ARCHITECTURE IN THE DIGITAL AGE · DESIGN AND MANUFACTURING

EDITED BY BRANKO KOLAREVIC

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ACKNOWLEDGMENTS

PREFACE

This book addresses contemporary architectural practice in which digital technologies are radically changing how the buildings are conceived, designed, and produced. It discusses these digitally-driven changes, their origins, and their effects, by grounding them in actual practices already taking place, while simultaneously speculating about their wider implications for the future. In that sense, the book is as much about the present (in which the digital is in the foreground) as it is about the future (in which the digital will be in the background).

The basic argument is that the digital age is forging a very different kind of architecture and, at the same time, providing unprecedented opportunities for the significant redefinition of the architect's role in the production of buildings. Digital technologies are enabling a direct correlation between what can be designed and what can be built, thus bringing to the forefront the issue of the significance of *information,* i.e. the issues of production, communication, application, and control of information in the building industry. By integrating design, analysis, manufacture, and the assembly of buildings around digital technologies, architects, engineers and builders have an opportunity to fundamentally redefine the relationships between conception and production. The currently separate professional realms of architecture, engineering, and construction can be integrated into a relatively seamless digital collaborative enterprise, in which architects could play a central role as *information master builders,* the twenty-first century version of the architects' medieval predecessors.

One of the most profound aspects of contemporary architecture is not the rediscovery of complex curving forms, but the newfound ability to generate construction information *directly* from design information through the new processes and techniques of digital design and production. The projects discussed in the book offer snapshots of emerging ideas and examples of cutting-edge practices. They should be seen as bellwethers of the current digital evolution in architecture and as harbingers of its post-digital future.

The contents of this book emerged out of the symposium on "Designing and manufacturing architecture in the digital age," held at the University of Pennsylvania in March 2002. That event brought together some of the leading individuals from very different realms, with the aim of providing informed views of what is seen as a critical juncture in architecture's evolving relationship to its wider cultural and technological context. The contributors to this book offer a diverse set of ideas as to what is relevant today and what will be relevant tomorrow for emerging architectural practices of the digital age.

1
INTRODUCTION

BRANKO KOLAREVIC
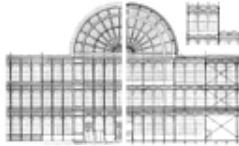
1.1. *Crystal Palace* (1851), London, UK, architect Joseph Paxton: section.
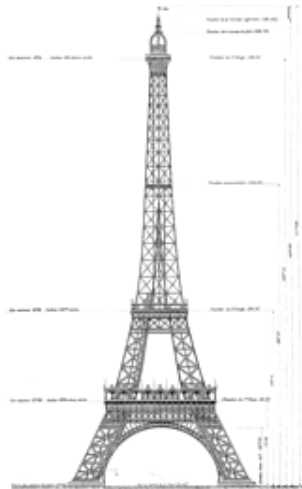
1.2. *Eiffel Tower* (1887), Paris, France, architect Gustave Eiffel: elevation.
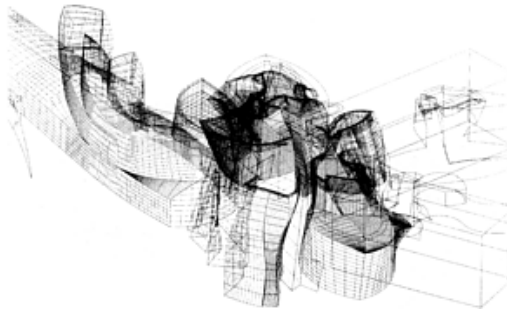
1.3 *Guggenheim Museum* (1997), Bilbao, spain, architect Frank Gehry: the digital model.

> Having abandoned the discourse of style, the architecture of modern times is characterized by its capacity to take advantage of the specific achievements of that same modernity: the innovations offered it by present-day science and technology. The relationship between new technology and new architecture even comprises a fundamental datum of what are referred to as avant-garde architectures, so fundamental as to constitute a dominant albeit diffuse motif in the figuration of new architectures.

> —Ignasi de Sola Morales[1]

Joseph Paxton's *Crystal Palace* (figure 1.1) was a bold building for its time, embodying the technological spirit of the Industrial Age and heralding a future of steel and glass buildings. Gustave Eiffel's *Tower* in Paris manifested the soaring heights that new buildings could reach. It then took another 100 years for the glass and steel buildings to become ubiquitous worldwide, with gleaming skyscrapers part of every metropolis' skyline.

The first Crystal Palaces and Eiffel Towers of the new Information Age have just been built over the past few years. Frank Gehry's *Guggenheim Museum* in Bilbao (figure 1.3) is probably the best known example that captures the zeitgeist of the digital information revolution, whose consequences for the building industry are likely to be on a scale similar to those of the industrial revolution: the Information Age, just like the Industrial Age before, is challenging not only how we design buildings, but also how we manufacture and construct them.

Digital technologies are changing architectural practices in ways that few were able to anticipate just a decade ago. In the conceptual realm, computational, digital architectures of topological, non-Euclidean geometric space, kinetic and dynamic systems, and genetic algorithms, are supplanting technological architectures. Digitally-driven design processes, characterized by dynamic, open-ended and unpredictable but consistent transformations of three-dimensional structures, are giving rise to new architectonic possibilities. The generative and creative potential of digital media, together with manufacturing advances already attained in automotive, aerospace and shipbuilding industries, is opening up new dimensions in architectural design. The implications are vast, as "architecture is recasting itself, becoming in part an experimental-investigation of topological geometries, partly a computational orchestration of robotic material production and partly a generative, kinematic sculpting of space," as observed by Peter Zellner in *Hybrid Space*.[2]

It is only within the last few years that the advances in computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies have started to have an impact on building design and construction practices. They opened up new opportunities by allowing production and construction of very complex forms that were, until recently, very difficult and expensive to design, produce and assemble using traditional construction technologies. A new digital continuum, a direct link from design through to construction, is established through digital technologies. The consequences will be profound, as new digitally-driven processes of design, fabrication and construction are increasingly challenging the historic relationship between architecture and its means of production.

New digital architectures are emerging from the digital revolution, architectures that have found their expression in highly complex, curvilinear forms that will gradually enter

the mainstream of architectural practice in the coming years. The plural (architectures) is intentional, to imply the *multiplicity* of approaches—in fact, no monolithic movement exists among the digital avant-garde in architecture. What unites digital architects, designers and thinkers is not a desire to "blobify" all and everything, but the use of digital technology as an enabling apparatus that directly integrates conception and production in ways that are unprecedented since the medieval times of master builders.

FROM LEIBNIZ TO DELEUZE

Contemporary approaches to architectural design are digitally enabled and digitally driven, but are also influenced and informed by the writings of theorists and philosophers, ranging from the German philosopher, mathematician and logician Gottfried Wilhelm Leibniz (1646–1716) to Gilles Deleuze (1925–1995), one of the most influential French thinkers of the twentieth century. It was Deleuze who demonstrated that there are a thousand "plateaus" (mille plateaux),[3] a multiplicity of positions from which different provisional constructions can be created, in essentially a non-linear manner, meaning that the reality and events are not organized along continuous threads, in orderly succession. Such positions were eagerly adopted by a number of contemporary avant-garde architects to challenge the pervasive linear causality of design thinking.

In his essay on "Architectural Curvilinearity,"[4] published in 1993, Greg Lynn offers examples of new approaches to design that move away from the deconstructivism's "logic of conflict and contradiction" to develop a "more fluid logic of connectivity." This new fluidity of connectivity is manifested through "folding," a design strategy that departs from Euclidean geometry of discrete volumes represented in Cartesian space, and employs topological conception of form and the "rubber-sheet" geometry of continuous curves and surfaces as its ultimate expression.

Folding is one of the many terms and concepts, such as *affiliation, smooth* and *striated space, pliancy,* and *multiplicity,* appropriated from Deleuze's work *The Fold.*[5] Deleuze's writing, aimed at describing baroque aesthetic and thought, reintroduced fold as an ambiguous spatial construct, as a figure and non-figure, an organization and non-organization, which, as a formal metaphor, has led to smooth surfaces and transitional spaces between the interior and the exterior, the building and its site. The fold, or *le pli,* as defined by Deleuze, posits a post-structuralist notion of space "made up of platforms, fissures, folds, infills, surfaces and depths that completely dislocate our spatial experience." The effect of folding is a new distinctive architecture of formlessness that questions existing notions of built space, its aesthetics, and utility.

FROM BAROQUE TO GEHRY

Digitally-generated forms evolve in complex ways and their freeform surfaces curve complexly as well. As exceptions to the norm—as formal transgressions challenging the omnipresent, fundamentally rectilinear conventions—these new forms raise profound and necessary questions of an aesthetic, psychological and social nature.

The contemporary digital architectures appear to reject any notion of urban and structural typology, continuity and morphology, and historic style and perspectival framework—they represent an ideological, conceptual and formal break much like Walter Gropius's *Bauhaus* in Dessau, Germany. They seem to prefigure an entirely new way of architectural thinking, one that ignores conventions of style or aesthetics altogether in favor of continuous experimentation based on digital generation and transformation of forms that respond to complex contextual or functional influences, both static and dynamic. The new digital architectures might be non-typological, discontinuous, amorphous, non-perspectival, ahistoric… But they are not without a precedent.

Since Baroque, architects have been trying to go beyond the Cartesian grid and the established norms of beauty and proportion in architecture. The parallels between contemporary and Baroque thought are indeed multiple, as contemporary reading of Deleuze's Fold shows, leading to labels such as "Neo-Baroque" being applied to new architectures.

The biomorphic forms are, of course, not new, from the excesses of Baroque to organic design vocabularies of the early- and mid-twentieth century. At a purely formal level, the precedents abound. Rafael Moneo speaks of "forgotten geometries lost to us because of the difficulties of their representation."[6] The forms of Gehry's recent projects could be traced to the Expressionism of the 1920s; one could argue that there are ample precedents for Greg Lynn's "blobs" in Surrealism. Earlier precedents could be found in the organic, biomorphic forms of Art Nouveau or, more specifically, in the sinuous curvilinear lines of Hector Guimard's Metro Stations in Paris. And then there is Gaudi's oeuvre of highly sculptural buildings with complex, organic geometric forms rigorously engineered through his own invented method of modeling catenary curves by suspending linked chains.

1.4 *Einsteinturm* (1921), Potsdam, Germany, architect Erich Mendelsohn.

There is a range of expressive precedents from the early 1920s onwards, from Erich Mendelsohn's *Einsteinturm* in Potsdam, Germany (1921, figure 1.4), to Le Corbusier's *Chapel at Ronchamp* (1955, figure 1.5) and Eero Saarinen's *TWA Terminal* in New York (1962, figure 1.6). It is worth remembering that it was Le Corbusier's "free plan" and "free façade" that allowed for elements of variable curvature to emerge in the modernist projects of the mid-twentieth century. Eero Saarinen attributed the reemergence of the plastic form to the advances in building technology, while acknowledging that "it is the aesthetic reasons which are [the] driving forces behind its use."[7] Alvar Aalto broke with the pristine

geometries of the International Style fairly early, applying sinuous curves to his designs from furniture and glassware to buildings. His *Finnish Pavilion* at the 1939 World's Fair in New York (figure 1.7), one of his best known projects, featured dramatic undulating curves in the interior of a modest, rectilinear shell.

1.5 *Chapel at Ronchamp* (1955), architect Le Corbusier.

It is interesting to note that Saarinen is rather cautious in his use of plastic form, implying that it has a rather limited applicability, and warning that the "plastic form for its own sake, even when very virile, does not seem to come off."[8] Saarinen's cautious approach to plastic form is exemplary of the apparent ambivalence of the modernists towards the curvilinear, an attitude that is still widely present. While it enabled them to break the monotony of the orthogonal and the linear, it also heralded the emergence of a new unknown geometry, about which they were still not sure, as noted by Bernard Cache;[9] the modernists "knew

1.6. *TWA Terminal* (1962), New York, architect Eero Saarinen.

that they had, above all, to avoid two opposite pitfalls: a dissolution into the indefinite and a return to the representation of natural form,"[10] the former manifested in "the loss of form," and the latter in "the organicist maze into which art nouveau had fallen."[11]

The utopian designs of the architectural avant-garde of the 1960s and early 1970s brought a certain state of formlessness, which, in strange ways, resembles the contemporary condition, as observed by Peter Zellner in 2001.[12] It was Reyner Banham's seminal book on *Theory and Design in the First Machine Age*[13] that provided a significant

ideological shift which led to the emergence of various groups and movements, such as Archigram, Metabolism, Superstudio, etc. Archigram's "soft cities," robotic metaphors and quasi-organic urban landscapes were images of fantasies based on mechanics and pop culture. Expanding on Buckminster Fuller's work, pop designers were creating "blobby" shapes throughout the 1960s and 1970s; "formable" materials, such as plastics, and concrete to a lesser extent, inspired a free and often unrestrained treatment of form. More importantly, the works of these architects, designers and thinkers offered a new interpretation of technology's place in culture and practice, transgressing the norms of beauty and function. Archigram, for example, explored in projects, such as *Plug-in City, Living Pod* and *Instant City,* the continuity of change and choice afforded by new technologies, going beyond the superficial appearance of novel forms.

As was the case in the past, the contemporary digital architectures find their legitimization in their exploitation of the latest technological advances, new digital means of conception and production, and the corresponding aesthetic of complex, curvilinear surfaces. As a manifestation of new information-driven processes that are transforming cultures, societies and economies on a global scale, they are seen as a logical and inevitable product of the digital zeitgeist.

1.7. *Finnish Pavilion* at the 1939 World's Fair in New York, architect Alvar Aalto.

SMOOTH ARCHITECTURES

The use of digital media by avant-garde practices is profoundly challenging the traditional processes of design and construction, but for many architects, trained in the certainties of the Euclidean geometry, the emergence of curvilinear forms poses considerable difficulties. In the absence of an appropriate aesthetic theory, the "hypersurface" forms (a term coined by Stephen Perrella[14]) often seem to be utterly esoteric and spatially difficult to comprehend, and are often dismissed as just another architectural "fad."

What is often overlooked is that these new "smooth" architectures are tied intrinsically to a broader cultural and design discourse. Rounded contours have been omnipresent in our lives for a good part of the past decade, from toothbrushes, toasters, and computers to cars and planes (figures 1.8–1.10); somehow, perhaps in the absence of a convincing

framework, the curves were widely ignored by the architectural culture until a few years ago. This formal ignorance of wider design trends also stems from yet another ignorance—the technological one—of three-dimensional digital modeling software that made the smooth curves easily attainable by industrial designers, who used them widely on everything from consumer products to airplanes. Historically, the building industry was among the last to change and adopt new technologies; CATIA (Computer Aided Three-dimensional Interactive Application) had been in use for 20 years before it was discovered by Gehry's office (and is currently used by very few design offices).

Why this sudden interest and fascination with "blobby" forms? Three-dimensional digital modeling software based on NURBS (Non-Uniform Rational B-Splines), i.e. parametric curves and surfaces, has opened a universe of complex forms that were, until the appearance of CAD/CAM technologies, very difficult to conceive, develop and represent, let alone manufacture. A new formal universe in turn prompted a search for new tectonics that would make the new undulating, sinuous skins buildable (within reasonable budgets).

1.8. *Gillette Venus* razor.

1.9. *Apple PowerMac G4.*

Inspired by the writings of thinkers ranging from Leibniz to Deleuze, as discussed earlier, some architects are exploring the spatial realms of non-Euclidean geometries, and some are basing their spatial investigations on topology, a branch of mathematics concerned with the properties of objects that are preserved through deformations. Thus, topological forms, such as torus (figure 1.11), the more complex Möbius strip (figure 1.12) and the Klein bottle (figure 1.13), have entered the architectural discourse; in some instances,

projects are even directly named after their topological origins, such as the *Möbius House* (1995, figure 1.14) by UN Studio (Ben Van Berkel and Caroline Bos) and the *Torus House* (2001, figure 1.15) by Preston Scott Cohen.

The appeal of the topological geometries is in part aesthetic, in part technological, and in part ideological. Topology is ultimately about relations, interconnections within a given spatial context, and not about specific forms—a single topological construct is manifestable through multiple forms (and those forms need not be curvilinear). Topology is, in other words, less about spatial distinctions and more about spatial relations. Because topological structures are often represented by mathematicians as curvilinear forms, one might think that topology is synonymous with curved surfaces, a fundamental misunderstanding which is now more or less widely adopted. Thus, in (uninformed) architectural discourse, "topological" often means "curved" and vice versa.

