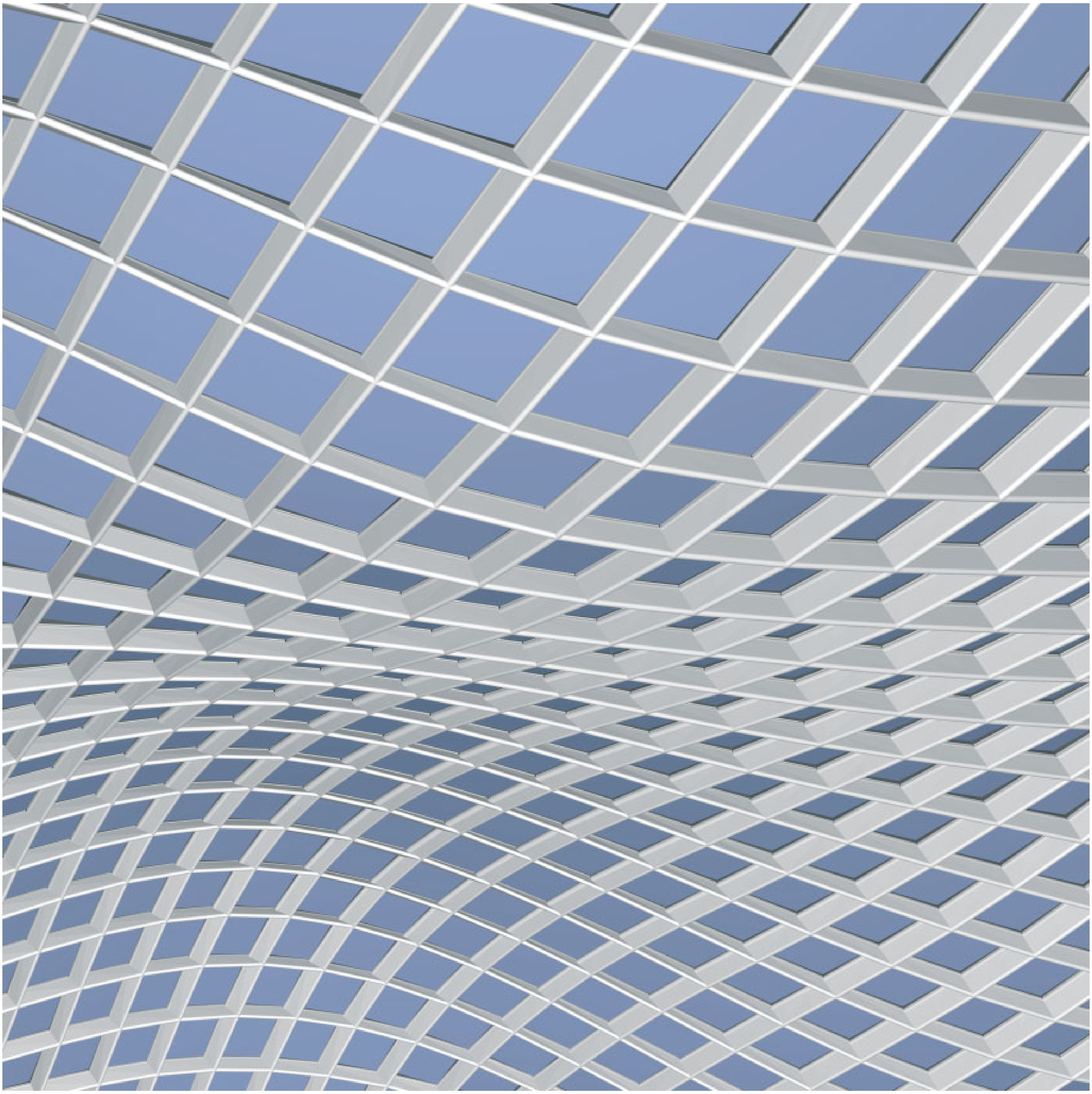
Foster and Partners, Smithsonian Institute Courtyard Enclosure, Washington DC, 2004
Courtyard enclosure roof structure.



Instrumental Geometry

For two decades, the individual members of the SmartGeometry Group have pioneered innovative computer-aided design (CAD) techniques and technologies. Now that they are situated in key positions in internationally renowned companies, the group is involved in developing a new generation of parametric design software. Here, Robert Aish (Director of Research at Bentley Systems), Lars Hesselgren (Director of Research and Development, KPF London), J Parrish (Director of ArupSport) and Hugh Whitehead (Project Director of the Specialist Modelling Group, Foster and Partners, London) discuss with Achim Menges the group's instrumental approach to geometry and their unique collaboration spanning the world of practice and software development.

Geometry has always played a central role in architectural discourse. In recent years, the importance of geometry has been re-emphasised by significant advances in computer-aided design (CAD) and the advent of digital fabrication and performance analysis methods. New design approaches are being developed that will profoundly change the current nature and established hierarchies of architectural practice. The arrival of parametric digital modelling changes digital representations of architectural design from explicit geometric notation to instrumental geometric relationships. Architects are beginning to shift away from primarily designing the specific shape of a building to setting up geometric relationships and principles described through parametric equations that can derive particular design instances as a response to specific variables, expressions, conditional statements and scripts.

Robert Aish, Lars Hesselgren, J Parrish and Hugh Whitehead have been at the forefront of these developments for many years. The formative period for their collaboration, when the intent and methodology of parametric design applied to architecture was established, was the time when all of them were working for, or in collaboration with, YRM in the mid-1980s. There they took Integraph's Vehicle Design System and applied it to pioneering buildings such as the Grimshaw Waterloo International Rail Terminal and the 'Stadium for the Nineties', a project that featured a retractable roof defined through fully associative geometry. Since then, Robert Aish has moved on to become Director of Research at Bentley Systems, where he is responsible for the development of new parametric design software. Lars Hesselgren is Director of Research and Development at KPF London, where he has been involved with many major building projects, most recently the Bishopsgate Tower. Hugh Whitehead leads the Specialist Modelling Group at Foster and Partners that has provided consultancy on such prominent buildings as the Swiss Re Tower, GLA City Hall, the Sage Gateshead and Beijing airport. J Parrish, Director of ArupSport, has contributed to the development of outstanding sports stadiums such as the Sydney Olympic Stadium and the Allianz Arena in Munich. Together they formed the SmartGeometry Group, and here they outline their common views on the aim of the group.

