The Digital Design Process in Contemporary Architectural Practice

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Abstract. *There is an increasing trend in contemporary architectural projects towards dependence upon digital processes for their organisation and technical evaluation of a range of design criteria. Digital representations are central not only to form generation and structural analysis, but also to the integration of fabrication and construction directly with the earlier design stages. It is important to bear in mind, however, that digital technology is only a means to an end which is the design process itself. Each technique of digital representation and analysis brings advantages and disadvantages to this process, and should therefore be described in these terms. It is becoming increasingly feasible to develop a rapid succession of distinct digital models, both geometric and dynamic, in early design stages. These can be tested and evaluated with respect to a range of analytical criteria, and the results of these analyses can affect further model development thus forming a cyclical process of 3-D digital model generation.*

Keywords. *Dynamic modelling, geometric modelling, surface modelling, parametric representation, digital fabrication.*

Introduction

The identification and recognition of a set of digital trends in contemporary architectural is important not only for design practitioners, but also for those of us in design education that aim to reflect contemporary practice in the context of a design curriculum. The particular technologies upon which these trends are based are well-documented, but it is the totality of their use in practice that constitutes a sea-change in the nature of the design process. They involve support for the following activities:

- the technological progression from digitisation to digital sketching (Fatah gen. Schieck, 2004; Szalapaj, 2005)
- the capacity for complex curvilinear form generation (Lee, 1999; Ozener et al., 2004)
- the analysis of digital models using integrated simulation software (Maneesatid and Szalapaj, 2003; Burry et al., 2004)
- the ability to express parametric relationships when needed (Mark, 2003; Williams, 2004; Szalapaj, 2005)
- the rapid prototyping of design models (Modeen, 2003; Sass, 2004; Norman, 2004)

• digital fabrication on an architectural scale (Lindsey, 2001; Maher et al., 2003)

Digital design takes place within office contexts in which many other activities occur. These include non-digital design processes such as physical modelling and sketching, interaction with other design team members, with engineers and environmental specialists, clients and contractors. Design criteria requiring specialist analysis range from innovative structural and constructional systems through to the many environmental issues that need to be resolved. The reality of everyday interactions in design offices is that they are still essentially people-centred activities. A dynamic design environment requires not only the ability to generate digital design information, therefore, but also the knowledge to organise and apply it to the whole process of design.

Case Studies from Design Practice

The Great Court Roof at the British Museum, London (Architects: Norman Foster and Partners; Structural Engineers: Buro Happold)

Figure 1. The Great Court Roof.

The toroidal form of the Great Court roof evolved as a consequence of having to provide a transition from the circular form of a central reading room to the quadrangle of the surrounding museum buildings. A rigorous non-linear computer analysis of the structural form under the differing load patterns was undertaken to tune the design and determine the roof's stiffness and deformed shape. Using parametric modelling techniques, together with a high level of engineering, complex roof forms such as this can be designed, analysed and constructed.

Co-ordinates of nodes on the inner (circular) and outer (rectangular) boundaries were established as fixed points. Intermediate points were represented in terms of parameterised design variables. Loads could be applied to both internal and boundary nodes, and stress parameters could also be associated with these points.

Good practice in the use of form-finding software is first to estimate maximum displacements, and then to rerun the software with the nodes in the displaced position. This will determine whether the predetermined form can support the maximum shape deformation, or whether local high stress points exist, perhaps leading to a collapse of the structure.

Ideally, parametric form-finding software allows users to define form, apply loads, measure dynamic response, check maximum displacements and check the form against those maximum displacements. To meet planning requirements, however, the parametric representation of the roof developed from a stress-defined form to one defined geometrically. This parametric model was then used to determine the actual structural member grid. This was a essentially a shape optimisation procedure in which the values of the optimal roof shape were determined. The advantage of this procedure is that sizing optimisation becomes a by-product of shape optimisation. The roof mesh layout was generated by a series of radial members starting from equally spaced points on the inner circle. These radials were each divided into an equal number of segments. Intermediate members were then defined as connectors between consecutive points on the radials. This process generated the spirals that are a feature of the roof, and ensured that the roof grid ended in nodes along the whole of the perimeter. The final form included a degree of shuffling of members across the surface in order to control glass panel sizes, but the principle for initial generation was the same. The result was a smooth flowing roof that kept to height restrictions, whilst curving over the existing stone porticos in the centre of each of the quadrangle's facades.