What should make the topology particularly appealing are not the new forms but, paradoxically, the shift of emphasis from the form to the structure(s) of relations, interconnections that exist internally and externally within an architectural project. Whether an architectural topological structure is given a curvilinear ("blobby") or a rectilinear ("boxy") form should be a result of particular performative circumstances surrounding the project, whether they are morphological, cultural, tectonic, material, economic, and/or environmental.

1.10. Detail of *BMW Z3 Roadster*.

1.11. Torus.

Admittedly, there is a considerable degree of novelty in complex, curvilinear forms (in spite of numerous precedents) and the new digital means of creating and physically producing and constructing them. The strong visual and formal juxtapositions created between

"blobs" and "boxes" intraditional urban contexts, as is often the case, add to their "iconic" status, and their perception of being exceptional and marvelous.

1.12. Möbius strip.

The "boxes" and "blobs," however, should not be seen as architectural opposites, but rather as instances on a sliding scale of formal complexity, that could even coexist within the same building, as was often the case in the notable modernist projects of the twentieth century and in some recent projects of the digital avant-garde. It is important to note that dissimilar forms—"blobs" and "boxes"—are not necessarily oppositional and that formal differences are not that essential (this does not mean that all geometries are alike). In the future, as buildings become more "intelligent," it will be the information the surface transmits to and from the surrounding environment—and not its form—that will matter more.

1.13. Klein bottle.

DIGITAL CONTINUUM

The use of digital modeling (three-dimensional) and animation (four-dimensional) software has opened new territories of formal exploration in architecture, in which digitally-
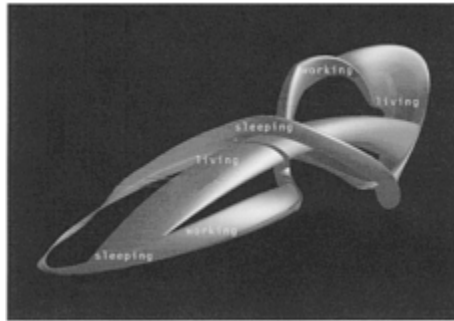
1.14. Conceptual diagram of the *Möbius House* (1995), Het Gooi, the Netherlands, architects UN Studio / Ben Van Berkel and Caroline Bos.

generated forms are not designed in conventional ways. New shapes and forms are created by generative processes based on concepts such as topological space, isomorphic surfaces, dynamic systems, keyshape animation, parametric design and genetic algorithms- discussed in more detail in the following chapter.

The changes are not purely formal. As noted earlier, by using digital technologies it is now possible to generate complex forms in novel ways and also to construct them within reasonable budgets. In other words, the processes of describing and constructing a design can be now more direct and more complex because the information can be extracted, exchanged, and utilized with far greater facility and speed; in short, with the use of digital technologies, the design information *is* the construction information.

This process-based change is far more significant than the formal change. It is the digitally-based convergence of representation and production processes that represents the most important opportunity for a profound transformation of the profession and, by extension, of the entire building industry. Much of the material world today, from the simplest consumer products to the most sophisticated airplanes, is created and produced using a process in which design, analysis, representation, fabrication and assembly are becoming a relatively seamless collaborative process that is solely dependent on digital technologies—a *digital continuum* from design to production. There is (the usual) one glaring exception—the building industry, which is bound to change as well, albeit very slowly, but change nevertheless.

It is interesting to note that it is the complexity of "blobby" forms that is actually drawing architects, out of sheer necessity, back into being closely involved with the making of buildings, thus giving them, perhaps surprisingly, more control of the building process. This position of greater control over the construction stems from the digitally-produced design information becoming construction information through the processes of data extraction and exchange.
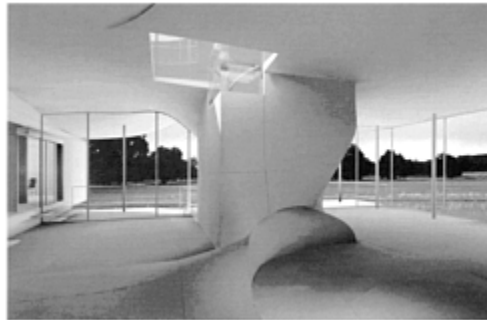
1.15. *Torus House* (2001), Old Chatham, New York, architect Preston Scott Cohen.

Thus, when applied to architecture, the use of digital technologies raises not only the questions of ideology, form or tectonics, but also the questions of the significance of information, and, more importantly, who controls it.
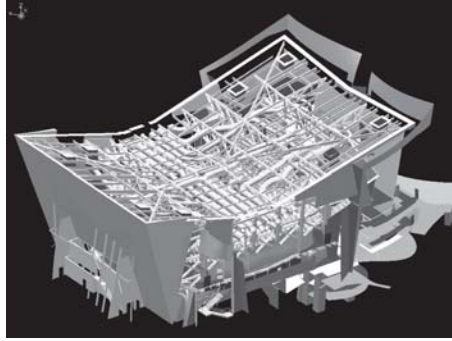
1.16. *Walt Disney Concert Hall* (2003), Los Angeles, architect Frank Gehry: four-dimensional model of the concert hall volume.

The ultimate goal becomes to construct a four-dimensional model encoded with all qualitative and quantitative dimensional information necessary for design, analysis, fabrication and construction, plus time-based information necessary for assembly sequencing. The result is a single, cohesive, complete model that contains all the information necessary for designing and producing a building (figure 1.16). This single source of information would enable the architects to become the coordinators (master builders) of information among various professions and trades involved in the production of buildings. By digitally producing, communicating and controlling the information exchanged between numerous parties in the building process, architects have an opportunity to place themselves in a central, key role in the construction of buildings and perhaps even regain the absolute powers of the medieval master builders. Whether they want to do that is a complex issue, as there are numerous social, legal and technical barriers to the complete restructuring of long-ago established relationships among the various building professions and trades.

1.18. *Basilica, Piazza dei Signori* (1617), Vicenza, Italy, architect Andrea Palladio.

The main technological issue is how to develop an information model for the building industry that facilitates all phases of building design and construction, and that can synthesize information produced and exchanged between various parties. This was a long-standing and yet unattained goal of the computer-aided design research community.

FROM SHIPS TO BUILDINGS

The processes developed by the shipbuilding industry over the past two decades to coordinate and connect design and construction are an example of the ways in which various parties from the building industry—architects, engineers, fabricators and contractors— could potentially integrate their services around the digital technologies of design, analysis, fabrication and assembly.

1.17. The Winston Churchill Aegis-class destroyer being built in the shipyard.

Ships, just like buildings, are objects of considerable technical complexity (figure 1.17). Just in terms of scale and use, there are sufficient similarities that warrant comparison (there are, of course, significant differences); it is precisely the similarities that offer opportunities for technology transfers. Both ships and buildings are large objects, with similarly complex service systems and interconnected spaces inhabited by people (in the case of passenger ships) and serving specific functions. Both have to respond to similar environmental influences and functional requirements. Both represent significant undertakings that require substantial financial and material resources. Both rely on shinlar principles, methods and processes of design, analysis and production.

Differences do exist, but do not negate the notion of similarity. Designing and building ships is, in fact, more complex. Structurally, ships have to resist not only gravity and wind loads, but also complex external hydrodynamic pressures. There are then additional stresses caused by propulsion systems and the motion of heavy loading equipment with which many transport ships are outfitted. Service systems in ships are more numerous, more complex, and need to operate with greater reliability. In short, ships have to perform in more ways than buildings.

Architects have relied historically on the building expertise of the shipbuilders. Palladio designed the roof of the Basilica at the *Piazza dei Signori* in Vicenza (1617, figures 1.18a–b) as an inverted ship hull and had to bring shipbuilders from Venice to construct it. This reliance on the building skills of shipbuilders has continued to modern times. Buckminster Fuller in his *Dymaxion House* (1946, figures 1.19a–b) co-opted the production methods from aircraft and shipbuilding industries. Fuller's design for the *Dymaxion Car* (*1933,*

figures 1.20a–bving to work with the original structure in the garage belowb) employed methods for framing and cladding modeled after the ship hull construction, and was fabricated by a shipyard in Bridgeport, Connecticut.
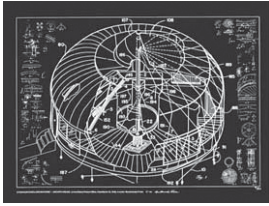
1.19a–b. *Dymaxion House* (1946), architect Buckminster Fuller.
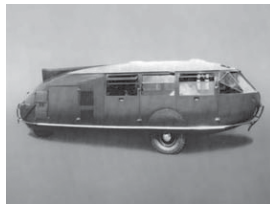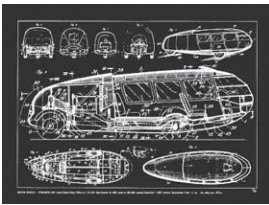
1.20a–b. *Dymaxion* Car (1933), designer Buckminster Fuller.

Frank Gehry's *Guggenheim Museum* in Bilbao would not have been possible without the local steel and shipbuilding industry. A number of other recently completed projects, of widely varying scales and budgets, made creative use of shipbuilder's expertise. The *Nat-West Media Centre at the* Lord's Cricket Ground in London (1999, figure 1.21), designed by Future Systems, was manufactured in a small shipyard in assembly at the building's site. The shipbuilder's expertise in making Cornwall, England (figure 1.22), and then transported in segments for aluminum yacht hulls was essential in designing and manufacturing the first semi-monocoque building structure from aluminum (figure 1.23). The conference chamber in Frank Gehry's *DG Bank* building (2000), Berlin, Germany, with its complex, curvilinear form, was clad in stainless steel plates produced and installed by skilled boatbuilders.

1.21. *NatWest Media Centre* (1999), Lord's Cricket Ground, London, UK, architect Future Systems.

1.22. *NatWest Media Centre:* aluminum shipyard.

Architects and builders have much more to learn from the shipbuilding industry. Shipbuilders have almost entirely eliminated drawings from the design and construction of ships, and are working instead with complete, comprehensive three-dimensional digital models from design to production (figure 1.24). Similar process changes have also taken place in automotive and aerospace industries. As in the building industry, they all work with numerous subcontractors to produce and assemble a large number of components with a high degree of precision. If we look beyond the complex, curved geometries of cars, planes and ships, which are increasingly becoming common in architecture as well, and focus on the centralized three-dimensional digital model, which is at the core of the transformation in those industries, the opportunities for architecture and the rest of the building industry become too apparent to ignore.
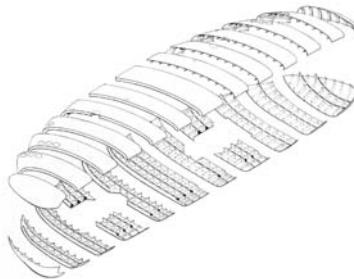
1.23. *NatWest Media Centre:* the semi-monocoque aluminum shell was made from 26 segments.
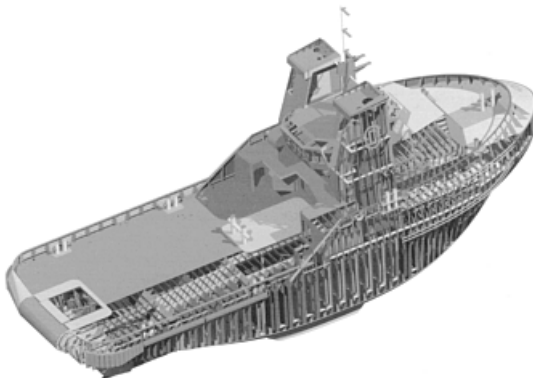
1.24. An example of a comprehensive three-dimensional model used in the shipbuilding industry.

LEARNING FROM OTHERS

CAD/CAM systems, used by architects whose work is featured in this book, were actually developed for the consumer product industry. Animation software, such as *Softimage, Alias,* and *Maya,* were developed for the special effects needs of the film industry.

This interest of architects in the re-use of technology and methods from other industries is nothing new. Architects have always looked beyond the boundaries of their discipline, appropriating materials, methods and processes from other industries as needed. Historically, these technology transfers have been at the core of many successful advances, widening the scope of innovation and continually affecting the prevalent norms of practice.

Today, much of the innovation and change stems from the adoption of digital design and production processes based on CAD/CAM processes, and from new materials invented for, and widely used in, the product design, automotive, aerospace and shipbuilding industries.

1.25 The digital model of the Boeing 737.

The impact of the adoption of innovative technologies in those industries was profound— there was a complete reinvention of how products were designed and made. Today, various appliances, cars, airplanes and ships are entirely designed, developed, analyzed and tested in a digital environment, and are then manufactured using digitally-driven technologies. Boeing 777, "the first 100% digitally designed aircraft," is probably one of the best-known examples (figure 1.25).

Buildings have that same potential to be digitally conceived and produced. While the CAD/CAM technological advances and the resulting changes in design and production techniques had an enormous impact on other industries, there has yet to be a similarly significant and industry-wide impact in the world of building design and construction. The opportunities for the architecture, engineering and construction (AEC) industries are beckoning, and the benefits are already manifested in related fields.

NOTES

1 Ignasi de Sola Morales. *Differences: Topographies of Contemporary Architecture.* Cambridge: MIT Press, 1997.

2 Peter Zellner. *Hybrid Space: New Forms in Digital Architecture.* New York: Rizzoli, 1999.

3 Gilles Deleuze. *A Thousand Plateaus: Capitalism and Schizophrenia.* Minneapolis: University of Minnesota Press, 1987.

4 Greg Lynn. "Architectural Curvilinearity: The Folded, the Pliant and the Supple" in Greg Lynn (ed.), *AD Profile 102: Folding in Architecture.* London: Academy Editions, 1993, pp. 8–15.

5 Gilles Deleuze. *The Fold: Leibniz and the Baroque.* Minneapolis: University of Minnesota Press, 1992.

6 Rafael Moneo. "The Thing Called Architecture" in Cynthia Davidson (ed.), *Anything.* New York: Anyone Corporation, 2001, pp. 120–123.

7 Aline Saarinen (ed.). *Eero Saarinen on His Work.* New Haven: Yale University Press, 1968.

8 *Ibid.*

9 Bernard Cache. *Earth Moves.* Cambridge: MIT Press, 1995.

10 *Ibid.*

11 *Ibid.*

12 Peter Zellner. "Ruminations on the Perfidious Enchantments of a Soft, Digital Architecture, or: How I Learned To Stop Worrying And Love The Blob" in Peter C. Schmal (ed.), *Digital, Real: Blobmeister First Built Projects.* Basel: Birkhauser, 2001.

13 Reyner Banham. *Theory and Design in the First Machine Age,* 2nd edition. Cambridge: MIT Press, 1980.

14 Stephen Perrella (ed.). *AD Profile 133: Hypersurface Architecture.* London: Academy Editions, 1998.

2
DIGITAL MORPHOGENESIS

BRANKO KOLAREVIC

In contemporary architectural design, digital media is increasingly being used not as a representational tool for visualization but as a generative tool for the derivation of form and its transformation—*the digital morphogenesis*. In a radical departure from centuries-old traditions and norms of architectural design, digitally-generated forms are not designed or drawn as the conventional understanding of these terms would have it, but they are calculated by the chosen generative computational method. Instead of modeling an external form, designers articulate an internal generative logic, which then produces, in an automatic fashion, a range of possibilities from which the designer could choose an appropriate formal proposition for further development.

The predictable relationships between design and representations are abandoned in favor of computationally-generated complexities. Models of design capable of consistent, continual and dynamic transformation are replacing the static norms of conventional processes. Complex curvilinear geometries are produced with the same ease as Euclidean geometries of planar shapes and cylindrical, spherical or conical forms. The plan no longer "generates" the design; sections attain a purely analytical role. Grids, repetitions and symmetries lose their past *raison d'être,* as infinite variability becomes as feasible as modularity, and as mass-customization presents alternatives to mass-production.

The digital generative processes are opening up new territories for conceptual, formal and tectonic exploration, articulating an architectural morphology focused on the emergent and adaptive properties of form. The emphasis shifts from the "making of form" to the "finding of form," which various digitally-based generative techniques seem to bring about intentionally. In the realm of form, the stable is replaced by the variable, singularity by multiplicity.

TOPOLOGY

Computational, digital architectures are defined by computationally-based processes of form origination and transformations, i.e. the processes of digital morphogenesis, where the plural ("architectures") emphasizes multiplicities inherent in the logics of the underlying computational concepts, such as topological geometries, isomorphic polysurfaces ("blobs"), motionkinematics and dynamics, keyshape animation (metamorphosis), parametric design, genetic algorithms (evolutionary architectures), performance, etc., which are discussed in more detail in the following sections.