'The objective of the SmartGeometry Group,' says Lars Hesselgren, 'is to create the intellectual foundations for a more profound way of designing. Change can only be additive, not subtractive, so SmartGeometry does not reject or deny existing, more informal or intuitive approaches to design. What SmartGeometry initially set out to achieve was to add to the established skills other complementary formal systems of notation that would allow for the creation and control of more complex geometry. We recognised that architecture, and design in the broadest sense, was critically dependent on geometry, but that a complete geometric tradition of the understanding of descriptive and construct geometry was being lost through lack of use in a bland planar and orthogonal minimalism or, indeed, through misuse by being excessively indulged at the "hyper" fringes of design. Against this background, the objective of the SmartGeometry Group was to reassert an understanding of geometry in design as more than an "experiential commodity". Rather than being wilful and arbitrary, even the most complex geometry could provide a formal resolution of competing forces and requirements. It could suggest and resolve both structural efficiency and environmental sensitivity.'

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He summarises the group's active engagement in building up new skills and techniques for current and future generations of architects: 'The group aims to help create the intellectual environment for further developments in this field that stretch beyond relatively simple geometric mechanisms into more complex approaches to the generation and evaluation of built forms.'

In pursuing an instrumental understanding of geometry, the group identified very early on the limits of 'conventional' CAD concepts that mimic pen and paper with mouse and screen, and constrain the architectural language through libraries of predetermined architectural elements. Robert Aish explains:

'There was a direct mapping between what was thought to be an architectural vocabulary of : "walls, windows and doors" and a simplified computational equivalent. Maybe this was all that could be implemented at the time. But the net result, and disastrous at that, was to entrench this highly limited form of architecture by making it "more efficient" and excluding to architecture based on more general geometry or less conventional components and configurations. What is different with recent parametric design tools is that the set of constructs is far more abstract, but at the same time the system is "extensible", so that it is the designer who can make his own vocabulary of components. We have broken the "hard-coded" naive architectural semantics. We are no longer interested in "local efficiency" within a restrictive CAD system, but rather the designer has the opportunity to define his own vocabulary from first principles, by first understanding the underlying geometric and algebraic abstractions.'

A parametric approach to design has already been in use in the aero, automotive, naval and product design industries. In fact, most related software applications are spin-offs from these industries. All of the SmartGeometry members were users or developers of some of the early parametric software for mechanical engineering and naval architecture. Hugh Whitehead and Robert Aish explain their views on concepts of parametric applications in those fields, comparing them to architecture and outlining the group's strategies for developing a new parametric design application as follows:

'Production industries for the engineering of cars, ships and aircraft are geared to minimise tooling costs by creating a range of standard models from mass-produced custom components. On the other hand, construction industries for the architecture of buildings aim to create one-off custom designs, but with an economy based on the use of standardised components. Of course, this is a simplistic historical view. However, it aims to highlight the different approaches of the two industry sectors. Both achieve a variety of products while exploiting standardisation in different ways to achieve efficiency. The advent of digital fabrication techniques has made possible the concept of "mass customisation", which is blurring this distinction and thereby allowing industries to learn from each other and also to borrow technologies. But the core technology for the shift resides in software engineering.

'The success of a piece of software is about the match or mismatch of assumptions between the software designer and the users. We can say that we all learnt from the assumptions made by the software developers of these other parametric systems for other industries. We learnt about what was transferable to architecture and we learnt what additional functionality would be required if the transition of parametric design to architecture was to be successful. There are two important characteristics of parametric design applied to aircraft or ship design that are not present in terrestrial architecture. The first is that concepts and configurations change relatively slowly. Secondly, a single design, with some minor variations, will be used for a production run of ten, hundreds, or possibly thousands of instances. Therefore, there is the time and resources to invest in the proper "genotype" and ensure that this can support the anticipated variations in the phenotypes. Contrast this with buildings where, in the main, each one is unique. There is no time or need to develop a highly adaptive genotype. There is only one instance so there is no need for a genotype that can support variations in the phenotype.

'There are three exceptions to this statement. First, with a building such as a sports stadium, which is distinctly "rule-based", it may be advantageous to develop a strong genotype the characteristics of which can be refined and shared with successive variants. Second, a building such as the Grimshaw Waterloo International Railway Terminal contains "variation" within a single configuration. In this case, establishing a viable genotype for the characteristic "banana" truss was an essential prerequisite for the design. Third, all design can benefit from refinement. We don't just build the first idea. The intellectual processes of externalisation, generalisation and abstraction that are essential in aircraft or ship design to define the genotype can also benefit a one-off building design. However, the important difference with terrestrial architecture is the rapid exploration of alternative configurations. This requirement for the convenient exploration of alternative configurations adds an important requirement to the functionality of parametric design tools. Thus it seemed to be of prime importance to create a system with great flexibility, particularly in the form and content of "collections".

'Buildings are collections of objects. If the design changes, as it will or should do, then these collections of objects have to respond. The content of the collections will change, and the individual members of the collection also have to respond uniquely to changes in their specific context. If we wish to support a flexible approach to design, then this requires that the concept of flexibility and responsiveness is programmed in from the very initial thoughts about the application, and then this concept has to be consistently implemented. But what this also means is that designers who use this software must understand how to control this type of flexibility, how to think abstractly about design with an "algebra of collections". The question is whether the need to understand and be completely conversant with a formal notation is acceptable to architects and designers. Is it either an essential way to add precision to the expression of design intent or an imposition that distracts from an intuitive sense of design? Historically architecture successfully combined different ways of thinking that spanned both the intuitive and the formal. So there is a strong precedence established. Of late, the formal component has been somewhat lacking, again with notable exceptions. Certainly the emerging architectural practices being started by the new generation of graduates emerging from architectural schools have no inhibitions in moving effortlessly between these two approaches and producing impressive results.'

One of the focal points of the group's work in synergising their individual expertise in a unique collaboration spanning the worlds of practice, research and education is the development of the GenerativeComponents software. All of the group's members contribute in different ways to the evolution of the software, and they are in agreement that 'the specification of GenerativeComponents is intentionally open-ended and generic in order to provide an integrated environment for design and development that is not tied to any specific industry or workflow conventions. It aims to support the evolution of ideas by exposing the language and making this accessible to both designer and developer in a consistent manner at all levels of interaction.'

Robert Aish, who is leading the development of GenerativeComponents as Bentley's Director of Research, more specifically explains the key concepts of this next generation of CAD software:

'We can describe GenerativeComponents as an "object oriented, feature based" modelling system and development environment that represents the convergence of design theory with computational theory. The GenerativeComponents technology is based on the following eight key concepts:

1. Implication: the ability to define "long-chain" associativity of geometric constructs, allowing the implications of change to be explored via automatic change propagation
2. Conditional modelling: the ability to encode and exercise alternative implications allowing changes in behaviour or configuration of the geometric construct
3. Extensibility: the ability to turn parametric models into new reusable components, where behaviour of the component is defined by the original model
4. Components: the transition from digital components representing discrete physical entities to devices for cognitive structuring
5. Replication: the ability to operate on sets of digital components, potentially where each set member can uniquely respond to variations in its context
6. Programmatic design: the ability to combine declarative representations in the form of an implication structure and procedural representations
7. Multiple representations: the ability for the user to simultaneously create and operate on different, complementary, linked representations
8. Transactional model of design: representations are an editable, re-executable design history.