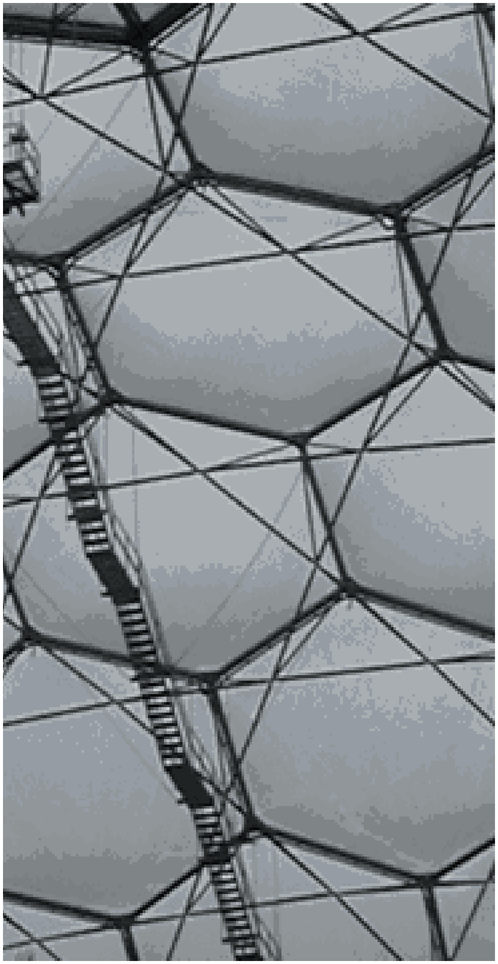

Figure 2. Biome interior, the Eden Project.

The Eden Project, Cornwall, UK (Architects: Nicholas Grimshaw and Partners; Structural Engineers: Anthony Hunt Associates)

Digital ground models based on aerial survey data were used to sculpt the site, and allowed detailed evaluations of cut and fill operations to take place.

A series of intersecting domes of varying diameter (biomes) were developed. Once the size and relative position of the domes was determined, the shape of the site became a secondary consideration. The structural form of the domes could then be confirmed, and the intersections between the superstructure and ground determined the position of foundations and extent of cladding. This enabled the team to proceed with design development of the biome envelope even before the final site survey was complete.

A principal criterion in the clients' brief was to maintain the transparency of the envelope at a maximum. To achieve this, the cladding material had to provide high levels of light transmission, and structural elements had to be kept to minimum size and number.

After a detailed study of various geometrical arrangements for a spherical surface, a geodesic arrangement was selected. By adopting hexagons with pentagonal intersections, an even distribution of structural members was achieved. Varying the frequency of subdivisions in the spherical elements gave rise to optimum cladding panel sizes and light levels. Once the type of cladding and intensity of environmental loads had been established, the design team focused on deriving optimum geometrical arrangements for the spherical structures. The objective was to use the largest cushion possible to maximise light transmission and to minimise cost. Large cushions meant fewer steelwork connections and reduced length of aluminium framing.

The environmental control systems consisted of natural ventilation and blowers. Consequently, the hexagons at the apex of each dome were subdivided into triangles to form opening vents. Air is introduced at the base of the domes via louvered panels in hexagonal openings. These panels also allow the passage of air ducting from the air-handling units through the envelope. To correctly position the blowers within the irregular shapes of the biomes, a dynamic thermal computer analysis was carried out to calculate and visualise the airflows and air temperatures throughout the spaces. The computational fluid dynamics (CFD) analysis produced 3-D graphs showing the speed and direction of the air movement, and the temperature distributions across the spaces.

