advantages that cannot be easily abandoned. A system of geometry constructed with a ruler and compass can also be marked out with nothing more than pins and string, so that the design intent can be reliably conveyed to fabricators and contractors by means of conventional drawings and a rule-based method statement. However, free-form designs developed with digital 3D models can only be implemented using surveying equipment based on laser technology and fabrication processes dependent on computerised numerical control systems. The higher levels of skill required are also often accompanied by higher risks and greater cost.

During the previous decade Foster + Partners explored the potential of free-form design with a series of six seminal buildings for which geometric principles were relaxed and gradually extended rather than suddenly abandoned. This allowed a systematic approach that still ensured delivery on time and on budget. The necessary research was undertaken by the formation of the Specialist Modelling Group as an in-house consultancy, which set a trend that has been followed by many architectural and engineering practices. At the time each project was a voyage into uncharted waters, but in retrospect they can be seen as part of a progression in which new design ideas were supported by new approaches to rationale that helped to make them buildable.

Design can also be described as an evolutionary process in which the result, the intended route and even the starting point cannot be pre-determined. The way in which potential solutions are generated, evaluated and selected is extremely Darwinian, yet it is one in which both logic and intuition play roles that are inextricably combined. In his book Lateral Thinking Edward de Bono famously described logic as the management of 'No'. The process of design requires a counterpart or corollary such as inspiration is the management of 'Yes'!

However, before construction can commence, a design has to be described in terms of a set of procedures which are to be performed in a sequence that is entirely logical and is therefore based on some system of geometry, mathematics or numerical control. In nature there is no such clear distinction between process and procedure – at a conceptual level the development of form is all process, while at a material level it is all procedure, but they occur simultaneously as growth. The use of computers is helping designers to blur this distinction by using procedural techniques earlier in their design process. As a result buildings are starting to appear more organic, not as an issue of style but because they are beginning to behave more like organisms that are both responsive and even adaptive to their environment.

The Swiss Re Headquarters, now known as 30 St Mary Axe but commonly referred to as 'the Gherkin', was the first of the six seminal buildings and its radical form was derived primarily from a response to context. Although at first sight the unusual shape might appear to be a wilful gesture attempting to be iconic, it would never have succeeded on this basis. In fact, true iconic status cannot be designed but is only conferred by the people who use or appreciate the building. While the Gherkin has now become the film maker's first choice for a location shot of London that symbolises the adventurous use of technology, yet the general public are probably not aware that the design logic is so tight. In retrospect, the resulting form seems almost inevitable. However, it was the fact that the building was in effect pre-rationalised that made it possible to develop parametric control systems,

which in turn made the detailed design, fabrication and construction possible. Coordination and accountability was ensured by issuing all consultants and contractors with a formal geometry method statement, from which they were required to build their own 3D models and then extract coordinates as part of checking procedures.

Learning from the experience of Swiss Re the next two buildings in the series, the Sage Music Centre and GLA City Hall, were essentially exercises in post-rationalisation. Both projects began as competition schemes where the design called for a free-form double-curved skin, but the panelisation of the surface, which was required in order to deliver an affordable building, was only developed after the concept stage. The challenge was to find a geometric rationale that would not compromise the original design concept. Whereas any curved surface can be easily subdivided into a triangular mesh, a quadrilateral mesh may result in panels that are twisted and therefore difficult to fabricate as a cladding system. Designers however, tend to prefer quadrilateral rather than triangular panels in terms of visual appearance and there are also compelling economic considerations that result from simpler node connections, fewer framing members and less material wastage. While there is now a large body of research into techniques for transforming quad meshes into planar facets, they generally use iterative calculations which converge to form a solution that is within tolerance limits, but there are relatively few approaches to deriving a precise solution by means of formal geometry. The Sage and City Hall are each based on a different principle, but they illustrate two of the primary strategies for creating curved surfaces for which there is a natural flat panel solution.

The cladding surface for the Sage is based on a wave-form profile swept around a spiral cross section. However, an arc swept around an arc produces a 'torus patch' which can always be sub-divided into planar facets. By rationalising the spiral curve into three tangential arcs and the wave-form into seven, the resulting surface is composed of twenty-one torus patches, which all fit together with perfect tangency across the boundaries. This surface can then be unfolded into a flat pattern development, which can be easily scheduled and also economically fabricated because there is repetition in the sweep direction. Furthermore, because the profile remains constant, the supporting ribs could all be formed to the same curvature. By setting up a parametric control system for the two defining curves the whole envelope could be continually varied in response to design changes in the shape of the auditoria. What was significant is that, far from compromising the original concept, the approach of developing geometry that could perform as a rule-based mechanism provided the flexibility to progressively refine the design, even at a relatively late stage in the project.