'All software is based on the concept of representation, so what is being represented with GenerativeComponents? Superficially, what the user sees on the screen is geometry that might represent some building or other more general design, but this is not the primary representation. At the next level of depth, GenerativeComponents is explicitly modelling the dependency or other more general relationships between geometry and other nongraphic elements such as variables, expressions, conditional statement and scripts. Again, this is not the primary representation. What is effectively being represented are design decisions or, more correctly, a "transactional" model that allows a sequence of alternative decisions to be constructed, exercised and evaluated. This corresponds to the process of design at its most fundamental.

Parametric design systems are introducing a whole new set of concepts, based on design theory, computational theory and object-oriented software engineering that may be quite unfamiliar to practising designers.

Nonetheless, parametric design systems are introducing a whole new set of concepts, based on design theory, computational theory and object-oriented software engineering that may be quite unfamiliar to practising designers. Yet the intention of GenerativeComponents is to apply these concepts in a way that is directly related and beneficial to the process of design.'

Some of these concepts have already been implemented in practice by members of the group in close collaboration with project-specific design teams. With the aim of exploiting advantages of parametric design processes, new ways of enabling and structuring the development of geometrically complex buildings have been established. Hugh Whitehead explains how such a parametric approach to design has become instrumental for the work of Foster and Partners:

'At Foster and Partners the Specialist Modelling Group provides inhouse consultancy to project teams at all stages from concept design to detailed fabrication. Although we provide tools, techniques and workflow, these are developed in the reverse order. Starting with the formulation of the problem, the first step is to propose an appropriate workflow. Within this frame of reference, suitable techniques are tried and tested in different combinations. The results then form the brief for the development of custom tools that are tested by the design team in a continuing dialogue. Custom tool-building ensures that a rationale becomes an integral part of the design concept. This then allows for the generation and control of more complex building geometries.

'In addition to the Smithsonian Institute project [see overleaf], another interesting example is the Swiss Re building that forced us to address the problem of how to design and produce details that are programmed rather than drawn. At each floor, the rules are always the same, but the results are always different. At the same time, even if every plan, section and elevation could have been drawn, this still would not adequately describe the design intent, even for tender purposes let alone construction. The building stands as a classic example of an associative framework providing a context for adaptive parametric components, so that fabrication follows a consistent dialogue between structural and cladding node geometry. The designer is in charge of the rehearsal, but the contractor is responsible for the performance. We are limited in what we can build by what we are able to communicate. Many of the problems we now face are problems of language rather than technology. The experience of Swiss Re established successful procedures for communicating design through a geometry method statement.

'Complex geometries involve very large parameter sets that are impossible to control by direct manipulation. With buildings like the Beijing airport, which has a double-curved roof that is 3 kilometres long, the approach was to develop control mechanisms that can be driven by law curves. Law curves control "rate of change" and can be geometric as graphs or algebraic as functions. By representing higher derivatives as curves, or even surfaces, complex behaviour can be achieved with simple manipulation.'

Such a parametric and editable approach to design offers a high degree of geometric control combined with the ability to rapidly generate variations. All of the group's members agree that parametric models therefore seem to be particularly versatile in providing the relevant information for digital performance tests. However, the requirements for different analysis methods need to be considered. Whitehead continues:

'Digital performance tests are carried out in collaboration with external consultants. This involves many different software applications and operating systems, but more importantly each requires a different simplified representation of the model as the input to their analysis routines. Structural analysis requires centre lines, thermal analysis requires volumes, acoustic analysis requires simple planes, and daylight analysis requires meshes. The more complex and detailed the model, the more difficult it is to decompose to an appropriate level of simplification. Because of the cost of simplifying or rebuilding models, consultants prefer to engineer a design only when the configuration has become stable. However, when the model is generative, it becomes easier to produce multiple representations, which remain associative to the conceptual framework. This ability allows one to track comparative options and to perform more iteration of the analysis cycles. Consequently, the main impact of such an approach on the practice of architecture is on the decision-making process. Previously the designer had to freeze the early strategic decisions in order to progress to increasing levels of detail. This involved cyclic explorations, but the early decisions can only be challenged if there are both time and resources to rework the downstream details. In a parametric approach, the ability to populate an associative framework with adaptive components allows us to defer the decision-making process until we are ready to evaluate the results.'

Parametric modelling has been understood as instrumental for its ability in improving workflow, its rapid adaptability to changing input and its delivery of precise geometric data for digital fabrication and performance analysis. But while accelerating and extending established design processes, the skills and techniques developed by the SmartGeometry Group do also inherently challenge the way we think about the design of buildings. One may argue that novel aspects in architecture emerge when deeply entrenched typologies, conventions and preconceptions of the organisation and materialisation of the built environment are challenged and rethought by the design team. The SmartGeometry Group envisions their approach to design to become instrumental for such processes of rethinking architecture. Hugh Whitehead explains:

'As of yet, designers use sketches and models to externalise a thought process, in order to provide both focus and stimulus for the development of shared ideas. The use of generative techniques that are editable promotes a higher level of awareness. It encourages all preconceptions to be challenged because they must first be formulated in language.'

Robert Aish concludes by highlighting the group's awareness of the importance of developing a culture of use of generative techniques in parallel to the digital tools themselves:

'In general, there is a shift in many human activities from "doing" to "controlling", involving the development of tools and a "culture of use" of these tools. Design as a discipline emerges from the craft process as a way of abstracting and evaluating alternative possible configurations, usage scenarios and materialisations without actually physically making and testing each possible alternative. Design involves many analogues of the finished artefact that, with varying fidelity, simulate or indicate the anticipated behaviour of the yet to be built result. These analogues, the design medium, introduce representational and manipulation techniques that may be interesting or attractive in their own right, and these may start to influence the resulting physical outcomes. Seen from this perspective, the development of computational design tools, including parametric tools, may not be too different to development of preceding design tools or to the development of tools in general.

'What we need to focus on is the relationship between the development of these tools and the corresponding development of the skills and the culture of use.'

Robert Aish, Bentley Systems, GenerativeComponents Parametric Design Software Development

Design involves both exploration and the resolution of ambiguity. Therefore, it is not sufficient that computational design tools can model a static representation of a design. What is important is that the design tools are able to capture both the underlying design rules from which a range of potential solutions can be explored, and facilitate how this 'solution space' can be refined into a suitable candidate for construction. The question is, how can these design rules be represented and how can this exploration and refinement process be supported? By way of illustration, let us consider the issues involved when a roof, initially based on a doubly curved freeform surface, is required to be constructed from planar components. Here, the designer might want to explore simultaneously two interrelated aspects of the design: alternative surface configurations and alternative penalisation strategies.