The notion of topology has particular potentiality in architecture, as emphasis shifts away from particular forms of expression to relations that exist between and within an existing site and the proposed program. These interdependences then become the structuring, organizing principle for the generation and transformation of form.

According to its mathematical definition, topology is a study of intrinsic, qualitative properties of geometric forms that are not normally affected by changes in size or shape, i.e. which remain invariant through continuous one-to-one transformations or elastic deformations, such as stretching or twisting. A circle and an ellipse, for example, or a square and a rectangle, can be considered to be topologically equivalent, as both circle and square could be deformed by stretching them into an ellipsoid or rectangle, respectively. A square and a rectangle have the same number of edges and the same number of vertices, and are, therefore, topologically identical, or homeomorphic. This quality of homeomorphism is particularly interesting, as focus is on the relational structure of an object and not on its geometry—the same topological structure could be geometrically manifested in an infinite number of forms (figure 2.1). Topological transformations, first and foremost, affect the relational structure, and, thus, the resulting form(s). For example, a rectangle could be transformed into a triangle with a single topological operation of deleting one of its vertices.

Because of their intrinsic property of one-sidedness, topological structures such as the Möbius strip[1] (figure 1.12 in Chapter 1) and the Klein bottle[2] (figure 1.13 in Chapter 1), have a potential for an architecture in which the boundaries between what is interior and what is exterior are blurred, an architecture that avoids the normative distinctions of "inside" and "outside." While the conceptual possibilities of these topological geometries are intriguing, their inherent, conceptual qualities are often difficult to truly manifest tectonically, as *Möbius House* (1995) by Ben Van Berkel and Caroline Bos shows to some extent. The transparent and solid boundaries of the shelter, which a house must provide, often work against the seamless continuities and erasure of inside/outside dichotomy imbued within the Möbius strip. What makes topology particularly appealing are not the complex forms, such as the Möbius strip, but the primacy over form of the structures of relations, interconnections or inherent qualities which exist internally and externally within the context of an architectural project.

2.1. Homeomorphic (topologically equivalent) figures.
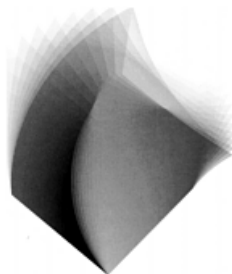
Because topological structures are often represented by complex, curvilinear forms, topology is popularly—and wrongly—considered synonymous with curved surfaces. Another common misnomer is to refer to topologically produced geometries as "non-Euclidean." As soon as a topological structure is given a geometric, architectonic form, the operative realm is firmly Euclidean. As the following section demonstrates, both Euclidean and non-Euclidean geometries are part of the same geometric universe, in which the Euclidean geometry is simply one special case, albeit one that has been firmly established in architectural thought and practice over the last few centuries.
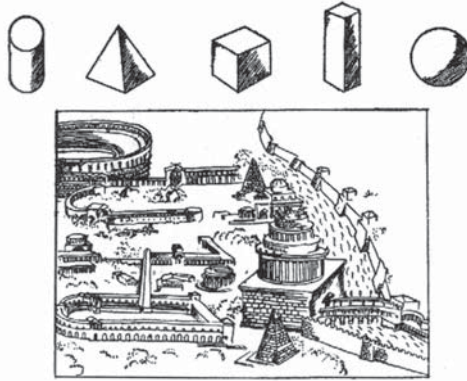
2.2. Le Corbusier: volumetric composition in ancient architecture.

NON-EUCLIDEAN GEOMETRIES

Architectural thinking throughout centuries was based firmly on Euclidean thought and Platonic solids, neatly depicted in Le Corbusier's sketch (figure 2.2) in his book *Vers une architecture.*[3] The cylinder, pyramid, cube, prism and sphere were not only the essential forms of the Egyptian, Greek and Roman architecture, as dryly observed by Le Corbusier, but were also universal geometric "primitives" of the digital solid modeling software of the late twentieth century. They are no longer seen, however, as some kind of unique, isolated archetypes, but as special cases of quadric parametric surfaces.

Euclid's *Elements* proposed five basic postulates of geometry, of which all were considered self-evident except the fifth postulate of "parallelism," which asserts that two lines are parallel, i.e. non-intersecting, if there is a third line that intersects both perpendicularly. The consequence of this postulate in Euclidean geometry is that through every point there is one and only one line parallel to any other line.

The first four postulates, as articulated by Euclid, are considered postulates of absolute geometry. It was this fifth postulate that opened the realm of non-Euclidean geometries. Though many had questioned Euclid's fifth postulate, it was Carl Friedrich Gauss and the mathematicians after him who have finally managed to successfully demonstrate the existence of non-Euclidean geometries. The publication of Eugenio Beltrami's seminal *Essay on an Interpretation of Non-Euclidean Geometry in* 1868 showed beyond doubt that curved lines could appear straight, that spherical geometry could seem planar, and that curved space could appear Euclidean, i.e. flat, thus turning the worlds of physics and astronomy upside down.[4] Albert Einstein's "Theory of Relativity," based on non-Euclidean

geometry, powerfully showed how Newtonian physics, based upon Euclidean geometry, failed to consider the essential curvature of space.

The work of Gauss, Lobachevsky, Riemann, von Helmholtz, and other mathematicians and physicists later on, showed that space is not only curved but also multi-dimensional. By showing that geometries could be based on non-Euclidean relationships (such as parallelism, for example), they opened up other spatial possibilities disconnected from empirical intuition.[5] In Riemannian geometry, which is also known as "spherical" geometry, the "plane" is situated on the surface of a sphere, and the "line" is a circle that has the same radius as the sphere. For every two points, there is one and only one circle that connects them; as a consequence of this definition and the underlying spherical geometry, no parallel "lines" exist in Riemannian geometry, and every infinite "line," i.e. circle, intersects every other infinite "line." Also, the distance between two points is always a curved distance, i.e. not a "flat" distance. In Poincaré geometry, for example, "lines" are hyperbolas on a Cartesian plane; there is an infinite number of "lines" through a chosen point that are parallel to another "line."

Each of these non-Euclidean geometries has a particular application. Riemannian geometry is used in navigation, and Poincaré geometry is used in ballistics and for the representation of electromagnetic forces. What makes these and other non-Euclidean geometries interesting from an architectural point of view is the possibility of mapping objects between them, thus providing for a radically different conceptualization of space. Some modeling software, for example, provides for limited transformations of the Cartesian modeling space, which can approximate spatial characteristics of some of the non-Euclidean geometries.

Another interesting concept, which Bernhard Riemann introduced, is the concept of curvature of space and the spaces of positive and negative curvature. In this definition of space, Euclidean "flat," planar space occupies the median position, having zero curvature. Euclidean geometry is then just a special kind of geometry, a special point on the infinite scale of bending, or folding, that produces "flatness" as a manifestation of an equilibrium that is established among various influences producing the curving of space in the first place. In other words, in the Riemannian conception of space, the "boxes" and "blobs" are simply instances on a sliding scale of formal complexity—a box could be turned into a blob and vice versa by simply varying the parameters of space within which they are defined.
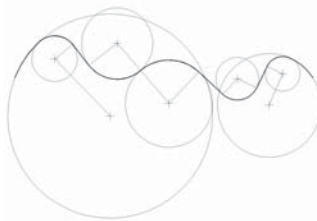
2.3. A composite curve constructed from tangent circular arcs and straight line segments.

As architectural conceptions of space move from the three dimensions of the Cartesian space to fourth-dimensional continuum of interactions between space and time, other dimensions and other conceptions of space begin to open up intriguing possibilities, which may or may not offer new potentialities for architectural thought. An architecture of warped multidimensional space would move beyond the mere manipulation of shapes and forms into the realm of events, influences and relationships of multiple dimensions.

NURBS

In pre-digital architecture, whose formal potentiality was, in large part, a direct extension of the limits of Euclidean geometry (lines, circles, quadrilaterals, etc.), the description and, consequently, the construction of compound, complex curves was accomplished through an approximation by concatenating tangent circular arcs and straight line segments (figure 2.3), which could be delineated with ease on paper and on the building site.

The introduction of digital modeling software into architectural design provided a departure from the Euclidean geometry of discrete volumes represented in Cartesian space and made possible the present use of "topological," "rubber-sheet" geometry of continuous curves and surfaces that feature prominently in contemporary architecture. The highly cur-vilinear surfaces in the architecture of the digital avant-garde are described mathematically as NURBS, which is an acronym that stands for Non-Uniform Rational B-Splines. What makes NURBS curves and surfaces particularly appealing is their ability to easily control their shape by interactively manipulating the *control points, weights* and *knots*. NURBS make the heterogeneous, yet coherent, forms of the digital architectures computationally possible and their construction attainable by means of computer numerically controlled (CNC) machinery.

But why NURBS? The main reason for their widespread adoption is the ability of NURBS to construct a broad range of geometric forms, from straight lines and Platonic solids to highly complex, sculpted surfaces. From a computational point of view, NURBS provide for an efficient data representation of geometric forms, using a minimum amount of data and relatively few steps for shape computation, which is why most of today's digital modeling programs rely on NURBS as a computational method for constructing complex surface models and, in some modelers, even solid models.

NURBS are a digital equivalent of the drafting splines used to draw the complex curves in the cross-sections of ship hulls and airplane fuselages. Those splines were flexible strips made of plastic, wood or metal that would be bent to achieve a desired smooth curve,

2.4. The shape of a NURBS curve can be changed by interactively manipulating the *control points, weights* and *knots*.

with weights attached to them in order to maintain the given shape. The term spline (the "S" in NURBS) actually has its origin in shipbuilding, where it was used to refer to a piece of steamed wood shaped into a desired smooth curve and kept in shape with clamps and pegs. Mathematicians borrowed the term in a direct analogy to describe families of complex curves.

The shape of a NURBS curve can be changed by manipulating its *control points* and associated *weights and knots* (figure 2.4), as well as the *degree* of the curve itself (figure 2.5). The NURBS curves are shaped primarily by changing the location of control points, which do not have to lie on the curve itself, except for the endpoints. Each control point has an associated weight, which determines the extent of its influence over the curve, in a direct analogy to drafting splines. Increasing the weight of a control point pulls the corresponding curve or surface toward that control point and vice versa.

Each control point has an associated polynomial equation, commonly referred to as a basis function (the "B" in NURBS, and in B-splines in general). A rational B-spline (the "R" in NURBS) is defined mathematically as the ratio of two polynomial equations, i.e. two basis functions. Each basis function affects only the curve section in the vicinity of the associated control point, and these sections are delimited by knots. A non-uniform rational B-spline is one in which the influence of a control point (i.e. the associated basis function) on a curvature can be varied by changing the location of the knots along the control segment that links two control points; in other words, a non-uniform rational B-spline is one with unequal knot spacing.

2.5. Varying the degree of a NURBS curve will produce different shapes.

2.6. Curvature graph for a cubic Bezier spline.

Another important parameter that can affect the shape of a NURBS curve is the degree, i.e. the highest exponent within the polynomial equations associated with control points. The lower the polynomial degree, the closer the curve is placed towards the control points. Thus, the second degree (quadratic) basis functions would pull the curve closer to control points than the third degree (cubic) ones (figure 2.5). The first degree (linear) functions produce a "curve" with straight line segments.

Other spline curves, as subcategories of NURBS, are typically available in modeling software. *B-splines* are actually NURBS with equally weighted control points (thus, weights are not displayed). Bézier curves, named after Pierre Bézier, the French automotive engineer who invented them, are B-splines with equal knot spacings (thus, knots are not shown). Cubic curves are actually third-degree continuous Bézier curves, and quadratic curves are second-degree continuous Bézier curves. In this pseudo-taxonomy of spline curves, at each level an additional set of controls over curvature is lost: weights in the case of B-splines, and both weights and knots in the case of Bézier curves.[6]

An important property of curves made by splines is that their curvature, i.e. the curve radius, changes continually along their length, in sharp contrast to curves made of tangent circular arcs, which, despite their smooth appearance, have discrete points at which the curvature changes abruptly. There are different levels of curvature continuity (figure 2.6): a curve with an angle or a cusp is said to have C0 continuity;[7] a curve without cusps but with changing curvature has C1 continuity;[8] a curve with constant curvature is C2 continuous[9]—higher levels of continuity are possible, but for most practical purposes, these three levels are sufficient. Besides fluid dynamics, the curvature continuity also has important aesthetic and manufacturing implications, which is why most modeling programs provide tools for the continuity analysis (figures 2.7 and 2.8).

The location of control points in a NURBS curve can affect its continuity locally, meaning that different segments can have different levels of continuity. For instance, two coincident control points in a NURBS curve would pronounce the curvature; three coincident control points would produce an angular cusp. This potentiality of NURBS curves of having varying continuity is referred to as *multiplicity*.

The definition of NURBS surfaces is a straightforward extension of NURBS curves. A control lattice that connects control points surrounds the surface (figure 2.9). Each control point has an associated weight parameter, and knots control the distribution of the local influence as in curves. In other words, the shape of a NURBS surface can be manipulated in the same ways as in curves.

2.7. Curvature continuity: the *zebra* analysis.

2.8. Curvature continuity: the *Gaussian* analysis.

Another property of NURBS objects, which is of particular importance from a conceptual point of view, is that they are defined within a "local" *parametric* space, situated in the three-dimensional Cartesian geometric space within which the objects are represented.[10] That parametric space is one-dimensional for NURBS curves, even though the curves exist in a three-dimensional geometric space. That one-dimensionality of curves is defined at a topological level by a single parameter commonly referred to as "U." Surfaces have two dimensions in the parametric space, often referred to as "U" and "V" in order to distinguish them from X, Y and Z of the Cartesian three-dimensional geometric realm. Isoparametric curves ("isoparms") are used to aid in the visualizing of NURBS surfaces through contouring in the "U" and "V" direction (figure 2.10). These curves have a constant U or V parameter in the parametric NURBS math, and are similar to topographic contour lines that are used to represent constant elevations in landscape.
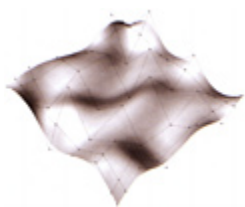
2.9. The control lattice for a NURBS surface.

The parametric description of forms *(parametrics)* provides a particularly versatile way to represent complex curves and surfaces. Sets of equations are used to express certain quantities as explicit functions of a number of variables, i.e. parameters, which can be independent or dependent. For instance, one set of parametric equations for a circle in two-dimensional Cartesian coordinate space could be given as $x = r \times \cos t$ and $y = r \times \sin t$, whereby the parameter *t* is the inscribed angle whose value can range from 0 to 2π (figure 2.11). Parametric representations are generally non-unique, i.e. the same quantities can be expressed by a number of different parameterization strategies (for example, the equation $r^2 = x^2 + y^2$ is another way to describe the geometry of the circle).
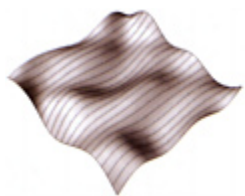
2.10. Isoparametric contours in the "U" direction of a NURBS surface.

PARAMETRICS

Parametrics can provide for a powerful conception of architectural form by describing a range of possibilities, replacing in the process stable with variable, singularity with multiplicity. Using parametrics, designers could create an infinite number of similar objects, geometric manifestations of a previously articulated schema of variable dimensional, relational or operative dependencies. When those variables are assigned specific values, particular instances are created from a potentially infinite range of possibilities.
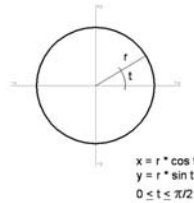
2.11. Parametric definition of a circle.

In parametric design, it is the parameters of a particular design that are declared, not its shape. By assigning different values to the parameters, different objects or configurations can be created. Equations can be used to describe the relationships between objects, thus defining an *associative* geometry—the "constituent geometry that is mutually linked."[11] That way, interdependencies between objects can be established, and objects' behavior under transformations defined. As observed by Burry, "the ability to define, determine and reconfigure geometrical relationships is of particular value."[12]

2.12a–d. *Paracube* by Marcos Novak.

Parametric design often entails a procedural, algorithmic description of geometry. In his "algorithmic spectaculars" (figures 2.12a–d), i.e. algorithmic explorations of "tectonic production" using *Mathematica* software, Marcos Novak constructs "mathematical models and generative procedures that are constrained by numerous variables initially unrelated to any pragmatic concerns… Each variable or process is a 'slot' into which an external influence can be mapped, either statically or dynamically."[13] In his explorations, Novak is "concerned less with the manipulation of objects and more with the manipulation of relations,

fields, higher dimensions, and eventually the curvature of space itself."[14] The implication is that the parametric design does not necessarily predicate stable forms. As demonstrated by Burry, one can devise a *paramorph*—an unstable spatial and topological description of form with stable characteristics (figure 2.13).