The shape for the City Hall began as a sphere, which had the advantage of providing minimal surface area for a given volume, but was then transformed into an egg shape with its central axis inclined towards the sun. The effect was to greatly reduce solar irradiation and hence the cooling load. Slicing this form with a set of horizontal planes produced floor plate shapes that were all close to elliptical. It was found that the proportions changed progressively up the building, with the long and the short axes becoming transposed through a circular floor plate at mid-height. This surprising result could have provided a way to rationalise the geometry, but the problem remained that twist in the cladding surface could only be resolved by triangulation, which would make it difficult to accommodate office partitions. However, by making all the floor plates conform to a circular plan the complex surface became a family of 'sheared cones'. While it is obvious that a cone with a vertical axis will have a simple flat panel solution, it was not widely known that when the cone axis is inclined the facets become trapezoidal, but they remain planar. Circular floor plates also allowed the internal space planning to be coordinated with a regular radial grid, while the partitions could be connected to inclined mullions with triangular closer pieces, each cranked to the required angle. As the design concept evolved the guiding principles emerged through experimentation, rather than being imposed as a formulaic solution.

In this sense the whole series was a cumulative process, in which each building increased the repertoire of successful techniques, but also created new points of departure for the next exploration. The design of Albion Wharf was based on spiral curves for both plan and section. Like Swiss Re the curvature produced a recessive form, in which the apparent mass reduces as the building is approached. Like the Sage, the façade was panelised with a torus patch solution, but the effect of double

curvature was further enhanced by adding an outer skin of tubular rods to provide solar protection. The roof however was designed as an undulating form with a soft silhouette, rising smoothly over the service cores to enclose the plant rooms. For this surface, twist was inevitable and a new approach had to be found for controlling the curvature. The idea was to use the Kalzip system, which could accommodate twist by means of pre-curved and tapered sheets with a standing seam joint, but the process of pre-fabrication required a design surface that could be precisely defined in a digital model. The solution was to use radial beams with a standard curvature but pivoted from the top edge of the façade. Controlled undulation of the roof could then be achieved by varying the angle of a standard profile according to a simple sine-wave function. This technique employed a combination of parametric control systems together with a generative script, so that both the design and the construction rationale became embedded in the tools that produced the form.

Embedded rationale was also used in the development of the Free University Library in Berlin. This project provided a new infill to an existing courtyard, where the concept was for a bubble-shaped building. Column-free steel trusses produced a framework of hoops that support a double skin enclosure, while the internal concrete floors are completely independent. A flat panel solution was required for both the inner and the outer skin, so a rule-based variational profile was developed to control the truss geometry at every cross section. Curvature is defined by three tangential arcs for which the segment angle is constrained to remain constant, so that as with City Hall, each portion of the surface conforms to sheared cone geometry. The transformation was controlled by using a bi-directional solver, which accepts both geometric and algebraic constraints and returns a 'degree of freedom' count. The concept of degrees of freedom is fundamental to any constraint management system, and allows designers to explore different types of behaviour resulting from different logical dependencies.

When the height of the cross sections was constrained by a profile curve in the long direction it was found that the solver returned zero degrees of freedom, so that for any given height there was a unique solution to the section shape. However this meant that the plan shape could not be directly controlled, but only varied by changing the curvature of the long section. Because of the loose fit relationship between the skin and the interior structure, this turned out to be an acceptable limitation. Although the use of embedded rationale is a very powerful technique, it is best applied when a design concept has already reached a stable configuration and just needs to be fine-tuned. There is always an element of compromise in adopting any rule-based approach. While a potential solution space can be explored in more depth, its breadth will inevitably be limited by the acceptance of constraints, which it is also important to challenge.

In the evolution of design ideas the use of pre-rationalised, post-rationalised or embedded rationale remains a matter of choice. However in the development of a system of descriptive geometry that will support the delivery of a project, the aim is to achieve integration between performance requirements, which will be based on the selection of appropriate materials but also informed by fabrication and construction techniques.