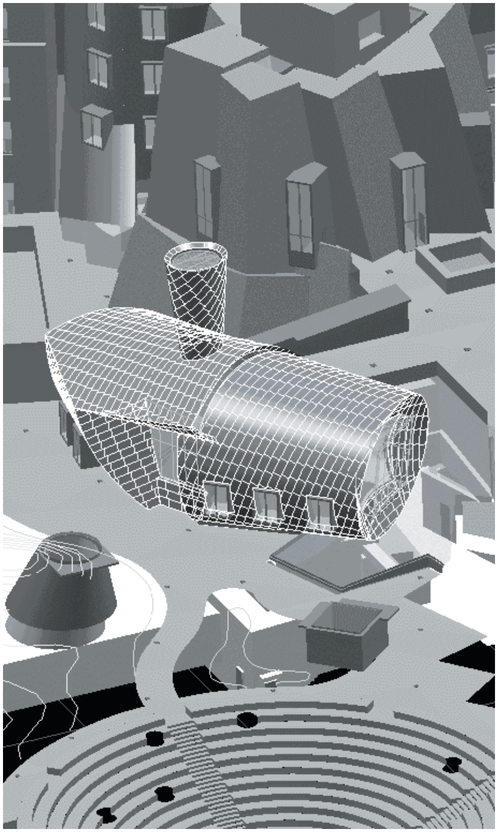

Figure 3. The Stata Center

The Stata Center at MIT (Architects: Gehry Partners, LLP; Structural Engineers: J. A. Martin and Associates)

The brief for the Stata Center was for it to house a number of research laboratories at MIT that facilitated both interdisciplinary and social interaction.

Gehry's design process has been well documented (Gehry, 1999; Lindsey, 2001), and typically begins with consultations with clients, sketching and physical modelling. When a proposal is ready to be taken further, the corresponding physical model (often made from polystyrene) is digitised in 3-D, and then further developed as a digital model.

Suggestions for more direct methods of digital sketching, exploiting the customisation of graphical input devices, have been made (Szalapaj, 2005). Customisation allows users to associate meanings with data that has been digitally captured. The idea of digital sketch modelling, in which the role of digital techniques is to support and preserve key sketch design ideas as they evolve and develop, is an important research issue.

Value engineering is a process of rationalisation used in Gehry's office in order to reduce costs, but only comes into play once the design work is complete. It can affect the building programme, the quality of the architecture, or its complexity. It is used to rationalise form relative to cost, taking into account complexity, material, and structure. According to Lindsey:

The process involves translating the architectural elements, skin panels, beams, columns, etc., into the following hierarchy: straight, flat, curved, doubly curved, and warped (highly shaped), each representing a higher cost. The translation continues through the following syntax: repetitive, similar, and unique, again each representing a higher cost of manufacture and assembly. (Lindsey, 2001)

Gaussian analysis is used in Frank Gehry's office to evaluate the degree of compound curvature of building components, particularly surface panels and skins. Curvature equations are used to calculate the rates of change of surface tangents to normal lines at each point on any given surface. Degrees of curvature along with the properties of materials, are represented as 3-D surface models allowing problem areas to be identified. Colour coded digital models can indicate the bending limitations of materials used on a scheme (op.cit.). Gaussian analysis may indicate that material curvature is within tolerance limits, but expensive to fabricate. Cost optimisation often involves moves towards the use of developable surfaces i.e. those that can be made by folding or bending flat surfaces.

From Digitisation to Digital Sketching

Increasingly, architectural practices are using digital techniques and representations for more than just their visualisation potential. Developments in digital sketching technology, combined with the direct manipulation of 3-D digital models, represent an important contemporary trend in the digital input of design schemes. Immediacy of digital sketch modelling is achieved at the expense of technical detail and textural information so that spatial design concepts become the focus of attention. The translation of sketches to a digital format is a process that may need to be repeated several times if the design changes. Designers need tools that give them the freedom to sketch rough design ideas quickly, the ability to test designs by interacting with them, and the flexibility to fill in the design details as choices are made.