The *International Terminal* at Waterloo Station in London (1993, figure 2.14), by Nicholas Grimshaw and Partners, offers a clear demonstration of conceptual and developmental benefits afforded by the parametric approach to design. The building is essentially a 400 m long glass-clad train shed, with a "tapering" span that gradually shrinks from 50 m to 35 m. Its narrow, sinuous plan is determined by the track layout and the difficult geometry of the site, which is the main source of the project's complexity and which gives such potency and significance to Grimshaw's design, especially its spectacular roof structure.
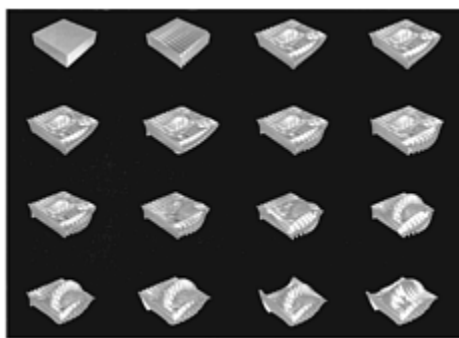
2.13. *Paramorph* by Mark Burry.

The roof structure consists of a series of 36 dimensionally different but identically configured three-pin bowstring arches (figure 2.15). Because of the asymmetrical geometry of the platforms, the arches rise steeply on one side with a shallower incline over the platforms on the other side. Each arch is different as the width of the roof changes along the tracks.

Instead of modeling each arch separately, a generic parametric model was created based on the underlying design rules in which the size of the span and the curvature of individual arches were related (figures 2.16a-b). By assigning different values to the span parameter, 36 dimensionally different, yet topologically identical, arches were computed and inserted in the overall geometric model.

The parametric model could be extended from the structural description of arches to the elements that connect them, the corresponding cladding elements, i.e. to the entire building form. Thus, a highly complex hierarchy of interdependences could be parametrically modeled, allowing iterative refinement, i.e. the dimensional fine-tuning of the project in all stages of its development, from conceptual design to construction.

As shown by this project, parametrics are particularly useful for modeling the geometry of complex building forms. Their successful application requires careful articulation of a clear strategy of tectonic resolution, such that a sufficiently clear description of

interdependences can be achieved; in other words, a well-defined design strategy is essential for the effective application of parametrics.

   Parametric approach to design, if consistently applied from its conceptual phase to its materialization, profoundly changes the entire nature and the established hierarchies of the building industry, as well as the role of the architect in the processes of building. For the first time in history, architects are designing not the specific shape of the building but a set of principles encoded as a sequence of parametric equations by which specific instances of the design can be generated and varied in time as needed. Parametric design calls for the rejection of fixed solutions and for an exploration of infinitely variable potentialities.

2.14. *International Terminal, Waterloo Station* (1993), London, UK, architect Nicholas Grimshaw and Partners.
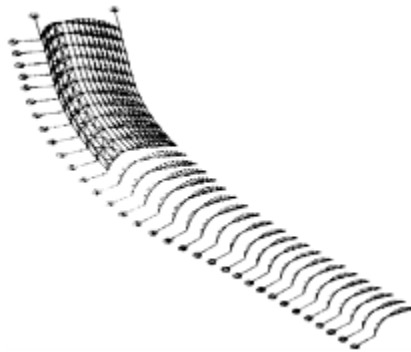
2.15. *International Terminal, Waterloo Station:* 36 dimensionally different but identically configured three-pin bowstring arches.
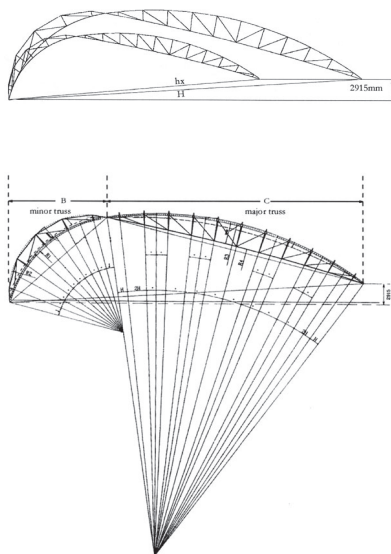
2.16a–b. Parametric definition of the scaling factor for the truss geometry: $h_x = ((2915^2 + (B + C)^2)^{1/2}$, where B is the minor truss span and C is the major truss span.

DYNAMICS AND FIELDS OF FORCES

As Greg Lynn observed in *Animate Form,*[15] "it is important for any parameter-based design that there be both the unfolding of an internal system and the infolding of contextual infor-mation fields." Architectural form, in other words, is not only a manifestation of its inter-nal, parameter-driven relational logics, but it also has to engage and respond to dynamic, often variable influences from its environmental and socio-economic context. Architectural form, instead of being conceived as a stationary, inert construct, is conceptually a highly plastic, mutable entity that evolves dynamically through its transformative interactions with external, gradient forces. According to Lynn, in place of a neutral abstract space, "the context of design becomes an active abstract space that directs from within a current of forces that can be stored as information in the shape of the form."[16]

Greg Lynn was one of the first architects to utilize animation software not as a medium of representation, but of form generation. He asserts that the prevalent "cinematic" model of motion in architecture eliminates force and motion from the articulation of form and reintroduces them later, after the fact of design, through concepts and techniques of optical procession. In contrast, as defined by Lynn, "animate design is defined by the co-presence of motion and force at the moment of formal conception."[17] Force, as an initial condition, produces as its effects both motion and particular inflections of form. According to Lynn, "while motion implies movement and action, animation implies evolution of a form and its shaping forces."[18]

In his seminal projects, showcased in *Animate Form,* Lynn utilizes an entire repertoire of motion-based modeling techniques, such as keyframe animation, forward and inverse kinematics, dynamics (force fields), and particle emission. Kinematics, in its true mechanical meaning, is used to study the motion of an object or a hierarchical system of objects

2.17a–c. Inverse kinematics is used in the *House Prototype in Long Island* project, architect Greg Lynn.
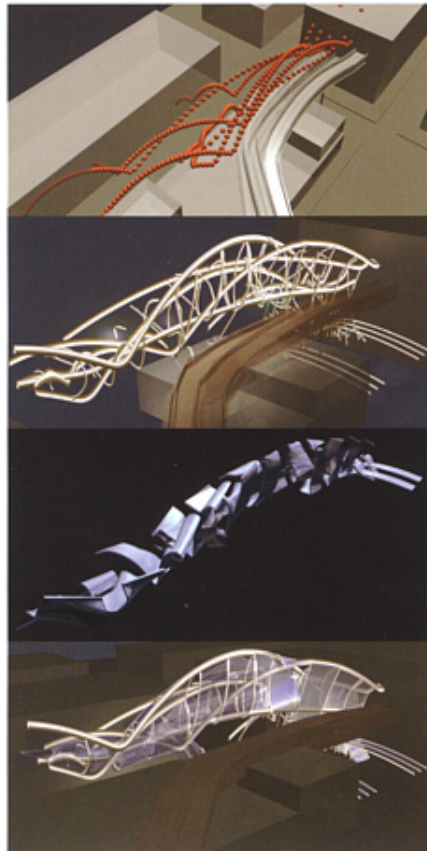
2.18a–d. The use of particle emission in the *Port Authority Bus Terminal* in New York competition project, architect Greg Lynn.

without consideration given to its mass or the forces acting on it. Hierarchical constructs, such as "skeletons" made of "bones" and "joints," which can have various associated constraints, allow designers to create an infrastructure of relations that determine the complex behavior of the model under transformations, which, for example, can result from the influence of external forces. A "global skin" assigned to such "skeletal" hierarchical organizations makes the deformations formally manifestable. As motion or external influences are applied, transformations are propagated down the hierarchy in forward kinematics, and upwards in inverse kinematics. In some of Lynn's projects, such as the *House Prototype in Long Island* (figures 2.17a–c), skeletons with a global envelope are deformed using inverse kinematics under the influence of various site-induced forces.

In contrast to kinematics, the dynamic simulation takes into consideration the effects of forces on the motion of an object or a system of objects, especially of forces that do not originate within the system itself. Physical properties of objects, such as mass (density), elasticity, static and kinetic friction (or roughness), are defined. Forces of gravity, wind, or vortex are applied, collision detection and obstacles (deflectors) are specified, and dynamic simulation computed. Gradient field influences are applied as direct abstract analogies for environmental influences, such as wind and sun, and contextual phenomena, such as pedestrian and vehicular movements, urban vistas, configurations, patterns and intensities of use, etc. Greg Lynn's design of a protective roof and a lighting scheme for the bus terminal in New York (Figures 2.18a–d) offers a very effective example of using particle systems to visualize the gradient fields of "attraction" present on the site, created by the forces associated with the movement and flow of pedestrians, cars and buses across the site.

The incorporation of movement into what was, by definition, static and unmovable is nothing new—it was one of the ideals of modern architecture. However, the architecture that was described by modernists as embodying movement simply promoted movement through its interior and exterior, becoming, as observed by Ignasi de Sola Morales, "above all a space for mobility, a container in which movement was prefigured."[19]

2.19. Form can be generated by subjecting the basic structures to force fields extrapolated from the context of the project (*"Dynaform,"* architect Bernhard Franken).

2.21a–b. The interacting "drops of water" (blobs) and the translation into a built form: The "Bubble," BMW's exhibition pavilion at the IAA '99 Auto Show in Frankfurt, Germany, architects Bernhard Franken and ABB Architekten.
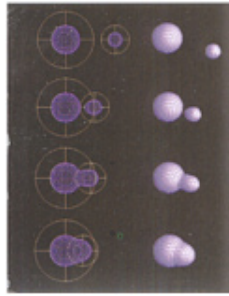
2.20. Isomorphic polysurfaces.

The architecture of motion, therefore, is not the same as the architecture of movement.[20] It prioritizes form over space by introducing the motion and force at the moment of formal conception.[21] It is the dynamics of forces, or, more precisely, force fields, as an initial condition that produces the motion and the particular transformations of form, i.e., the digital morphogenesis (figure 2.19). The form and its changes become products of the dynamic action of forces, a proposition adopted by Lynn directly from D'Arcy Thompson's *On Growth and Form,* published in 1917, in which Thompson argues that the form in nature and the changes of form are due to the "action of force."[22] One of Lynn's principal arguments is that "traditionally, in architecture, the abstract space of design is conceived as an ideal neutral space of Cartesian coordinates," but that in other design fields, "design space is conceived as an environment of force and motion rather than as a neutral vacuum."[23] According to Lynn, "while physical form can be defined in terms of static coordinates, the virtual force of the environment in which it is designed contributes to its shape,"[24] thus making the forces present in the given context fundamental to the form making in architecture. Lynn attributes to this position the significance of a paradigm shift "from a passive space of static coordinates to an active space of interactions," which he describes as "a

2.22. *Wozoco's Apartments* (1997), Amsterdam-Osdorp, the Netherlands, architect MVRDV.

move from autonomous purity to contextual specificity."[25] Instrumental to this conceptual shift is the use of digital media, such as animation and special-effects software, which Lynn uses as tools for design rather than as devices for rendering, visualization and imaging.

Instead of subjecting generic formal constructs to the influences of force fields, designers could directly visualize the shape of the force fields using *isomorphic polysurfaces,* which represent yet another point of departure from Platonic solids and Cartesian space. Blobs or metaballs, as isomorphic polysurfaces are sometimes called, are amorphous objects constructed as composite assemblages of mutually-inflecting parametric objects with internal forces of mass and attraction. They exercise fields or regions of influence (figure 2.20), which could be additive (positive) or subtractive (negative). The geometry is constructed by computing a surface at which the composite field has the same intensity—hence the name isomorphic polysurfaces.

Isomorphic polysurfaces open up yet another formal universe where forms may undergo variations, giving rise to new possibilities. Objects interact with each other instead of just occupying space; they become connected through a system of interactions where the whole is always open to variations as new blobs (fields of influence) are added or new relations made, creating new possibilities. The surface boundary of the whole (the isomorphic polysurface) shifts or moves as fields of influence vary in their location and intensity (figures 2.21a–b). In that way, objects begin to operate in a temporally-conditioned dynamic, rather than a static geography.

DATASCAPES

With his pioneering work on using motion dynamics to generate architectural form, Lynn has convincingly demonstrated what Nicholas Negroponte had only hinted at in his seminal work from some 30 years ago, *The Architecture Machine,* and which is also acknowledged in Lynn's writing:

"Physical form, according to D'Arcy Thompson, is the resolution at one instant of time of many forces that are governed by rates of change. In the urban context the complexity of these forces often surpasses human comprehension. A machine, meanwhile, could procreate forms that respond to many hereto un-manageable dynamics. Such a colleague would not be an omen of professional retirement but rather a tickler of the architect's imagination, presenting alternatives of form possibly not visualized or not visualizable by the human designer."[26]

Buildings and projects in general are conceived within a complex web of planning and building regulations (which are by no means fixed constructs), various technical constraints, environmental conditions, such as sun, wind, precipitation, etc., and are meant to operate in a highly dynamic socio-economic and political context, which has its own "force fields" such as, for instance, numerous interest groups. Some of these influences could be quantified and their changes modeled in order to simulate past, and predict present and future, impact.

2.24a–d. Deformation diagrams for *Bibliothèque de L'IHUEI* (1996–), University of Geneva, Switzerland, architect Peter Eisenman.

2.23. *Üstra Office Building* (1999), Hanover, Germany, architect Frank Gehry.

The design approach of the Dutch firm MVRDV acknowledges explicitly the existence of these "gravity fields" and their principal role in the shaping of the built environment (figure 2.22). In order to harvest the informational potential of the complexities inherent in various forces and the complex web of their interactions, MVRDV came up with the concept of *datascapes,*[27] which are visual representations of quantifiable forces that could influence or impact the conception and development of design projects. These informational landscapes become essential in understanding how these intangible influences manifest themselves in the built environment and how societal, economic, political and cultural fluxes and shifts influence contemporary architecture.

In MVRDV's approach, for each influence a separate datascape is constructed. Various datascapes, relevant for the selected context, are then superposed, creating a complex spatial envelope, with often contradictory, paradoxical conditions, which embodies within its limits the inherent possibilities for the genesis of an architectural project. The challenge, of course, is how to avoid a literal transcription of the diagrams of contextual flows and forces into an architectural form, as the superposition of datascapes, static or dynamic, often generates spatial and temporal constructs with apparent architectonic qualities.

2.26. The *Ost/Kuttner Apartments* (1996), New York, USA, architect Kolatan and Mac Donald.

METAMORPHOSIS

Digital modeling software offers a rich repertoire of transformations a designer could use to further explore formal potentialities of an already conceived geometry. Simple, topologically invariant transformations, such as twisting and bending, are particularly effective means for creating alternative morphologies. For instance, Gehry's *Üstra Office Building* in Hanover, Germany (1999), has a simple prismatic form, which twists in the direction of the nearby open park area (figure 2.23).

By adding a fourth, temporal dimension to the deformation processes, animation software adds a possibility to literally express the space and form of an object's metamorphosis. In *keyshape* (keyframe) animation, different states of an object (i.e. keyshapes or keyframes) are located at discrete points in time, and the software then computes through interpolation a smooth, animated, time-encoded transition between them. A designer could choose one of the interpolated states for further development, or could use the interpolation as an iterative modeling technique to produce instances of the object as it transitions, i.e. morphs from one state to another (figures 2.24a–d).

A particularly interesting temporal modeling technique is *morphing,* in which dissimilar forms are blended to produce a range of hybrid forms that combine formal attributes of the "base" and "target" objects. Kolatan and Mac Donald used morphing in a number of their

PILLOW
LAMP
VANITY
SEAT
CHAIR BACK

BATHTUB
BATHTUB
SOAPDISH
SINK
SINK
KITCHEN CABINET

REFRIGERATOR

BED
BED

O / K APARTMENT : CROSS-PROFILE REFERENCING

O / K APARTMENT : "CO-CITATION" MAPPING
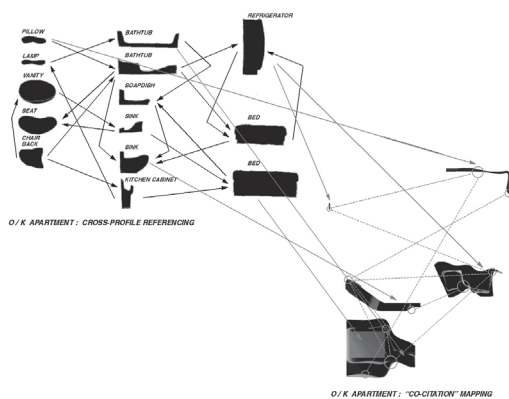
2.27. *Ost/Kuttner Apartments:* the "cross-section referencing" diagram.