Chesa Futura in St Moritz provided extreme challenges due to a combination of adverse climatic conditions and a desire to use natural traditional materials in new ways, so as to create a futuristic form that would optimise the potential of a restricted and steeply sloping site. The building is a timber shell shaped like a kidney bean but raised above the ground on raking steel supports. Although it is clad with timber shingles, cut by hand and fixed on site, the frame and the wall panels were prefabricated in Germany using advanced CNC machinery. This was driven directly by curves extracted from a solid model, which involved multiple offsets, cuts and difference operations, so that precise geometry could be derived for every component. Even with the experience of the previous five projects, it became apparent that in order to design Chesa Futura, it would also be necessary to design a modelling process that was based on a full understanding of the underlying technologies.

The free-form shape was controlled only by a schematic plan and section, which were rationalised as tangential arcs and then linked to act together as parametric templates. This provided a simple control mechanism which allowed the complex interactions between internal spatial and external contextual relationships

to be explored and resolved in a fine tuning process that took many months.
To create the full design surface of the form, transition points between the arcs
were locked to sloping planes so as to define paths along which a variational
profile could be driven by a generative script. Any change in the two defining
templates caused the whole form to regenerate, but always as a fair surface
with continuous curvature and a precise definition. By using parametric templates
composed of rational curves, the resulting form was interpreted by the solid
modeller as a mathematical surface for which precise offsets are easily produced.
This approach guaranteed the precision and robustness which was required
to reliably drive the machinery in the fabrication workshop.

So far this chapter has described the evolution of design methodologies
which were developed in response to the challenges presented by an initial series
of six projects. In the next section two more recent case studies illustrate how
these ideas have been further developed. The ability to define geometry as a rule
based mechanism became extended by the use of generative techniques, which
were based on an algorithmic approach. Computational skills are now empowering
designers to become both tool-builders and digital craftsmen through the ability
to communicate directly with performance analysis and fabrication techniques.
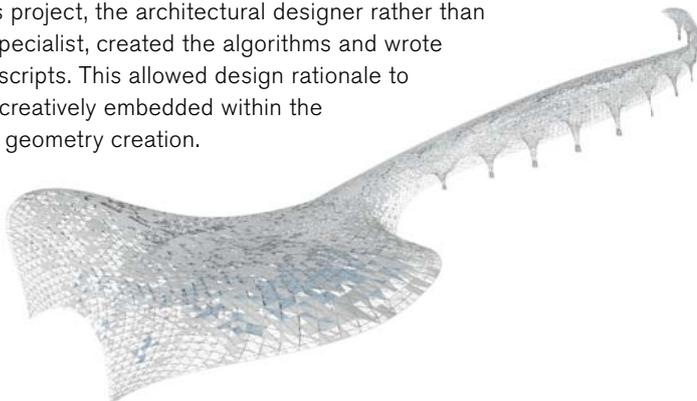
CASE STUDY 1
The Great Canopy, West Kowloon Cultural District

Introduction – The Great Canopy is a key component of Foster + Partners proposal
for the West Kowloon Cultural District. This master plan provides an unprecedented
collection of arts, performance, and leisure venues for Hong Kong. The Great
Canopy unifies the whole development, protects the site, and its gentle flowing
curves complete the waterfront composition providing an interesting counterpoint
to the vertical massing of its surroundings. It is seen as the symbol for the whole
development and as a new icon for Hong Kong. Conceptually, the canopy is a
smooth and seamless surface that gracefully and effortlessly floats over the site.

The Great Canopy – Elevation

The ability to quickly, easily and precisely control the form of the canopy surface
was critical. A single design surface was the starting point; this surface was then
used as a carrier for different component strategies. A series of parametric control
systems and generative scripts were used to create multiple structure and cladding
options. The parameters developed to control the structure and cladding were
driven by performance criteria. This project developed techniques that had been
introduced in previous projects. Computer programming was increasingly used
throughout the project as a tool to develop architectural ideas.
Critically, in this project, the architectural designer rather than
the computer specialist, created the algorithms and wrote
the generative scripts. This allowed design rationale to
be quickly and creatively embedded within the
mechanisms of geometry creation.

The Great Canopy

Design Surface and Form Generation

The height, width, and curvature vary along the length of the canopy, presenting a smooth, undulating form when viewed from both its topside and underside. A system of modular parametric controllers was used to control the complex geometry of the design surface. This modular system could easily be extended if a larger surface was required or if more detail was needed in a specific area. A plan, elevation, and section controller constituted one module.