Current applications do not fully exploit multidimensional graphical input devices. Means for their integration with modelling sytems are presently still missing, but when developed will bring new design possibilities. Offices such as those of Frank Gehry are developing their own strategies for integrated design, in which new types of graphical input device are incorporated into creative software environments. These imprecise and intuitive forms of digital input all aim to support and stimulate designers' creativity. The emphasis is on expression and communication allowing fast exploration of multiple design solutions. Digital sketch design environments, therefore, rather than simply being drafting accessories which are used after designs have been developed (much as conventional CAD systems are used), will instead become widespread working tools for the creation of early stage design proposals.

Curvilinear Form Generation

In the case of form generation, curved forms are increasingly feasible provided digital data can be exchanged with fabricators and contractors thus minimising cost overruns. NURBS curves and surfaces are increasingly being used for the representation of geometries such as conics and free-form shapes. However, anyone who has modelled with NURBS will be aware that complex forms made up of many NURBS components often have to be fixed to avoid holes and gaps between surfaces. This stymies the expression of parametric relationships between disparate surfaces. Furthermore, digital operations on NURBS objects, such composition, intersection and projection do not necessarily result in NURBS objects. All such issues distract from focusing on design interactions in order to resolve technical problems. This is just one example of how digital designers need to maintain a critical outlook whilst keeping an eye on new developments in modelling technology. Generalisations of NURBS such as T-splines and T-NURCCs can potentially overcome some of the problems in this particular case (Sederberg et al., 2003).

The Analysis of Digital Models

Progress has been made in integrating the digital representations of a range of dynamic processes with mainstream geometric modelling techniques that form the basis of CAD systems. Analyses based upon the mathematical techniques of computational fluid dynamics (CFD) and finite element analysis (FEA) attempt to capture architecturally significant dynamic processes such as energy transfer, structural and lighting effects, and movements of air and sound. Simulation software has traditionally been numerically based, with awkward and counterintuitive methods of interaction that have prevented their widespread use in the initial stages of the design process. They have had limited application as tools for validating finalised design schemes. Contemporary developments in graphical user-interfaces, however, are making environmental analysis software more accessible to designers. Systems such as Ecotect (energy analysis based on the admittance method, combined with lighting, solar shading, acoustics and cost analysis) have been developed to provide visual feedback at conceptual design stages (Marsh, 1997). Current versions of Radiance (lighting analysis based on ray tracing algorithms) are more graphically oriented than their precursors (Ward, 1994).

Knowing when to Express Parametric Relationships

Particular stages of the design process require the expression of relationships between interconnected and dependent parts of proposed design schemes. Parts may intersect and overlap, giving rise to a requirement for some form of digital co-ordination. In software terms, such relationships can be represented in terms of parametric expressions between objects. These expressions typically encapsulate mathematical and geometric constraints between objects, which can either be used as functions to check the effects of design changes, or, in their more automated form, to generate new forms by propagating local changes throughout digital models. Parametric modelling techniques, therefore, can be used to integrate the development of design schemes, rather than modelling components separately and individually. The parametric framework is substantially different from conventional CAD modelling approaches, requiring less effort on re-modelling and the maintenance of consistency.

The most useful role of parametric representations in the design process appears to be in supporting generic descriptions of design solutions, but these in turn are only really useful once designs have been clarified to provide concise descriptions of solution sets. The development of architectural form in the real world is still very much concerned with the resolution of functional issues, whilst taking into account structural and constructional problems and the limitations of materials. It is in these areas that CAD is beginning to play an increasingly important and integrative role, particularly in the relationships between design and engineering. A graphically interactive parametric modelling system should support designers in their creation of digital models, as well as in their ability to express constraints between key component parts. To maintain a holistic view of design development, it is important that digital modelling technologies should assist designers in the generation of architectural forms in intuitive and interactive ways.