2.25a–e. Kolatan and Mac Donald's "chimerical" *Housings* project.

2.28. Path animation: four rectilinear volumes move along four separate curved paths.

projects. In *Housings,* a normative three-bedroom, two-and-a-half bathroom colonial house was used as a "base" object that was then morphed into a range of everyday objects as "targets," producing a large range of what they call "chimerical" designs (figures 2.25a-e). In the Ost/Kuttner *Apartments* (1996, figure 2.26), they digitally blended cross-referenced sectional profiles of common household furniture, such as a bed, sink, sofa, etc., to generate new hybrid forms that establish a "chimerical condition between furniture, space, and surface"[28] (figure 2.27). Kolatan and Mac Donald intentionally employed digital generative processes whose outcomes were "unknown and impossible to preconceive or predict,"[29] i.e. they relied on processes characterized by non-linearity, indeterminacy and emergence, which are discussed later in this chapter.

Other techniques for the metamorphic generation of form include deformations of the modeling space around an object using a bounding box (lattice deformation), a spline curve, or one of the coordinate system axes or planes, whereby an object's shape conforms to the changes in geometry of the modeling space. In *path* animation, for example, an object is deformed as it moves along a selected path (figure 2.28).
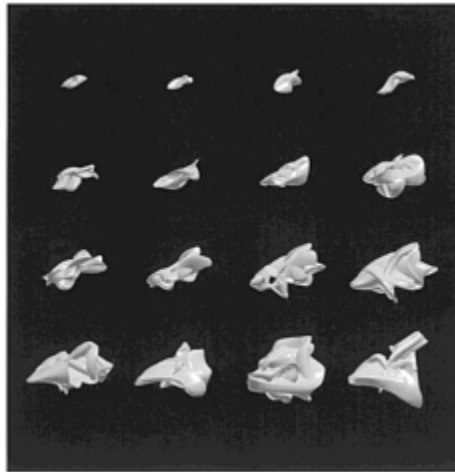
2.29. *Interactivator* (1995) by John and Julia Frazer: experimental evolution of form by interaction with actual visitors and environmental sensors (programming by Manit Rastogi, Patrick Janssen and Peter Graham).

GENETICS

The "rules" that direct the genesis of living organisms, that generate their form, are encoded in the strands of DNA. Variation within the same species is achieved through gene crossover and mutation, i.e. through the iterative exchange and change of information that governs the biological morphogenesis.

The concepts of biological growth and form, i.e. the evolutionary model of nature, can be applied as the generative process for architectural form as well, argues John Frazer in his book *Evolutionary Architecture*.[30] According to Frazer, architectural concepts are expressed as a set of generative rules, and their evolution and development can be digitally encoded. The generative script of instructions produces a large number of "prototypical forms which are then evaluated on the basis of their performance in a simulated environment."[31] According to Frazer, the emergent forms are often unexpected.

The key concept behind the evolutionary approach to architecture is that of the genetic algorithm, "a class of highly parallel evolutionary, adaptive search procedures," as defined by Frazer. Their key characteristic is a "string-like structure equivalent to the chromosomes of nature," to which the rules of reproduction, gene crossover and mutation are applied. Various parameters are encoded into "a string-like structure" and their values
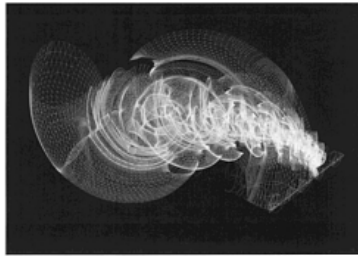
2.30. *X Phylum* project by Karl Chu.

changed, often randomly, during the generative process. A number of similar forms, "pseudo-organisms," are generated (figure 2.29), which are then selected from the generated populations based on a predefined "fitness" criteria. The selected "organisms," and the corresponding parameter values, are then crossbred, with the accompanying "gene crossovers" and "mutations" thus passing "beneficial and survival-enhancing traits" to new generations. Optimum solutions are obtained by small incremental changes over several generations.

2.31. The FEM analysis for the fabric envelope of *"Dynaform,"* BMW Pavilion at the IAA'01 Auto Show in Frankfurt, Germany, architects Bernhard Franken and ABB Architekten.

Karl Chu's approach to digital morphogenesis and to what he calls the "proto-bionic" architecture is a formal system based on the generative logic of the *Lindermayer System* (L-System)[32] and its implementation in digital modeling software, where it is used for the simulation of plant growth. L-systems are based on a recursive, rule-based branching system, conceived on the simple technique of rewriting, in which complex objects are created by successively replacing parts of an initially constructed object using a set of simple rewriting rules. The generative rules of an L-system can be very succinctly expressed. A simple set of carefully defined rules can produce a very complex object in a recursive process consisting of only a few levels (figure 2.30).

In both approaches to generative design based on biological metaphors, the task of the architect is to define the common source of form, the "genetic coding" for a large family of similar objects, in which variety is achieved through different processes of "reproduction." As was the case with other contemporary approaches to design, in processes of genetic coding the emphasis shifts to articulating the inner logic of the project rather than the external form.
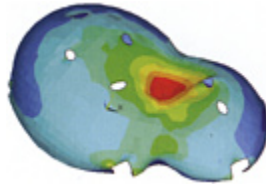
2.32. The FEM analysis for the glass envelope of the *"Bubble,"* BMW Pavilion at the IAA'99 Auto Show in Frankfurt, Germany, architects Bernhard Franken and ABB Architekten.

2.33. *Project ZED* (1995), London, UK, architect Future Systems.

PERFORMATIVE ARCHITECTURE

Another kind of architecture is also emerging, using building performance as a guiding design principle and adopting a new list of performance-based priorities for the design of cities, buildings, landscapes and infrastructures. This new kind of architecture places broadly defined performance above form-making; it utilizes the digital technologies of quantitative and qualitative performance-based simulation to offer a comprehensive new approach to the design of the built environment.

In this new information- and simulation-driven design context, the emerging paradigm of performance-based design is understood very broadly—its meaning spans multiple realms, from financial (the owner's perspective), spatial, social and cultural to purely technical (structural, thermal, acoustical, etc.). The emphasis on building performance (again, broadly understood from the financial, spatial, social, cultural, ecological and technical perspective) is redefining expectations of the building design, its processes and practices.
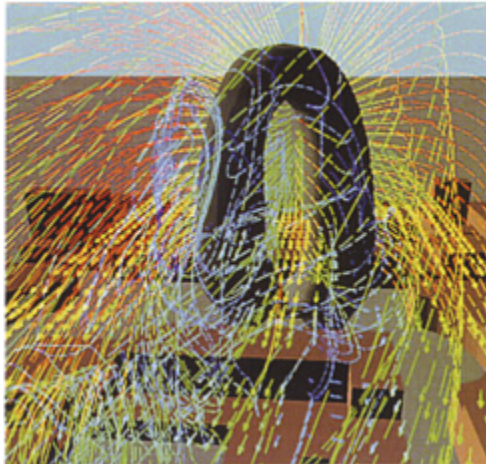
2.34. The CFD analysis of wind flows for *Project ZED* (1995), London, UK, architect Future Systems.
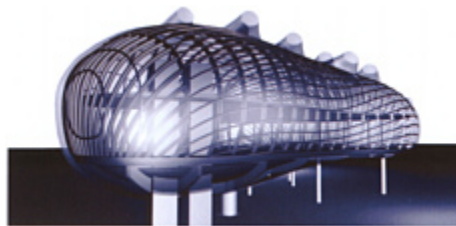
2.35. *Kunsthaus* (2003), Graz, Austria, architects Peter Cook and Colin Fournier.

Analytical computational techniques based on the finite-element method (FEM), in which the geometric model is divided into small, interconnected mesh elements, are used to accurately perform structural, energy and fluid dynamics analyses for buildings of any formal complexity. These quantitative evaluations of specific design propositions can be qualitatively assessed today thanks to improvements in graphic output and visualization techniques (figures 2.31 and 2.32). By superposing various analytical evaluations, design alternatives could be compared with relative simplicity to select a solution that offers optimal performance.

In computational fluid dynamics (CFD) software, used mainly to analyze airflows within and around buildings, fluid flow physics are applied to the digital model of a building to compute not only the dynamic behavior of the fluids (air, smoke, water, etc.), but also the transfer of heat mass, phase change (such as the freezing of water), chemical reactions (such as combustion), and stress or deformation of building structure (in fire, etc.).

Future Systems, a design firm from London, used CFD analysis in a particularly interesting fashion in its *Project ZED,* the design of a multiple-use building in London (1995, figure 2.33). The building was meant to be self-sufficient in terms of its energy needs by incorporating photovoltaic cells in the louvers and a giant wind turbine placed in a huge hole in its center. The curved form of the façade was thus designed to minimize the impact of the wind at the building's perimeter and to channel it towards the turbine at the center. The CFD analysis was essential in determining the optimal performance of the building envelope (figure 2.34).

The original blobby shape of Peter Cook's and Colin Fournier's competition winning entry for the *Kunsthaus in Graz,* Austria (2003, figure 2.35), was altered somewhat after the digital structural analysis, by consulting engineers Bollinger + Grohmann from Frankfurt, revealed that its structural performance could be improved with minor adjustments in the overall form. Likewise, Foster and Partners' design for the main chamber of the Greater *London Authority (GLA) Headquarters* (2002, figure 2.36) had to undergo several significant changes after engineers from Arup analyzed its acoustical performance using in-house developed acoustic wave propagation simulation software (figure 2.37). It is interesting to note that the "pebble"-like form of the building resulted from optimizing its energy performance by minimizing the surface area exposed to direct sunlight (figure 2.38). The building's

2.36. *GLA Headquarters:* (2002), London, UK, architect Foster and Partners.
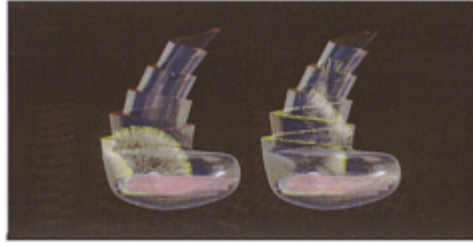
2.37. *GLA Headquarters:* one of the acoustical studies (by Arup).
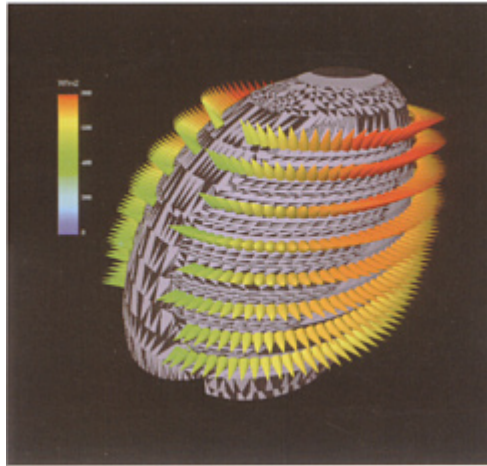
2.38. *GLA Headquarters:* one of the solar studies (by Arup).

"blobby" form is actually a deformed sphere, which has a 25% smaller surface area than a cube of identical volume, resulting in a reduced solar heat gain and heat loss through the building's skin. The cladding configuration was a direct outcome of the analysis of sunlight patterns throughout the year.

Foster's performative approach to the design of the GLA building could imply a significant shift in how "blobby" forms are perceived. The sinuous, highly curvilinear forms could become not only an expression of new aesthetics, or a particular cultural and socioeconomic moment born out of the digital revolution, but also an optimal formal expression for the new ecological consciousness that calls for sustainable building. If wind turbines were to become a reality of mankind's future, as futuristic designs by Future Systems suggest, the built environment would attain new morphology in which "boxes" could become as exotic as "blobs" are today.

Although digital technologies, in particular performance-based simulations, have made the notion of performative architecture possible, challenges and opportunities do exist in the ways these technologies are being conceptualized and used. Instead of being used in

a passive, "after-the-fact" fashion, i.e. after the building form has been articulated, as is currently the case, analytical computation could be used to actively shape the buildings in a dynamic fashion, in a way similar to how animation software is used in contemporary architecture. An already-structured building topology, with a generic form, could be subjected to dynamic, metamorphic transformation, resulting from the computation of performance targets set at the outset. This dynamic range of performative possibilities would contain, at one end, an unoptimized solution and, at the other end, an optimized condition (if it is computable), which might not be an acceptable proposition from an aesthetic, or some other, point of view. In that case, a sub-optimal solution could be selected from the in-between performative range, which could potentially satisfy other non-quantifiable performative criteria.

This new kind of analytical software would preserve the topology of the proposed schematic design but would alter the geometry in response to optimizing a particular performance criteria (acoustic, thermal, etc.). For example, if there is a particular geometric configuration comprised of polygonal surfaces, the number of faces, edges, and vertices would remain unchanged (i.e. the topology does not change), but the shapes (i.e. the geometry) would be adjusted (and some limits could be imposed in certain areas). The process of change could be animated, i.e. from the given condition to the optimal condition, with the assumption that the designer could find one of the in-between conditions interesting and worth pursuing, even though it may not be the most optimal solution.

NON-LINEARITY, INDETERMINACY AND EMERGENCE

Contemporary approaches to architectural design have abandoned the determinism of traditional design practices and have embraced the directed, *precise indeterminacy* of new digital processes of conception. Instead of working on a *parti,* the designer constructs a generative system of formal production, controls its behavior over time, and selects forms that emerge from its operation. In this model of design, a system of influences, relations, constrains or rules is defined first through the processes of *in-formation,* and its temporal behavior is specified; the resulting structure of interdependences is often given some generic form *(formation),* which is then subjected to the processes of *de-formation* or *transformation,* driven by those very same relations, influences or rules imbedded within the system itself.

The new approaches to design open up a formal universe in which essentially curvilinear forms are not stable but may undergo variations, giving rise to new possibilities, i.e. the *emergent form*. The formal complexity is often intentionally sought out, and this morphological intentionality is what motivates the processes of construction, operation and selection. The designer essentially becomes an "editor" of the morphogenetic potentiality of the designed system, where the choice of emergent forms is driven largely by the designer's aesthetic and plastic sensibilities. The capacity of digital, computational architectures to generate "new" designs is, therefore, highly dependent on the designer's perceptual and cognitive abilities, as continuous, dynamic processes ground the emergent form, i.e. its discovery, in qualitative cognition. Even though the technological context of design is thoroughly externalized, its arresting capacity remains internalized. The

generative role of new digital techniques is accomplished through the designer's simultaneous interpretation and manipulation of a computational construct (topological surface, isomorphic field, kinetic skeleton, field of forces, parametric model, genetic algorithm, etc.) in a complex discourse that is continuously reconstituting itself-a "self-reflexive" discourse in which graphics actively shape the designer's thinking process. For instance, designers can see forms as a result of reactions to a context of "forces" or actions, as demonstrated by Greg Lynn's work. There is, however, nothing automatic or deterministic in the definition of actions and reactions; they implicitly create "fields of indetermination" from which unexpected and genuinely new forms might emerge; unpredictable variations are generated from the built multiplicities.

It is precisely the ability of "finding a form" through dynamic, highly non-linear, indeterministic systems of organization that gives digital media a critical, generative capacity in design. Non-linear systems change indeterminately, continually producing new, unexpected outcomes. Their behavior over time cannot be explained through an understanding of their constituent parts, because it is the complex web of interdependencies and interactions that define their operation. In addition, in non-linear systems, it is often the addition or subtraction of a particular kind of information that can dramatically affect its behavior—in other words, a small quantitative change can produce a disproportionally large qualitative effect. It is this inherent capacity for "threshold" behavior that assigns to non-linearity the qualities of emergent behavior and infinite potential for change.

By openly embracing non-linearity, indeterminacy and emergence, the new digital design techniques challenge conventions such as stable design conceptualization, monotonic reasoning and first order logic that were (and still are) the underlying foundation for the design of mainstream computational tools for architectural production. In contemporary computational approaches to design, there is an explicit recognition that admittance of the unpredictable and unexpected is what often paves the way to poetic invention and creative transformation. The non-linearity, indeterminacy and emergence are intentionally sought out.