The design surface was generated in separate surface patches corresponding to the parametric control modules. These surface patches each contained the minimum number of control points required to create the desired curvature characteristics – thus creating smooth, gently flowing surfaces. The parametric system automatically maintained tangency between surface patches; it allowed precise control over one of the most visually critical characteristics of the design surface geometry – its edge condition. Structural rules were built into this system through adjustable parameters controlling the section geometry. This parametric control mechanism produced an overall surface geometry that could be easily manipulated and precisely control. Once developed, this rule-based mechanism provided a flexible and lightweight solution that allowed for the rapid adjustment of the roof surface; this was important as adjustments to the canopy geometry were necessary on a near daily basis until late in the design process.

Though the parametric control mechanism very carefully defined the design surface in terms of visual intent, the top design surface was rebuilt and a new offset bottom surface was created, to embed structural performance criteria into the geometry of the canopy. A parametric section controller was developed to control the relationship of the top surface to a new offset surface. This offset surface defines the structural depth of the canopy. This amount of offset has been tuned to provide optimal stiffness in the areas where it is needed and minimal intrusion in less demanding zones. The variation in structural depth is controlled through the use of 'law curves' which give a simple graphical interface to control complex relationships. The profiles were placed along a sinuous centre line and their spacing related to the structural spacing and cladding module. The parameterisation of the surfaces generated from these profiles inherited this information.

Parametric Section Controller

Design Surface – Parametric Control Mechanism

Structural Spacing and Depth Control

Generating Structure – The Designer as Tool Builder

While many structural strategies were investigated it was determined that a space truss solution was particularly suited to the varying geometry of the canopy. As a modular component-based system, it could be infinitely varied with minimal cost and provided a unifying structural solution that accommodated the varying depths and spans in the head and tail areas. The top surface of the space truss allowed for direct cladding support and minimised the need for secondary steelwork.

The Great Canopy, stretching nearly 1.4 kilometres in length, incorporates a vast quantity of structural and cladding components; a single space truss option contains nearly 200,000 members. As the geometry varies from one end to the other, all these components are potentially different. To draw every single one of these components using standard three-dimensional CAD tools would have taken an impossibly long time, even with a large team. However, the generating rules of these components can be easily defined. These algorithms can be translated into computer programs, which can then be used to generate many structure and canopy options.

Through the use of parametric control mechanisms it is possible to generate and control hundreds of profiles or components; however, by using computer programs to generate geometry the creation of hundreds of thousands of components is possible. While the definition of each algorithm is carefully considered, the geometric results were not always predictable. The effect of the rapid generation of these new geometric constellations of elements was profound. New possibilities and new forms emerged.

The generating scripts were written by an architectural designer. This new approach allowed the definition of new digital tools, freeing the designer from the limited palette of commands available in the standard CAD package. These programmed generative tools were developed as the design progressed and altered on a daily basis. The computer scripts were developed in a fast and fluid way; a method termed 'sketching with code'.

Other team members and consultants quickly realised the potential of this approach and became part of the process of creation of these new tools, embedding their own ideas into the generating code. While the detailed structural investigations were taking place, the geometry of the design surface was still changing. Scripting disengages one design problem from another, allowing the design to be developed in many areas simultaneously. Parametric models can be swapped, input geometry can be modified, variables updated and scripted modules can be inserted or removed without having a large impact on other parts of the process.

The canopy columns were designed to be continuations of the space truss system; both transferring the load of the canopy to the ground, but also appearing to grow out of the ground like trees, becoming the canopy overhead. The columns were generated by a computer script that uses a line marker, top and bottom design surfaces, and a parameter set as input. These line markers were easily moved, angled in different ways, or copied along the canopy to create new column configurations.