Rapid Prototyping of Design Models

Rapid prototyping technology allows designers to create rough design models through what is essentially a digital sketch modelling process. Digitally produced prototypes can form the basis for later fabrication processes. There is nothing intrinsically new about the desire to build with prefabricated components. The structural system on the Eden project was simple, using hexagonal components as the primary structural elements. Geodesic forms are particularly suited to the fabrication of modular components that map onto their geometries. Digital support is needed for the development and refinement of the structural system. The continual redevelopment requires analysis of structural and loading characteristics, as well as analysis of relationships between structural materials. The structural analysis calculations in turn are often carried out using finite-element methods. Once a structural solution has been reached, the integrative power of digital modelling technology can simulate the assembly and construction of a multitude of modular components.

Digital Fabrication on an Architectural Scale

If component parts are more varied in their geometries, then once structural and cladding systems have been determined, techniques are needed to ensure that components are capable of being manufactured, with minimal fabrication costs. Fabricated components often have degrees of complexity that can only be resolved through 3-D digital representation. The decomposition of complex curved surfaces into developable surfaces, for example, provides a technique for the representation of surfaces such that parts can be fabricated and then joined together to form whole facades. CNC plasma cutting tools can be used to cut curved structural members. Computer-controlled rolling machines can be used to bend steel, and computer-controlled welding machines can assemble steel components. The placement and alignment of parts on site is often carried out with laser positioning and surveying equipment, thereby extending the digital process into the construction process.

Conclusions

The constraints of design practice invariably affect the role of digital techniques in individual offices. The case studies highlight ways in which digital technologies serve to maintain the design vision of particular office practices. They are an important means to an even more important end, and never an end in themselves. The digital customisation of office practice can be achieved by configuring digital environments in ways appropriate to the design philosophies associated with particular offices.

Significant developments in environmental simulation technology include improved methods of user-interaction, and the realistic simulation of specific environmental phenomena. In design, improved integration is needed not only between various environmental factors, but also between modelling and analysis. The use of environmental analysis and simulation is an increasingly essential feature at both conceptual and detail design stages. Changes in structural form and topology require corresponding re-evaluations of environmental criteria. The downfall of all simulation-based methods, however, has always been that users cannot easily design-in desired behaviours, making simulations unpredictable and not easily targeted at desired environmental goals. Evidence is emerging from computer animation disciplines that control of simulations may indeed be possible (Treuille et al., 2003; Guendelman et al., 2003, James and Fatahalian, 2003). If such techniques can be incorporated into environmental analysis software, then this would enable designers to have interactive control of detailed environmental features at the design stage.

The increasing trend towards digital construction processes has implications for responsibility and liability and the roles of professional organisations in general. Project management, new procurement practices and competitive tendering all have an impact on the organisation of office practice and consequently on the role of digital technology. A greater awareness of the design and construction possibilities of digital representations makes it possible for design practices to customise their own interactions with digital technologies without compromising the integrity of individual offices. Digital technology has reached a level of embeddedness in some architectural practices at which it is possible and feasible for designers to express design intentions directly without being distracted from the design vision of the project. Distractions in the past have been caused by the limitations of digital representations in their capacity to model form, in their prescriptive structuring of design information, and in the deficiencies of the human-computer interface. The extension of modelling techniques to a wider range of geometries has coincided with improvements in graphical user-interfaces, leading to more expressive modelling and visualisation environments. A further important lesson that emerges in particular from the Great Court roof project is the value of iterative design, in which design prototypes are successively created and evaluated. Iterative design techniques seem to be more valuable as the number of iterations made during a project becomes larger. It is important to iterate quickly in the early part of the design process because that is when radically different ideas can and should be generated and examined. In complex structural forms, the modelling process might start from an initial coarse definition of topology, but with some control of surface curvature. The process from then on is one of gradual refinement, increasing mesh densities until sufficient accuracy for fabrication is reached. During parametric processes, therefore, topologies can change constantly.

The issue of prescriptiveness has also been addressed. Contemporary digital design processes support user-defined modularity without the need to conform to common, pre-defined model structures. Libraries of prescribed components are as outmoded within CAD systems as they are in fabrication technology. Fabricators and contractors now receive digital data directly from design offices instead of having to interpret conventionally produced design drawings. The combination of these phenomena is leading to a digital revolution in both office and construction practice. The onus is on us to reflect these phenomena in design education.

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