IT IS NOT ABOUT "BLOBS"

The changes brought about by the Information Age and globalization, as its most radical manifestation, are having a dramatic and profound impact on societies, economies and cultures worldwide. Architects, as they have done for centuries, are trying to interpret these changes and find an appropriate expression for an architecture that captures the zeitgeist of the dawn of the Information Age, which befits the information revolution and its effects. There is a wide range of approaches, discussed in this chapter, all of which express the unprecedented generative potentiality of digital techniques. The "blobby" aesthetics, which seem to be pervasive in the projects of the avant-garde, are often sidetracking the critical discourse into the more immediate territory of formal expression and away from more fundamental possibilities that are opening up, such as the opportunity for architects to reclaim the lost ground and once again become fully engaged in the act of building (as *information* master-builders). This is not to say that the profession should not maintain a critical attitude towards the potentiality of the digital, but that it should attempt to see beyond the issues of

the formal aesthetics. Some extravagant claims were made, of course, and some unreasonable expectations were projected, which is not surprising given the totalizing fashion with which the digital domain is embraced in certain academic circles. But speculative design work, enabled by digital technologies, should at least provoke a healthy debate about the possibilities and challenges of the digital future.

Obviously, the "blobs" will not have a significant impact on architecture's future if they are understood in formal terms alone, or if they are seen as utopian architectural visions, as already happened in the 1960s. The challenge for the profession is to understand the appearance of the digitally-driven generative design and production technologies in a more fundamental way than as just tools for producing "blobby" forms.

NOTES

1   The Möbius strip, named after August Möbius, the German mathematician who first published this single-sided figure in 1865, can be simply constructed by connecting two ends of a twisted linear strip.

2   The Klein bottle is an edgeless, self-intersecting surface.

3   Le Corbusier. *Towards a New Architecture* (translated by F. Etchells). New York: Dover Publications, 1931.

4   Roberto Bonola. *Non-Euclidean geometry: A Critical and Historical Study of its Development* (translated by H.S.Carslaw). New York: Dover Publications, 1955.

5   *Ibid.*

6   It is important to note, however, that unequally weighted control points become necessary for constructing the curves of conic sections: circles, ellipses, parabolas, and so on.

7   Mathematically, this means that the curve is continuous but has no derivative at the cusp.

8   The first derivative is continuous, but the second one is not.

9   Both the first and second derivatives are continuous.

10   For more information about NURBS parametric definition, see Les Piegl and Wayne Tiller, *The NURBS Book,* 2nd edition. New York: Springer, 1997.

11   Mark Burry. "Paramorph" in Stephen Perrella (ed.), *AD Profile 141: Hypersurface Architecture II.* London: Academy Editions, 1999.

12   *Ibid.*

13   Marcos Novak. "Transarchitectures and Hypersurfaces" in Stephen Perrella (ed.), *AD Profile 133: Hypersurface Architecture.* London: Academy Editions, 1998.

14   *Ibid.*

15   Greg Lynn. *Animate Form.* Princeton: Princeton Architectural Press, 1998.

16   *Ibid.*

17   *Ibid.*

18   *Ibid.*

19   Ignasi de Sola Morales. *Differences: Topographies of Contemporary Architecture.* Cambridge: MIT Press, 1997.

20 Lynn, *Animate Form. op cit.*

21 *Ibid.*

22 D'Arcy Thompson. *On Growth and Form.* Cambridge (UK): Cambridge University Press, 1917.

23 Lynn. *Animate Form. op cit*

24 *Ibid.*

25 *Ibid.*

26 Nicholas Negroponte. *The Architecture Machine.* Cambridge: MIT Press, 1970.

27 MVRDV. *Metacity/Datatown.* Rotterdam, the Netherlands: 010 Publishers, 1999.

28 Sulan Kolatan. "More Than One/Less Than Two_RESIDENCE[S]" in Peter C. Schmal (ed.), *Digital, Real: Blobmeister First Built Projects.* Basel: Birkhauser, 2001. pp. 68–79.

29 *Ibid.*

30 John Frazer. *Evolutionary Architecture.* London: Architectural Association, 1995.

31 *Ibid.*

32 A mathematical theory of plant development named after its inventor, biologist Aristid Lindenmayer (1925–89).

3
DIGITAL PRODUCTION

BRANKO KOLAREVIC
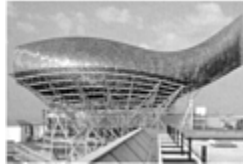
3.1. *Fish Sculpture* (1992), Vila Olimpica, Barcelona, Spain, architect Frank Gehry.

The digital age has radically reconfigured the relationship between conception and production, creating a direct link between what can be conceived and what can be constructed. Building projects today are not only born out digitally, but they are also realized digitally through "file-to-factory" processes of computer numerically controlled (CNC) fabrication technologies.

It was the complexity of "blobby" forms that drew architects, out of sheer necessity, back into being closely involved with the production of buildings. The continuous, highly curvilinear surfaces, which feature prominently in contemporary architecture, brought to the fore the question of how to work out the spatial and tectonic ramifications of such complex forms. It was the challenge of constructability that brought into question the credibility of spatial complexities introduced by the new "digital" avant-garde. But as constructability becomes a direct function of computability, the question is no longer whether a particular form is buildable, but what new instruments of practice are needed to take advantage of the opportunities opened up by the digital modes of production.


3.2. Digitizing of a three-dimensional model in Frank Gehry's office.

One of the first projects to be developed and realized digitally was Frank Gehry's design for the large *Fish Sculpture* at the entrance to a retail complex called Vila Olimpica in Barcelona, Spain (1992, figure 3.1). The project's financial and scheduling constraints led Gehry's partner Jim Glymph to search for a digital design and manufacturing software environment that would make the complex geometry of the project not only describable, but also producible, using digital means in order to ensure a high degree of precision in fabrication and assembly. The solution was found in the three-dimensional modeling and manufacturing program developed for the French aerospace industry (Dassault Systems), called CATIA, an acronym that stands for *Computer Aided Three-dimensional Interactive Application*. Thus, the software made for the design and manufacture of airplanes was used to develop and construct a built structure. Three-dimensional digital models were used in the design development, for structural analysis, and as a source of construction information, in a radical departure from the normative practices of the profession. The bellwether of digital revolution for architecture had finally arrived.

THREE-DIMENSIONAL SCANNING: FROM PHYSICAL TO DIGITAL

For some designers, such as Frank Gehry, the direct tactility of a physical model is a much preferred way of designing than a "flat" digital manipulation of surfaces on a computer screen. In Gehry's case, the digital technologies are not used as a medium of conception but as a medium of *translation* in a process that takes as its input the geometry of the physical model (figure 3.2) and produces as its output the digitally-encoded control information which is used to drive various fabrication machines (figures 3.3a-c). As it will be demonstrated in this chapter, digital representations of geometry can be used in ways the original physical models cannot.

The process of translation from the physical to the digital realm is the inverse of computer-aided manufacturing. From a physical model a digital representation of its geometry can be created using various three-dimensional scanning techniques in a process often referred to as "reverse engineering." A pattern of points, called the "point cloud" (figure 3.4a), is created from the physical model through scanning, and is then interpreted by the conversion software to produce a close approximation of the model's geometry. Typically, patterns of scanned points (figure 3.4b) are used to generate profile NURBS (Non-Uniform Rational B-Splines) curves (figure 3.4c), which are then used to generate lofted
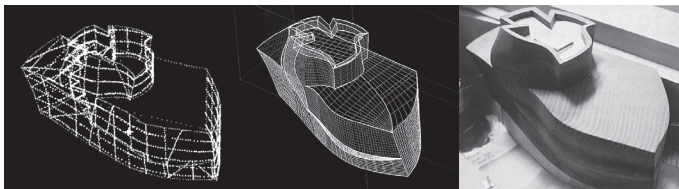
3.3a–c. The *translation* process in Gehry's office: (a) digitized points; (b) digital surface reconstruction; and (c) digitally fabricated model.
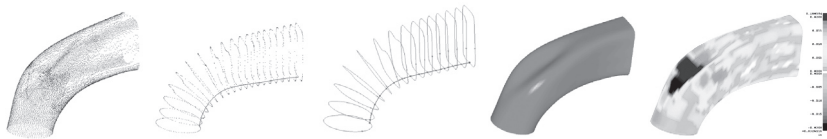
3.4a–e. The reverse engineering process: (a) point cloud from three-dimensional scanning; (b) and (c) cross-sectional curve generation; (d) surface lofting, and (e) comparison with the point cloud.

NURBS surfaces (figure 3.4d). The resulting surfaces can be compared to the scanned point cloud for an analysis of deviations from the original physical model (figure 3.4e).

A common method for three-dimensional scanning involves the use of a digitizing position probe to trace surface features of the physical model. This procedure can be done manually using three-dimensional digitizing arms (figure 3.5) or automatically using a Coordinate Measuring Machine (CMM), which has a digitizing position sensor that is mechanically kept in contact with the surface of the scanned object.

An alternative is to use *non-contact* scanning methods, which require more expensive scanning devices, but are faster, more accurate, less labor intensive, and often more effective when scanning small-scale objects. These devices commonly use laser light to illuminate the surface of a scanned object (figure 3.6) in a step-by-step fashion, producing patterns of bright dots or lines, which are captured by digital cameras (two are often used). The recorded images are processed using optical recognition techniques to construct the three-dimensional geometric model of the scanned object, which can then be exported in a desired data format for use in digital analysis or modeling applications.

Three-dimensional scanning techniques can be used to digitally capture not only the physical models, but also existing or as-built conditions, or even entire landscapes. Laser scanning technologies, based on different measurement techniques, are commonly used in surveying on construction sites worldwide (figure 3.7). In each of the different devices available on the market, a laser beam is emitted by the scanner and the reflected beam is captured, and its properties analyzed to calculate the distances to the measured object. Four pieces of information are captured for each individual point measurement: X, Y and Z coordinates plus the intensity of the reflected beam, which can be used to assign different light intensities or even colors to the point cloud.

Laser scanning technologies can create very accurate three-dimensional models of existing objects.[1] Today, they are used increasingly on construction sites in place of conventional measuring devices to quickly measure distances and to precisely determine locations for the installation of various building components. It is conceivable that the laser scanning will also be used to continuously scan the building's structure as it is erected and to immediately detect deviations from the geometry of the digital model. The "point cloud" is already in the builder's vocabulary, and the laser scanning has already rendered the tape measure obsolete on numerous construction sites.

DIGITAL FABRICATION: FROM DIGITAL TO PHYSICAL

The long tradition of Euclidean geometry in building brought about drafting instruments, such as the straightedge and the compass, needed to draw straight lines and circles on paper, and the corresponding extrusion and rolling machinery to produce straight lines and circles in material. The consequence was, as William Mitchell observed, that architects drew what they could build, and built what they could draw.[2] This reciprocity between the means of representation and production has not disappeared entirely in the digital age. Knowing the production capabilities and availability of particular digitally-driven

3.5. The *Microscribe* three-dimensional digitizer.

3.6. Three-dimensional laser scanner.

3.7. Three-dimensional laser scanner for site surveying.

3.8a–b. *Nationale-Nederlanden Building* (1996), Prague, Czech Republic, architect Frank Gehry: irregularly-shaped glass panels were cut using digitally-driven cutting machines.

fabrication equipment enables architects to design specifically for the capabilities of those machines. The consequence is that architects are becoming much more directly involved in the fabrication processes, as they create the information that is translated by fabricators directly into the control data that drives the digital fabrication equipment. For instance, the irregularly-shaped glass panels on Frank Gehry's *Nationale-Nederlanden Building* in Prague, Czech Republic, (1996, figures 3.8a-b), were cut using digitally-driven cutting machines from the geometric information extracted directly from the digital model, as was also the case with more than 21,000 differently shaped metal shingles for the exterior of the *Experience Music Project* (EMP) in Seattle, also designed by Frank Gehry (2000, figures 3.9a–b). A growing number of successfully completed projects, which vary considerably in size and budgets, demonstrate that digital fabrication can offer productive opportunities within schedule and budget frameworks that need not be extraordinary.

The new digitally-enabled processes of production imply that the constructability in building design becomes a direct function of computability. The fact that complex geometries are described precisely as NURBS curves and surfaces, and, thus, computationally possible, also means that their construction is attainable by means of CNC fabrication processes. Production processes based on cutting, subtractive, additive and formative fabrication, which are described in more detail in this chapter, offer rich opportunities for the tectonic exploration of new geometries.[3]
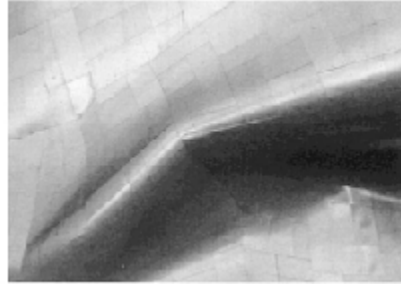
3.9a–b. *Experience Music Project* (EMP) (2000), Seattle, USA, architect Frank Gehry: 21,000 differently shaped metal shingles for the exterior were cut digitally.
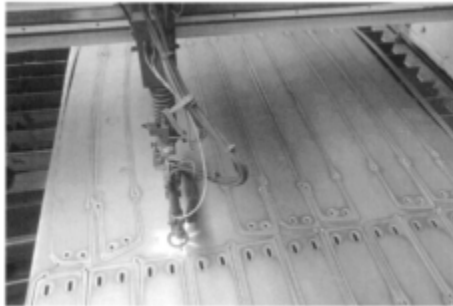
3.10. Plasma-arc CNC cutting of steel supports for masonry walls in Frank Gehry's *Zollhof Towers* (2000) in Düsseldorf, Germany.
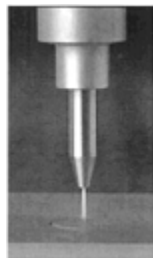
3.11. A water-jet nozzle.

TWO-DIMENSIONAL FABRICATION

CNC cutting, or two-dimensional fabrication, is the most commonly used fabrication technique. Various cutting technologies, such as plasma-arc, laser-beam and water-jet, involve two-axis motion of the sheet material relative to the cutting head, and are implemented as a moving cutting head, a moving bed or a combination of the two. In plasma-arc cutting, an electric arc is passed through a compressed gas jet in the cutting nozzle, heating the gas into plasma with a very high temperature (25,000°F), which converts back into gas as it passes the heat to the cutting zone (figure 3.10). In water-jets, as their name suggests, a jet of highly pressurized water is mixed with solid abrasive particles and is forced through a tiny nozzle in a highly focused stream (figure 3.11), causing the rapid erosion of the material in its path and producing very clean and accurate cuts (figure 3.12). Laser-cutters use a high-intensity focused beam of infrared light in combination with a jet of highly pressurized gas (carbon dioxide) to melt or burn the material that is being cut. There are, however, large differences between these technologies in the kinds of materials or maximum thicknesses that could be cut. While laser-cutters can only cut materials that can absorb light energy, water-jets can cut almost any material. Laser-cutters can cut material up to 5/8 inches (16 mm) cost-effectively, while water-jets can cut much thicker materials, for example, up to 15 inches (38 cm) of thick titanium.
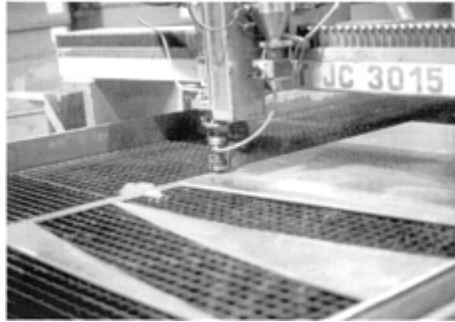
3.12. The *"Bubble"* (1999), BMW Pavilion, Frankfurt, Germany, architects Bernhard Franken and ABB Architekten: the aluminum frame is cut directly from digital data using CNC water-jet technology.

SUBTRACTIVE FABRICATION

Subtractive fabrication involves the removal of a specified volume of material from solids (hence the name) using electro-, chemically- or mechanically-reductive (multi-axis milling) processes. The milling can be axially, surface or volume constrained. In axially constrained devices, such as lathes, the piece of material that is milled has one axis of rotational motion, and the milling head has two axes of translational motion. Surface constrained milling machines are conceptually identical to the cutting machines discussed previously.

In two-axis milling routers, the rotating drill-bit is moved along *X* and Y axes to remove two-dimensional patterns of material.

The milling of three-dimensional solids is a straightforward extension of two-dimensional cutting. By adding the ability to raise or lower the drill-bit, i.e. to move it along the third, *Z* axis, the three-axial milling machines could remove material volumetrically. Because of the inherent limitations of three-axial milling, the range of forms that could be produced with these machines is limited. For example, undercuts as shown in figure 3.13 cannot be accomplished with three-axis milling devices. For such shapes, a four- or five-axis machines are used. In four-axis systems, an additional axis of rotation is provided, either for the cutting head or the cutting bed that holds the piece (the A-axis), and in five-axis systems one more axis of rotation (the B-axis) is added (figure 3.14). In this fashion, the cutting head can perform the "undercuts" and can substantially increase the range of forms that can be produced using milling.