To model not just one solution to this problem, but the design rules that can be used to explore alternative solutions, requires a complex 'graph' of 'associative geometry'. The system of geometric relationships illustrated here is quite complex to understand, even when presented with the finished model. It is necessary to imagine how more complex it was to originate the model. Our contention as software developers is that a 3-D geometric representation, while essential, would be insufficient to describe the complex geometric associativities required to present the underlying design rules. So in addition to the standard geometry model (Figure 1) we include a symbolic model (Figure 2) that externalises and presents these relationships in an explicit graphical form. Also represented is a law curve 'controller' (Figure 3) that provides a geometric input at one stage removed from the geometric models and the flat pattern layout of the panels (Figure 4) ready for laser cutting. (In this context, the law curve is controlling the elevation profile of the roof surface, independently of the plan 'S' configuration of the 'spine' curve.)

What variations does this model allow us to explore? a) the poles of the spine curve can be moved in Cartesian space; b) the position of the planes on the spine curve can be moved in 1-D parametric space (along the spine curve); c) the poles of the cross-sectional curves can be moved in the 2-D planar space; d) the number and spacing of the points on the surface can be defined within the surface's 2-D parameter space; e) various alternative 'lacing' options are available to use the points on the surface to populate either planar or nonplanar quadrilateral or triangular panels; and f) the order of the spine curves and cross-sectional curves can be varied. Having defined this process, the designer can then explore variations within the solution space, not in some rigid parametric way, but by using an intuitive process of 'direct manipulation' and 'hand–eye coordination'.

Here, the designer can graphically select and manipulate one of the control points of the law curve model and observe: a) the law curve update; b) the cross-section curves update; c) the surface update; d) the points on the surface update; e) the quadrilateral panels on the surface update; and f) the planar unfolded fabrication model update. The whole process is being intuitively controlled in dynamics with the designer completely in control of the 'form making' process and its materialisation. While these variations are reasonably complex, it should be stressed that they are only the variations that can be explored within this particular logical and geometric configuration. The designer can also change the configuration (by editing the relationships in the symbolic model), which then opens up alternative ranges of variations to be explored.

To arrive at this level of expression and control required that the designer had to be skilled in the logic of design, in order to define and refine the complex system of geometric, algebraic and logical relationships that is the essential foundation of this process. Ultimately, it is this combination of intuition and logic, of ideas and skills, that is of interest.

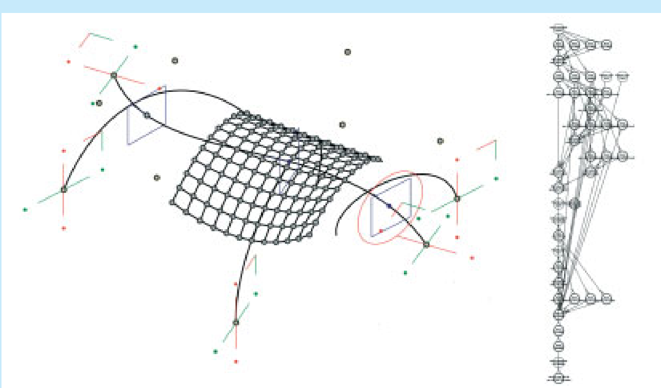


Figure 1 (left): Geometry model. Figure 2 (right): Symbolic model of the same parametric geometry of a double-curved surface.

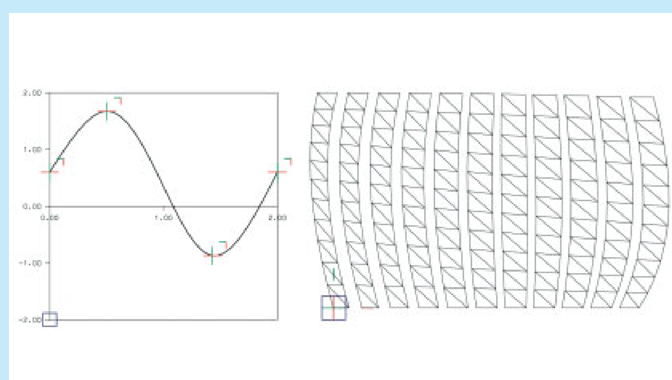


Figure 3 (left): Law curve 'controller' of parametric surface model. Figure 4 (right): Flat pattern layout of its faces.

Hugh Whitehead, Brady Peters and Francis Aish, SMG Foster and Partners, Specialist Modelling Group, Smithsonian Institute Courtyard Enclosure, Washington DC, 2004

In 2004, Foster and Partners won an invited international architecture competition to design a new courtyard enclosure for the Smithsonian Institute's Patent Office building in Washington DC. Early in the project, the Specialist Modelling Group was brought in to advise the project team on modelling techniques, to develop new digital tools, and help solve the complex geometric issues involved. Norman Foster's early sketch shows a diagonal grid of structural elements gently flowing over the central courtyard. The undulating roof structure is supported by eight columns arranged in three domes, the central peak being the highest and having the greatest span.

Instead of simply translating a sketch, capturing design intent involves the development of a digital schematic that can be easily used by the designers to control and manipulate the complex geometry. Design constraints are encoded within a system of associated geometries. Three surfaces, column markers and a computer script control the entire roof geometry. Constraints such as edge beam location, dome heights and drainage locations are informed by the design surface, which is created from a series of simple control lines. The parameterisation of the grid surface sets out the plan locations of the design nodes, while the height location is given by the design surface. The relationship between these surfaces and a third surface controls the beam twist. The set-out geometry performs as a mechanism to control the parameters of a generative script.