Canopy Column
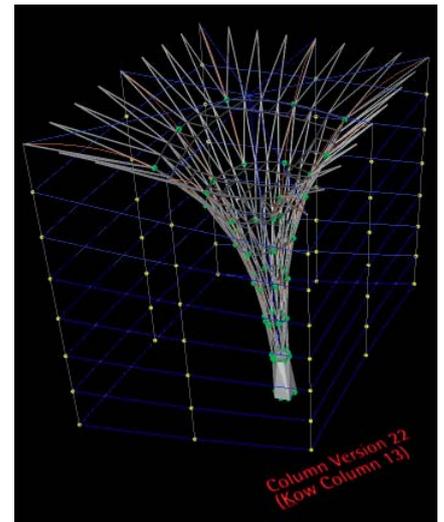
Column Geometry
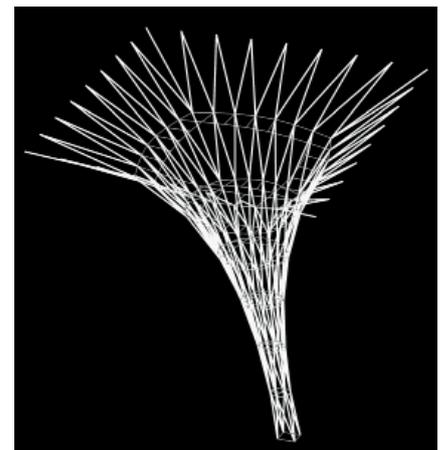
The West Kowloon Cultural District

## Integrating Environmental Performance

The cladding of the canopy is an array of different panels distributed over the supporting structure. The nature of the cladding is seen as an ephemeral cover that 'breathes' and has a distinctive surface pattern that serves to visually break down the scale of the expansive roofscape. Individual panels can be compared to the leaves of a tree, which combine to give a distinctive dappled effect. The canopy acts as a climate modifier to moderate the microclimates of the semi-outdoor spaces underneath. As a climate modifier, the canopy enhances outdoor thermal comfort, minimises solar heat gain, optimises natural cross ventilation, offers protection from rain and wind, and optimises natural lighting.

While structural rules were built into the generating rules of the canopy, the principles that governed the environmental strategy were more complex, and so a different strategy needed to be used. Environmental consultants developed a two-dimensional map locating the different panel types. Six different materials were selected for their ability to respond to the varying functional requirements of the canopy cladding: open trellis, glass, aluminium panels, ETFE cushions, louvers, and specials (i.e. solar thermal collection panels and photovoltaic cells). As it was not necessary to update the environmental analysis with each new canopy option, a loose-fit strategy was developed by which this panel layout could be mapped onto the three dimensional form. The geometry of the cladding components could then be generated from this information.

Digital Fabrication

The computational techniques used to design the roof resulted in a very detailed structure with many components. Just as new techniques were needed to create the digital model, new techniques were necessary to fabricate the physical model. Digital fabrication techniques were used to manufacture the canopy structure and its glazing components. Through this process the canopy could literally be printed in 3D directly from the information produced by the generative scripts. The canopy structure was built using the selective laser sintering process. Because of the size limitations of the process the canopy was produced in seven parts. Glazing components were laser cut from digital files. These parts were carefully assembled by the in-house model shop and combined with a model of the rest of the scheme.
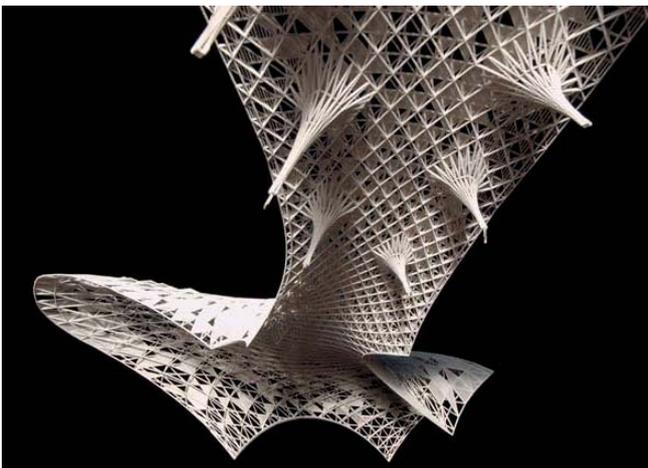
Environmental Strategy Sketch

Six Panel Types
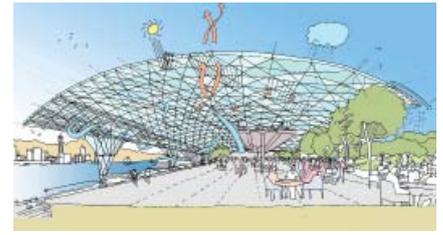
Louvers   Glazing Panels   ETFE Cushions

Rapid Prototyping Model of Canopy

Plan of Panel Types