The drill bits inserted into the cutting heads can be of different sizes, i.e. diameters. Large bits are used for the coarse removal of material, and smaller bits for finishing. The milling itself can be done at different rotational speeds, depending on the hardness or other properties of the material that is milled.

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O0001
N005 G54 G90 S400 M03
N010 G00 X1. Y1.
N015 G43 H01 Z.1 M08
N020 G01 Z-1.25 F3.5
N025 G00 Z.1
N030 X2.
N035 G01 Z-1.25
N040 G00 Z.1 M09
N045 G91 G28 Z0
N050 M30
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3.15. A simple CNC program.
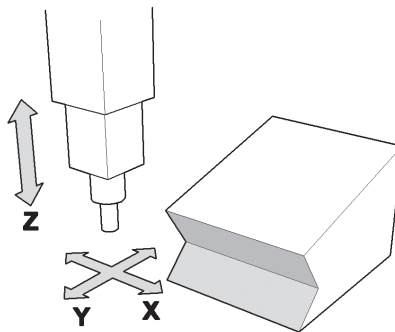
3.13. Undercuts cannot be milled with three-axis milling machines.

In CNC milling, a dedicated computer system performs the basic controlling functions over the movement of a machine tool using a set of coded instructions. The geometry

is imported into so-called post-processing software that generates the CNC instructions which are transmitted to the milling machine. The CNC instructions control the motion, the feedrate, operation of the spindle drive, coolant supply, tool changes, and other operational parameters. As milling of shapes can be accomplished in a variety of ways, generating an appropriate "tool path" is not a trivial task, especially for four- or five-axis machines, which is often executed by skilled operators. The tool path itself is expressed as a CNC program, which is nothing more than a sequence of coded instructions for the machine to execute (figure 3.15). The CNC programs are made of commands that consist of words, each of which has a letter address and an associated numerical value. The so-called preparatory functions that, for example, control the motion of the machining tool, are often designated with a "G" letter. In a typical CNC program, the majority of "words" are these preparatory functions. Because of this, the CNC code is often referred to as "G-code" among CAM (computer-aided manufacturing) operators.

The CNC multi-axis milling is one of the oldest digital fabrication technologies. Early experiments in using CNC milling machines to produce architectural models were carried out in early 1970s in the United Kingdom. Large architectural firms in the United States,
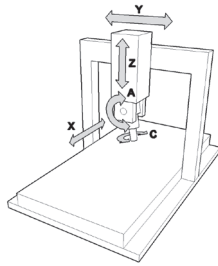
3.14. Five-axis milling system.

such as Skidmore, Owings and Merrill's (SOM) office in Chicago, have used CNC milling machines and laser cutters extensively in the production of architectural models and studies of construction assemblies. Automated milling machines were used in the late 1980s and in the 1990s to produce construction components,[4] such as stones for New York's *Cathedral of Saint John the Divine* and columns for the *Sagrada Familia Church* in Barcelona. Frank Gehry's project for the *Walt Disney Concert Hall* in Los Angeles represents the first comprehensive use of CAD/CAM to produce architectural stonework (before that project was redesigned with a metal skin). For the initial 1:1 scale model, the stone panels with double-curved geometry were CNC milled in Italy and then shipped to Los Angeles, where they were positioned and fixed in place on steel frames. Gehry's office used this same fabrication technique for the stone cladding in the Bilbao project

The CNC milling has recently been applied in new ways in the building industry—to produce the formwork (molds) for the off-site and on-site casting of concrete elements with double-curved geometry, as was done in one of Gehry's office buildings in Düssel-

dorf, Germany, in 2000, and for the production of the laminated glass panels with complex curvilinear surfaces, as in Gehry's *Condé Nast Cafeteria* project in New York (2000) and Bernard Franken's *"Bubble"* BMW pavilion (1999, figures 3.16a-c).

3.16a–c. The double-curved acrylic glass panels for Bernhard Franken's produced using CNC-*"Bubble"* BMW pavilion (1999) were milled molds.
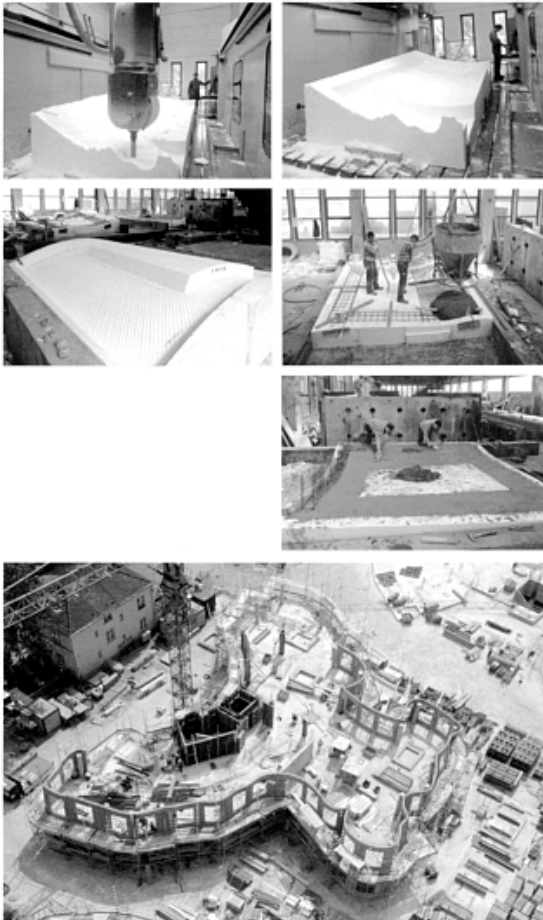
3.17a–f. The reinforced concrete panels for Gehry's Zollhof Towers (2000) in Düsseldorf, Germany, were precast in CNC-milled Styrofoam molds.

In Gehry's project in Düsseldorf *(Zollhof Towers),* the undulating forms of the load-bearing external wall panels, made of reinforced concrete, were produced using blocks of light-weight polystyrene (Styrofoam), which were shaped in CATIA and were CNC milled (figures 3.17a-f) to produce 355 different curved molds that became the forms for the casting of the concrete.[5]

ADDITIVE FABRICATION

Additive fabrication involves incremental forming by adding material in a layer-by-layer fashion, in a process which is the converse of milling. It is often referred to as *layered manufacturing, solid freeform fabrication, rapid prototyping,* or *desktop manufacturing.* All additive fabrication technologies share the same principle in that the digital (solid) model is sliced into two-dimensional layers (figure 3.18). The information of each layer is then transferred to the processing head of the manufacturing machine and the physical product is generated incrementally in a layer-by-layer fashion.

Since the first commercial system based on stereolithography was introduced by *3D Systems* in 1988 (figure 3.19), a number of competing technologies have emerged on the market, utilizing a variety of materials and a range of curing processes based on light, heat, or chemicals.[6] *Stereolithography* (SLA) is based on liquid polymers that solidify when exposed to laser light. A laser beam traces a cross-section of the model in a vat of light-sensitive liquid polymer. A thin solid layer is produced in the areas hit by the laser light. The solidified part, which sits on a submerged platform, is then lowered by a small increment into the vat, and the laser beam then traces the next layer, i.e. the cross-section of the digital model. This process is repeated until the entire model is completed. At the end of the process, the platform with the solidified model is raised from the vat, and the model is then cured to remove extraneous liquid and to give it greater rigidity.

In *Selective Laser Sintering* (SLS), the laser beam melts layer by layer of metal powder to create solid objects. In *3D Printing* (3DP), layers of ceramic powder are glued to form objects (figure 3.20). Sheets of material (paper or plastic), either precut or on a roll, are glued (laminated) together and laser cut in the *Laminated Object Manufacture* (LOM) process. In *Fused Deposition Modeling* (FDM), each cross-section is produced by melting a plastic filament that solidifies upon cooling. *Multi-jet manufacture* (MJM) uses a modified printing head to deposit melted thermoplastic wax material in very thin layers, one layer at a time, to create three-dimensional solids (figure 3.21).

3.18. Layered manufacturing.

3.19. The SLA 250 stereolithography system by 3D Systems.

3.20. ZCorp's Z406 3D printer.

3.21. Thermojet printer by 3D Systems.

Because of the limited size of the objects that could be produced, costly equipment and lengthy production times, the additive fabrication processes have a rather limited application in building design and production. In design, they are used mainly for the fabrication of (massing) models with complex, curvilinear geometries (figure 3.22). In construction, they are used to produce components in series, such as steel elements in light truss structures, by creating patterns that are then used in investment casting (figures 3.23a–b).

Recently, however, several experimental techniques based on sprayed concrete were introduced to manufacture large-scale building components directly from digital data. A fairly recent additive technology called *contour crafting,* invented and patented by Behrokh

Khoshnevis from the University of Southern California, allows fairly quick layered fabrication of highly finished buildings.[7] Contour crafting is a hybrid automated fabrication method that combines extrusion for forming the surface shell of an object and a filling process based on pouring or injection to build the object's core. Computer-controlled trowels, the flat blades used for centuries to shape fluid materials such as clay or plaster, are used to shape the outside edges (rims) of each cross-section on a given layer, which are then filled with concrete or some other filler material. Since material deposition is computer-controlled, accurate amounts of different materials can be added precisely in desired locations, and other elements, such as various sensors, floor and wall heaters, can be built into the structure in a fully automated fashion.

3.22. The stereolithography model of the *House Prototype in Long Island* project by Greg Lynn.
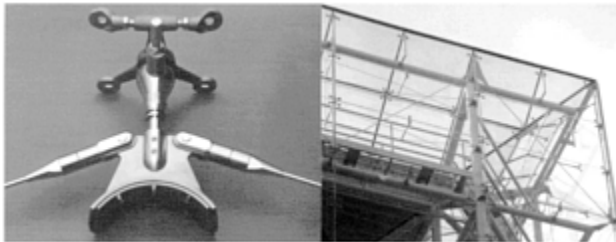
3.23a–b. TriPyramid, a fabricator in New York, used rapid prototyping to manufacture truss elements for Polshek's *Rose Center for Earth and Sciences* (2000) in New York.

FORMATIVE FABRICATION

In formative fabrication mechanical forces, restricting forms, heat or steam are applied to a material so as to form it into the desired shape through reshaping or deformation, which can be axially or surface constrained. For example, the reshaped material may be deformed permanently by such processes as stressing metal past the elastic limit, heating metal and then bending it while it is in a softened state, steam-bending boards, etc. Double-curved, compound surfaces can be approximated by arrays of height-adjustable,

numerically- controlled pins, which could be used for the production of molded glass and plastic sheets and for curved stamped metal. Plane curves can be fabricated by the numerically-controlled bending of thin rods, tubes or strips of elastic material, such as steel or wood, as was done in several exhibition pavilions designed by Bernhard Franken for BMW (figures 3.24a–b).

ASSEMBLY

After the components are digitally fabricated, their assembly on site can be augmented with digital technology. Digital three-dimensional models can be used to precisely determine the location of each component, move each component to its location and, finally, fix each component in its proper place. Traditionally, builders took dimensions and coordinates from paper drawings and used tape measures, plumb-bobs and other devices to locate the building components on site. New digitally-driven technologies, such as electronic surveying and laser positioning (figure 3.25), are increasingly being used on construction sites around the world to precisely determine the location of building components. For example, as described by Annette LeCuyer, Frank Gehry's *Guggenheim Museum* in Bilbao "was built without any tape measures. During fabrication, each structural component was bar coded and marked with the nodes of intersection with adjacent layers of structure. On site bar codes were swiped to reveal the coordinates of each piece in the CATIA model. Laser surveying equipment linked to CATIA enabled each piece to be precisely placed in its position as defined by the computer model."[8] Similar processes were used on Gehry's EMP project in Seattle (figures 3.26a-c).[9] As LeCuyer notes, these processes are common practice in the aerospace industry, but relatively new to building.[10]

The geometric data extracted from the digital three-dimensional model can be used to control construction robots that can automatically carry out a variety of tasks on construction sites. In Japan, a number of robotic devices for the moving and fixing of components were developed, such as Shimizu's *Mighty* Jack for heavy steel beam positioning, Kajima's *Reinforcing Bar Arranging Robot,* Obayashi-Gumi's *Concrete* Placer for pouring

3.24a–b. The CNC bending of the aluminum profiles for the *"Brandscape"* BMW Pavilion at the 2000 Auto Show in Geneva, Switzerland, architects Bernhard Franken and ABB Architekten.

concrete into forms, Takenaka's *Self-Climbing Inspection Machine,* Taisei's *Pillar Coating Robot for* painting, and Shimizu's *Insulation Spray Robot* (figure 3.27).

3.25. Trimble's 5600 Series Total Station advanced surveying system.

It is conceivable that in the not so distant future architects will directly transmit the design information to a construction machine that will automatically assemble a complete building. The SMART system, which stands for *Shimizu Manufacturing system by Advanced Robotics Technology,* is the world's first digitally-driven, automated construction system that was actually applied to a full-scale building project. In the 20-storey *Juroku Bank Building* in Nagoya, Japan, Shimizu's SMART construction machine automatically erected and welded the structural steel frame and placed and installed the concrete floor panels and exterior and interior walls. The SMART system showed that it is possible to fully automate the identification, transport and installation of building components using a computerized information management system.

These experiments by Japanese construction companies are System (GPS) harbingers of the inevitable digital evolution in the building industry. A radical reconceptualization of building practices is technologically possible today; the realities of economic and social constraints in the building industry simply mean that the processes of change will be evolutionary rather than revolutionary, and will most likely occur over several decades.
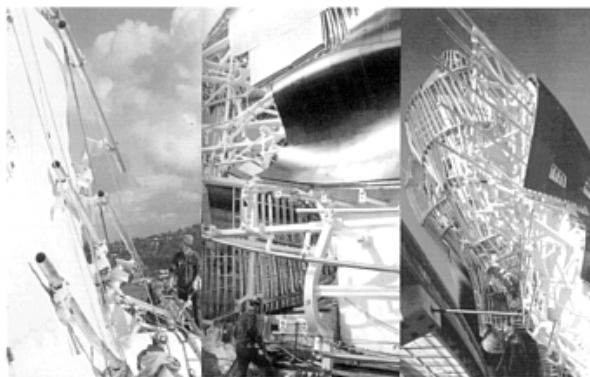
3.26a–c. Global Positioning technology was used on Frank Gehry's *Experience Music Project* in Seattle (EMP) (2000) to verify the location of components.

SURFACE STRATEGIES

Architects today digitally create and manipulate NURBS surfaces, producing building skins that result not only in new expressive and aesthetic qualities, but also in new tectonic and geometric complexities. It is the surface and not necessarily the structure that preoccupies the work of the digital avant-garde in its exploration of new formal territories. The exterior surface of a building—its skin—becomes necessarily emphasized due to the logics of formal conception inherent in the NURBS-based software, as discussed in the previous chapter.

The explorations in constructability of geometrically complex envelopes in the projects of the digital avant-garde have led to a rethinking of surface tectonics. The building envelope is increasingly being explored for its potential to reunify the skin and the structure in opposition to the binary logics of the Modernist tectonic thinking. The structure becomes embedded or subsumed into the skin, as in *semi-monocoque* and *monocoque* structures, in which the skin absorbs all or most of the stresses. The principal idea is to conflate the structure and the skin into one element, thus creating self-supporting forms that require no armature. That, in turn, prompted a search for "new" materials, such as high-temperature foams, rubbers, plastics and composites, which were, until recently, rarely used in the building industry. As observed by Joseph Giovannini, "the idea of a structural skin not only implies a new material, but also geometries, such as curves and folds that would enable
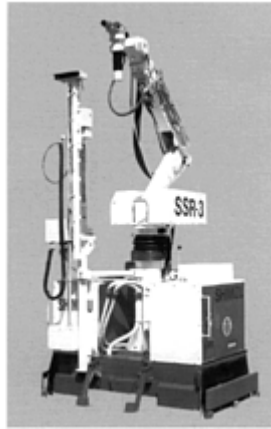
3.27. Shimizu's *Insulation Spray Robot*.

the continuous skin to act structurally, obviating an independent static system: The skin alone does the heavy lifting."[11] Thus, an interesting reciprocal relationship is established between the new geometries and new materialities: new geometries opened up a quest for new materials and vice versa. Kolatan and Mac Donald's *Raybould House* addition (2003) project in Connecticut (figure 3.28) nicely illustrates that reciprocity—the building is to

be made of polyurethane foam sprayed over an egg-crate plywood armature that should be CNC cut (figure 3.29); the resulting monocoque structure is structurally self-sufficient without the egg-crate, which should remain captured within the monocoque form.