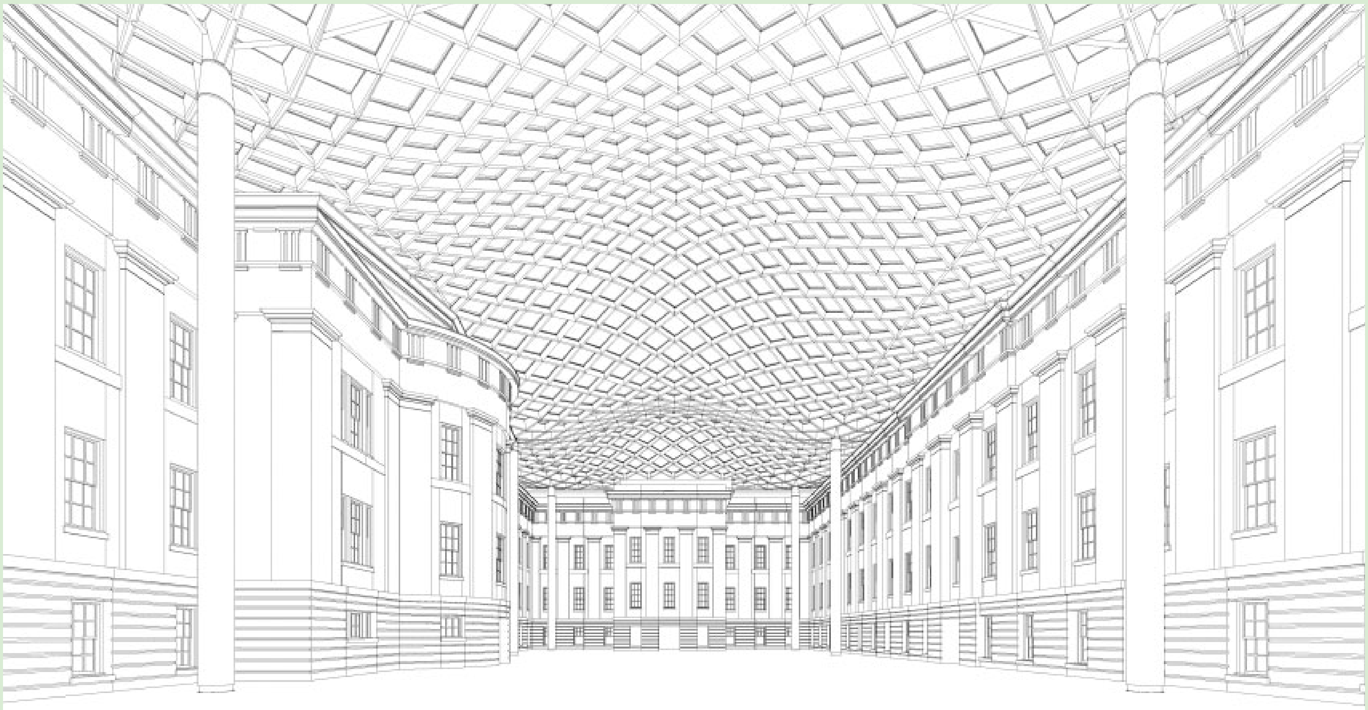
Using the set-out geometry and a set of parameter values, a computer script creates a variety of detailed roof components. The script adapts each component to its local condition and, through a performance evaluation, the components respond to their environment. The use of scripting as a design approach provided many benefits:

1 The simultaneous generation of multiple representations within a single model; a centre-line model for structural analysis; a triangulated flat-panel model for acoustic analysis; a simplified model for hidden line visualisations; lighting node position models; node and beam set-out drawings and spreadsheets; unfolded beams for the digital fabrication of scale models; and a complete model of all roof elements for the creation of drawings by the project team.
2 The independent development of roof configuration and individual component strategies. The roof geometry was free to change without affecting the logic of the beam section or panelisation system. Within the script, different modules of code could be inserted, removed or edited to create new roof options. Using this approach, the long-chain dependencies of a fully associative system did not exist, and modification was simpler and regeneration much faster. When changes were made to the script or to the set-out geometry, a new digital model could be generated rapidly. A dynamically parametric model was not necessary.
3 A computer-generated model gave very precise control over the values and relationships within the roof system. It produced consistent and repeatable results where the design history was saved as a copy of the generating script and the set-out geometry used.

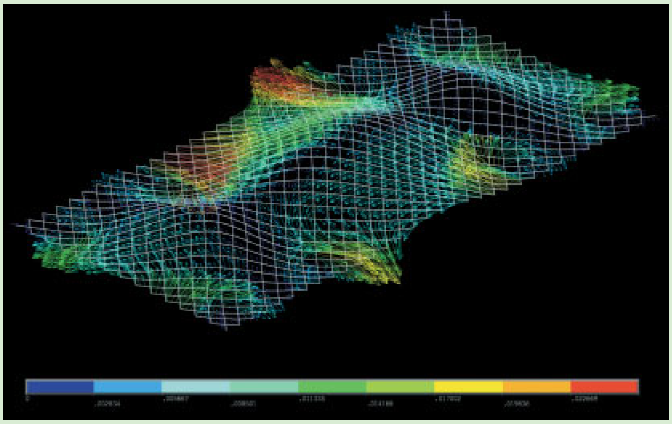
The design evolution involved the use of many different media and techniques and an intense dialogue between a large team and many consultants. The script became a synthesis of all the design ideas and was constantly modified and adapted during the design process. Scripting was used as a sketching tool to test new ideas. This explorative approach required knowledge of both programming and architectural design combined with interpretative skills on many levels. It proved a fast and flexible approach. The final version of this generating code was 5000 lines in length and had 57 parameters – some numeric values and others switch-controlling options. Using only the set-out geometry as input, the script generated approximately 120,000 elements in about 15 seconds; 415 models were generated over six months.

It is possible to generate thousands of different options by using scripting. It therefore becomes increasingly important to not only understand the system constraints, but to have a clear strategy for evaluating the generated options. The design was evaluated by many methods: structural, environmental, acoustic and aesthetic. While there was no attempt to automate the feedback process, it did prove beneficial to work closely with consultants to better understand their data-input needs for their analyses. By building the production of this information into the script, the generation/analysis cycle could be shortened. Working closely with the structural engineers, Buro Happold, reduced the time taken for the generation/analysis loop. As well as creating traditional visualisations and animations, a new technique was employed in which an image set was automatically generated and reviewed for a matrix of options. In parallel, the physical production of digitally fabricated scale models and the production of 1:1 mock-ups was critical to the decision-making process.

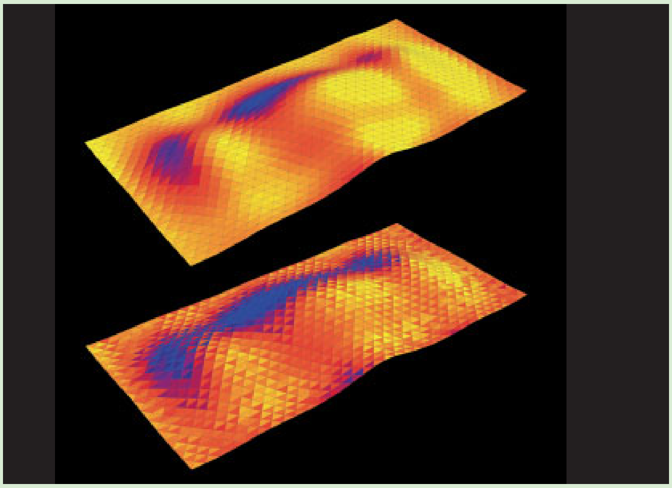
Digital detail of roof beam connection and gutter arrangement (left) of the roof structure (centre left); flat panel solution for glazing panels arrayed on double-curved roof surface (centre right); and related full-scale mock-up of roof beams and glazing built at the Gartner HQ in Gundelfingen, Germany (right).

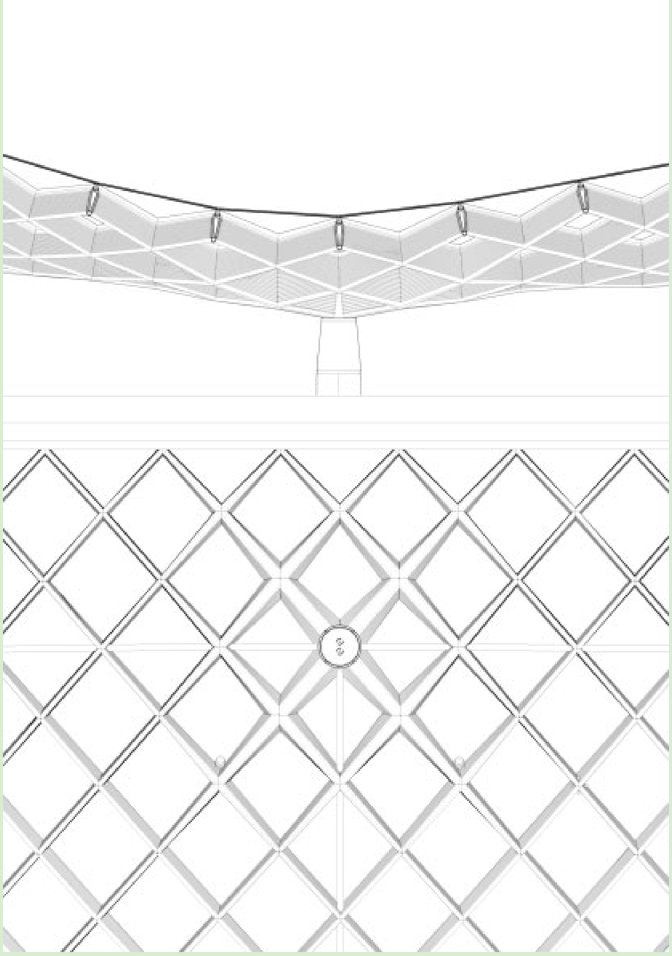


Courtyard enclosure interior study.



Above: Structural analysis of rotational deflections under self-weight.
Below: Analysis of average daily insulation on roof panels without shading device (top) and with shading device (bottom).





Elevation of column and section through roof beams (top) and reflected plan of column and roof beam connection (bottom).

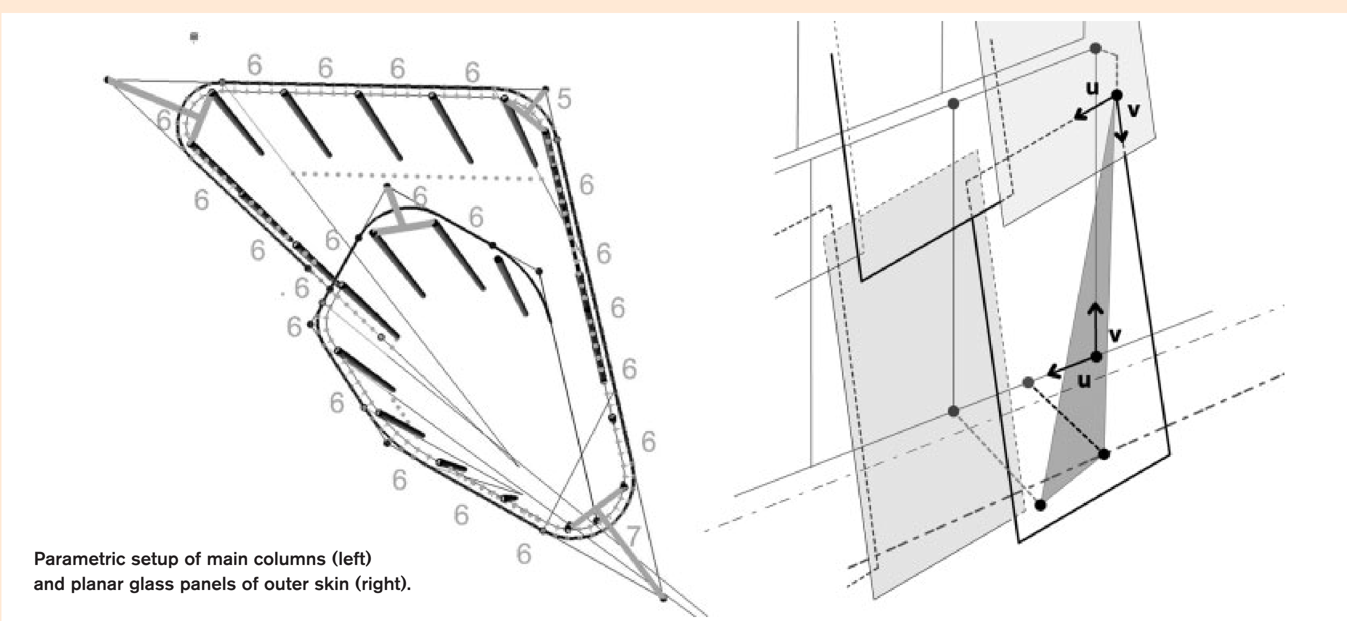
Lars Hesselgren and Stylianos Dritsas, KPF London, Bishopsgate Tower, City of London, 2005

The springing height is horizontal and supports the unique arc, which is tangential at the plane of every planning module vector. Each arc is divided into a harmonic series based on the length of the arc. Each set of points is connected longitudinally, forming the centre-lines of the canopy 'hoops', which are doubly curved in space.

The Bishopsgate Tower project utilises only simple geometry – lines and tangent arcs – in order to facilitate manufacture. The footprint polygon is carefully calibrated to fit the site. The setting out progresses from the root point of the building, and the primary geometry is a set of tapered planes chamfered with sheared cones. The taper on each plane provides the only control mechanism within the geometric system to control the taper of the sheared cones. The helical crown is a solution to the visual problem posed by the viewing of the building from multiple points.

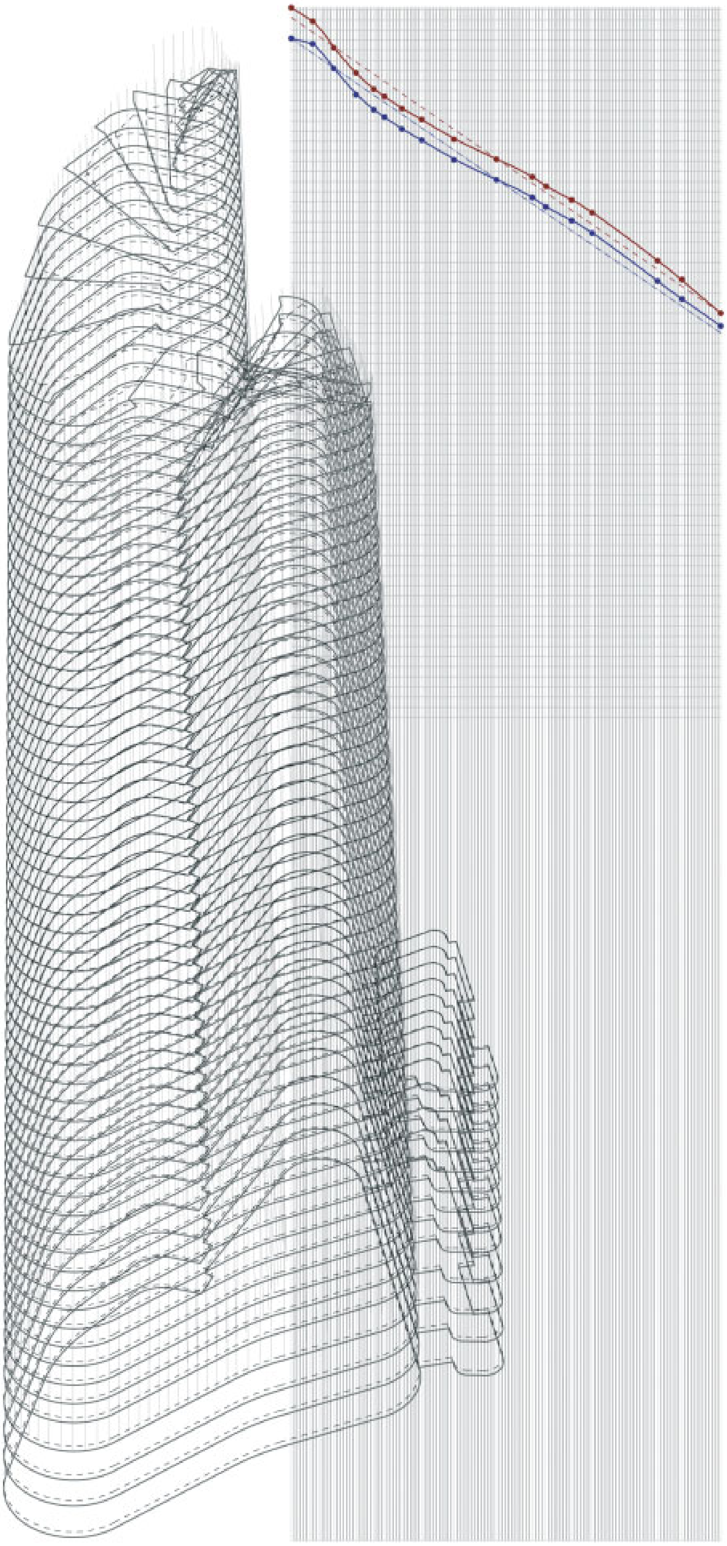
The parametric modelling allowed easy tuning of the exact height of the crown. To achieve natural control of the helical curve in space, a 'normalised graph' was built. The visual verification of the crown results in the curve having a slight 'S' shape. The essential rule for the structural system is that it is offset from the design skin. Each column has its centre-line on a vector that is parallel to the setting-out geometry, with the result that all columns are straight and no column is vertical. The mullions are on a simple module set out linearly from the point of origin and, since the building tapers, the modules are offset, introducing shear in the facade.

To achieve natural ventilation there is an outer glass skin made of flat, planar glass panels of identical size. The panels are tipped in space to create overlaps both in plan and on section, which act as ventilation spaces. The system for establishing correct overlap involved the development of a programmed extension to the parametric system. The selected methodology respects the attitude of a particular panel with respect to its neighbours. The canopy is tangential to the main design surface for aesthetic and aerodynamic reasons. The differing requirements along the canopy length, ranging from near vertical sections to 'peaked hat' lift-up sections for protecting and signalling entrances, is solved by an edge curve driven by two law curves. The springing height is horizontal and supports the unique arc, which is tangential at the plane of every planning module vector. Each arc is divided into a harmonic series based on the length of the arc. Each set of points is connected longitudinally forming the centre-lines of the canopy 'hoops', which are doubly curved in space.

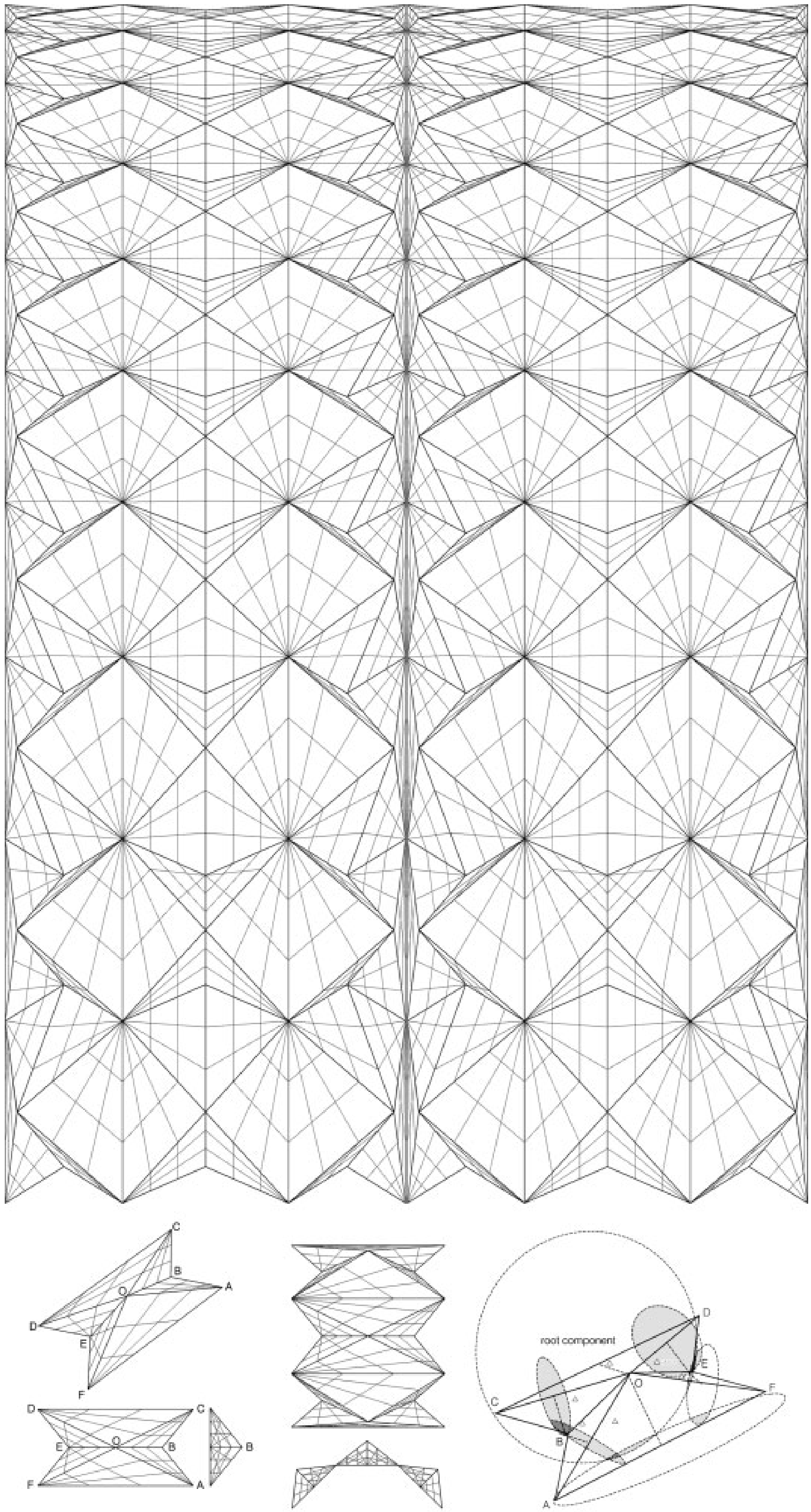


Parametric setup of main columns (left) and planar glass panels of outer skin (right).

Rendered view of digital model (rendering by Cityscape/model by KPF).

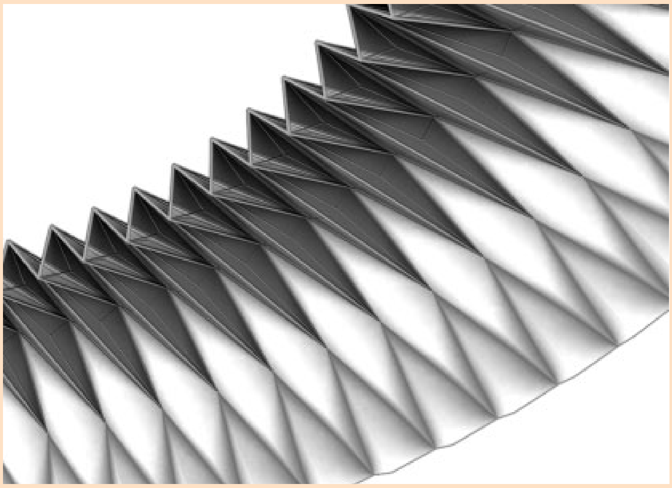


Digital parametric model with control curves.



Parametric model of the folded generative component (bottom), and proliferation of component in one design solution (top).

Digital model of one design solution for a folded-plate roof structure.

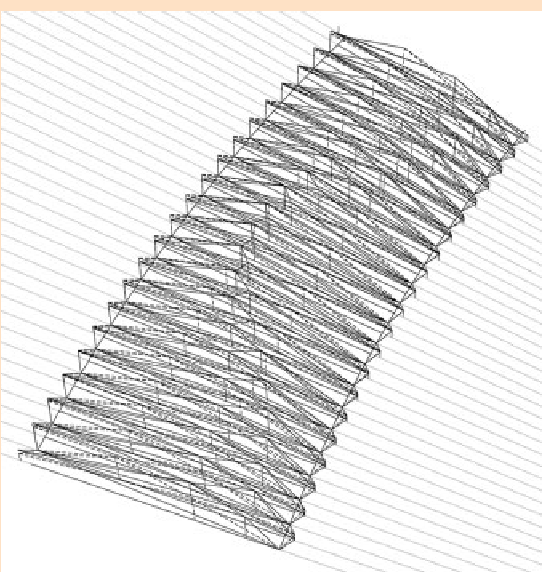


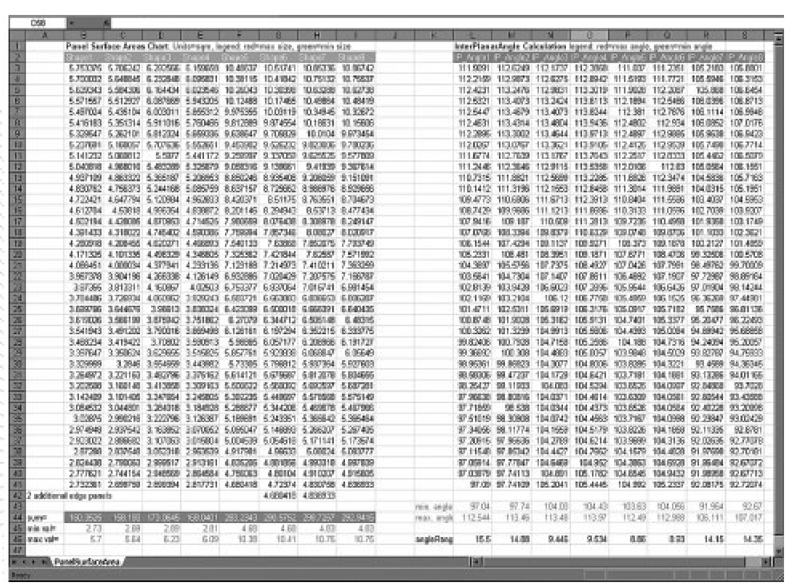
Lars Hesselgren and Neri Oxman, KPF London, Folded-Plate Roof research project, 2005

This project is a research-oriented work in progress. It was designed as a differentiated lightweight folded-plate structure that can be suspended between two masses of a building. The base geometrical plan layout is comprised of two nonconcentric arcs. The total arc length is approximately 100 metres (330 feet), and the span dimensions range from 7 to 16 metres (23 to 52 feet). In such classes of surface-active structures, the structural surfaces can be composed to form mechanisms that redirect forces. Therefore, structural continuity of the elements in two axes (surface resistance against compressive, tensile and shear stresses) is the first prerequisite and first distinction of surface-active structures. Compression and tensile forces are measured as continuous force-flows across the whole length of the structure. These force-flows may differ to quite an extent depending on the way local or regional scale components are assembled.

Differentiation of the regularity of the structure must be carefully studied for its structural, as well as its geometric, implications. A physical origami-like structure maintains its triangular surface-area dimensions when translational and/or rotational operations are applied. Assuming the global geometry of the roof structure was nonuniform in nature, and given that the design required the differentiation of the folded-plate geometry according to structural load, the aim was to construct a digital parametric model that would mimic the behaviour of the physical paper model and could be informed, beyond the geometrical logic of the system, by structural performance.

This folded-plate structure was modelled in Bentley's GenerativeComponents software, creating an environment that supported the adaptive exploration of the design solution. The local-scale component was comprised of six plates connected to one common vertex; all surface areas of the elements were maintained constant when translational and rotational operations were applied. The global-scale model consisted of approximately 400 plates and has, on the other hand, confirmed the doubt that when constrained to the global geometry restrictions posed by the two nonconcentric arcs, the plate surface dimensions will gradually change by a given increment across the longitudinal section of the roof. AD





Parametric model of folded-plate roof project with spreadsheet of digitally derived geometric data.