The fusion of the structure and the skin in monocoque and semi-monocoque envelopes is already having a considerable impact on the design of structures and cladding in particular. The new thin, layered building envelopes are made of panels that provide not only enclosure and structural support, but also contain other systems typically placed into ceilings or floors. These developments in cladding are driven in part by technologies and concepts from other industries, such as the "stressed skins" long used in automotive, aerospace, and shipbuilding production. For example, in airplanes, the cage-like structure called *airframe* (figure 3.30), made from aluminum alloys, is covered by aluminum panels to form a semi-monocoque envelope in which the structure and skin are separate tectonic elements but act in unison to absorb stresses.

The "blobby" shell of the *NatWest Media Centre* (1999) building (figure 1.21) at Lord's Cricket Ground in London was designed by Future Systems and built as an aluminum semi-monocoque structure in a boatyard. Aluminum was the material of choice because it does not corrode and it can be formed to make a waterproof skin; the skin is also structural in this case, thus making a separate framing structure or cladding unnecessary. The shell was manufactured from CNC cut, 6 and 12 mm thick aluminum plates and was pre-assembled in a boatyard (figure 1.22). It was then divided into 26, 3 m wide sections (figure 3.31) and transported to the site, where it was reassembled on two giant concrete pillars. Aluminum semi-monocoque structures were also used by Jakob and MacFarlane in the *Georges Restaurant* (2000), at Centre Pompidou, Paris, France (figures 3.32 and 33a-b). The structural elements were digitally cut out of 10 mm thick aluminum; the skin was made from 4 mm thick sheets of aluminum that were bent into doubly-curved shapes using traditional boat building methods.

The implications of these new structural skins are significant, as noted by Joseph Giovannini, because they signify a radical departure from Modernism's ideals:
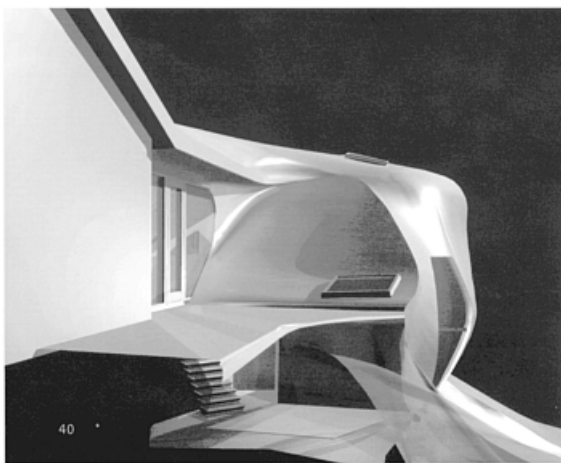
3.28. Kolatan and Mac Donald's *Raybould House* addition (2003) in Connecticut.
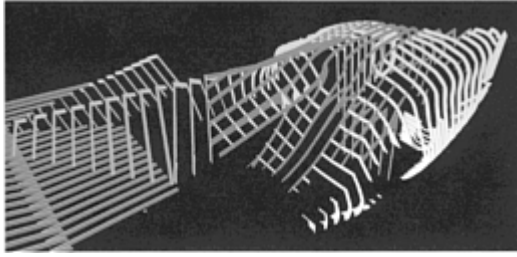
3.29 Raybould House: eggcrate armature for the polyurethane shell.
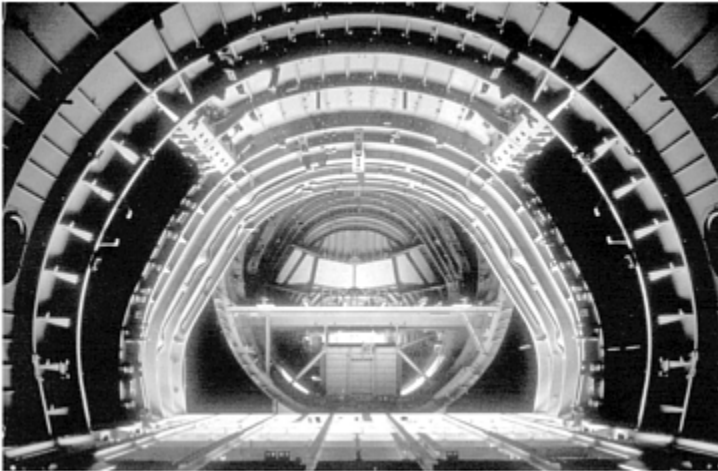
3.30. In airplanes the structure and the skin act in unison to absorb stresses.

"In some ways the search for a material and form that unifies structure and skin is a counterrevolution to Le Corbusier's *Domino House,* in which the master separated structure from skin. The new conflation is a return to the bearing wall, but one with freedoms that Corb never imagined possible. Architects could build many more exciting buildings on the *Statue of Liberty* paradigm, but complex surfaces with integrated structures promise a quantum leap of engineering elegance and intellectual satisfaction."[12]
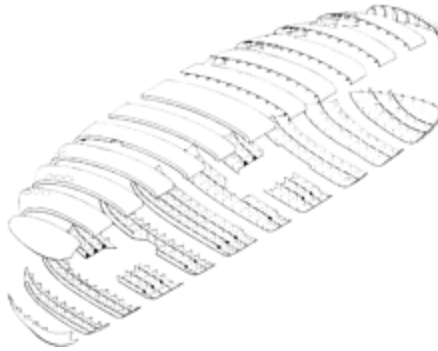
3.31. *NatWest Media Centre* (1999), Lord's Cricket Ground, London, UK, architect Future Systems: the semi-monocoque aluminum shell was made from 26 segments.

3.32. *Restaurant Georges* (2000), Centre Pompidou, Paris, France, architects Jakob + Mac-Farlane.

Other less radical strategies involve offsetting the structure from the skin into its own layer (figure 3.34), which is the approach Frank Gehry has applied to most of his recent projects. The process of working from the skin to the structure is a common practice in automotive and aerospace industries, where the spatial envelope is fixed early on. Such an approach is a relative novelty in architecture, a clear departure from the "primacy of structure" logics of the Modernism. Another approach is a distinct separation of the skin and the structure, where the spatial juxtaposition can produce potent visual interplays. Gustave Eiffel's structural frame for Auguste Bartholdi's contoured skin for the *Statue of Liberty* (figure 3.35)
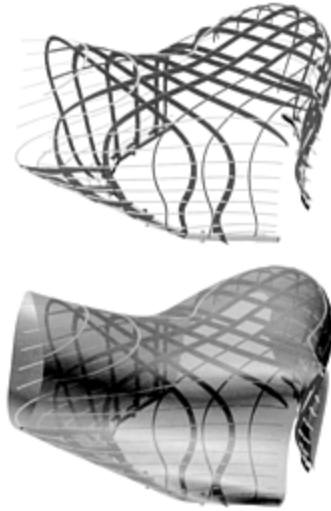
3.33a–b. *Restaurant Georges:* model of the monocoque shell for the "bar" volume.

3.34. Assembly of the structural frame for the *Disney Concert Hall* (2003), Los Angeles, architect Frank Gehry.

provides a telling precedent that demonstrates clearly the possibilities that open up by such an approach to surface tectonics. There is also a conventional approach in which the sinuous skin is attached to a conventionally-conceived structural grid, which, if carefully applied, can produced interesting results. Each of these approaches to skin and structure is perfectly valid and each has different repercussions for the development of the project relative to its overall cost and desired spatial qualities.

   The strategies for articulating the tectonics of NURBS-based envelopes are driven by their geometric complexity, possibilities and resistances offered by the intended material composition, and structural considerations, all of which could have significant implications for the overall cost of the project These "rules of constructability" often demand rationalizations in the geometry of tectonic components, which could be ordered according

to their cost (from lower to higher) into straight or flat, radially bent, doubly curved, and highly shaped (or distorted, often by stretching). The digital technologies enable architects to attain exact control over the budget by precisely controlling the geometry.

3.35. *Statue of Liberty* (1886), New York, architects Gustave Eiffel and Auguste Bartholdi: folds, armature and bracing.
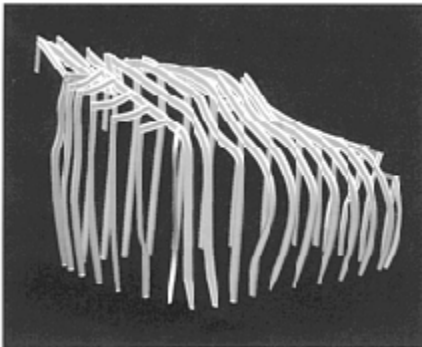
3.36a–b. Structural frames in Frank Gehry's *Experience Music Project* (2000) in Seattle were produced by contouring.
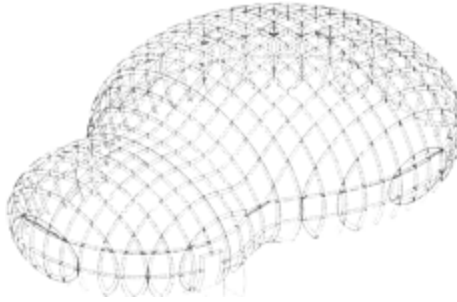
3.37. Structural framework for Bernhard Franken's "Bubble" BMW Pavilion produced by bi-directional contouring.

PRODUCTION STRATEGIES

The production strategies used for two-dimensional fabrication often include *contouring, triangulation* (or *polygonal tessellation*), use of *ruled, developable surfaces,* and *unfolding.* They all involve the extraction of two-dimensional, planar components from geometrically complex surfaces or solids comprising the building's form. The challenge in the two-dimensional interpretation, of course, is to choose an appropriate geometric approximation that will preserve the essential qualities of the initial three-dimensional form. Which of the production strategies is used depends on what is being defined tectonically: structure, envelope, a combination of the two, etc.

In contouring, a sequence of planar sections, often parallel to each other and placed at regular intervals, are produced automatically by modeling software from a given form and can be used directly to articulate structural components of the building, as was the case in a number of recently completed projects (figures 3.36a-b and 3.37). Contouring is conceptually identical to a process called *lofting* in shipbuilding, in which the shape of a ship's hull is defined by a sequence of planar lateral cross-sections that become "ribs" mounted on a "spine" that runs lengthwise (figure 3.38).
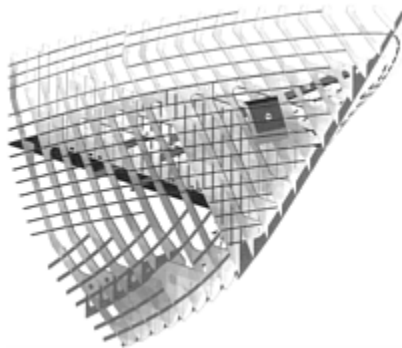
3.38. Structural framework for a ship's hull.

The wireframe cross-sections, produced by contouring, can be further manipulated to create a complete abstraction of the building's structural framework, which could then be processed by the structural analysis software to generate the precise definition of all structural members. In Gehry's Bilbao project, the contractor used a software program from Germany called *Bocad* to automatically generate a comprehensive digital model of the structural steel, including the brace-framed and secondary steel structures for the museum (figure 3.39).[13] More importantly, that same program was used to automatically produce the fabrication drawings, or CNC data, to precisely cut and pre-assemble the various components.[14] Similar structural steel detailing software (and fabrication) were used on the *Walt Disney Concert Hall* and other recent projects by Gehry's office.
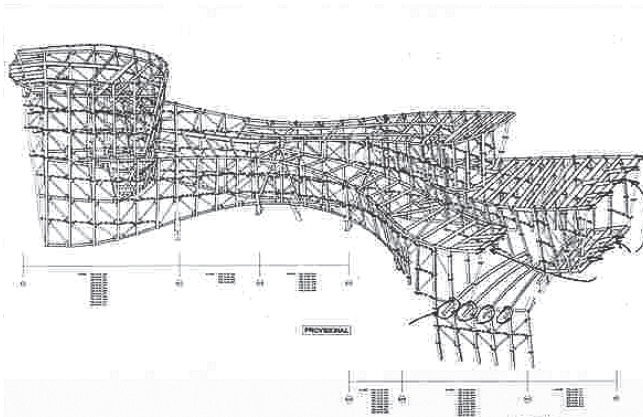
3.39. Steel detailing software was used to generate a comprehensive digital model of the steel structure for Gehry's *Guggenheim Museum* (1997) in bilbao, Spain.

A potentially interesting contouring technique involves the extraction of the isoparametric curves ("isoparms") used to aid in visualizing NURBS surfaces through contouring in the "U" and "V" direction, as discussed in the previous chapter. For example, the tubular members for the *"Brandscape"* BMW Pavilion (figure 3.40), designed by Bernhard Franken in association with ABB Architekten for the 2000 Autoshow in Geneva, featured CNC-formed, doubly-curved geometry extracted as isoparms from the complex NURBS surface (figure 3.41). Sometimes, due to budgetary or other production-related constraints, the complex geometry of the NURBS curves can be approximated with circular, radial geometry, which can be inexpensively manufactured using rolling machines (figure 3.42). In this approach, the complexity lies in the precise connection among different pieces and the required temporary structures for assembly. This approximation, using radial geometry, was also used by Franken and his team for the production of structural members in the *"Brandscape"* BMW Pavilion.

3.40. Assembly of the *"Brandscape"* BMW Pavilion at the 2000 Auto Show in Geneva, Switzerland, architects Bernhard Franken and ABB Architekten.

While isoparms can lead to a "true" tectonic expression of the three-dimensional form, they pose non-trivial production challenges, as fabrication of doubly-curved structural members requires expensive equipment and temporary egg-crate (created through planar contouring) or other structures for the precise positioning in the construction assembly. The use of NURBS isoparms may also lead to suboptimal structural solutions; instead, isoparametric curves produced by structural analysis could be used for defining the geometry of structural components.
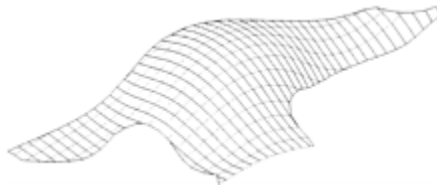
3.41. *"Brandscape":* the frame members' geometry was derived from the NURBS surface isoparms.

3.42. *"Brandscape":* the geometry of the perimeter tubes was rationalized into tangent circular arcs.

Complex, curvilinear surface envelopes are often produced by either *triangulation* (figure 3.43) or some other planar tessellation, or by the conversion of double-curved into ruled surfaces, which are generated by linear interpolation between two curves (figure 3.44). Triangulated or ruled surfaces are then unfolded into planar strips (figures 3.45 and 3.46), which are laid out in some optimal fashion as two-dimensional shapes on a sheet (in a process called *nesting*), which is then used to cut the corresponding pieces of the sheet material using one of the CNC cutting technologies.

3.43. Triangulation of a doubly-curved surface.
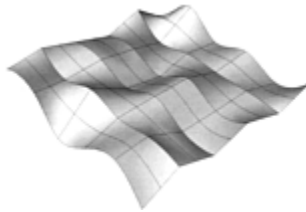
3.44. Ruled surface
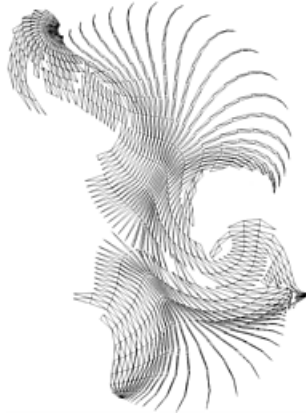
3.45. Unfolded triangulated surface (shown in 3.43).
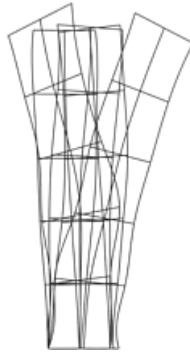
3.46. Unfolded ruled surface (shown in 3.44).
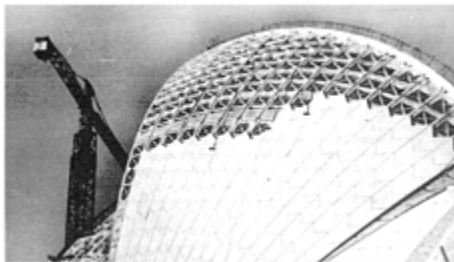
3.47. Tessellated roof shell of the *Sydney Opera House* (1973), architect Jørn Utzon.

One of the best know examples of polygonal tessellation are the roof forms of the *Sydney Opera House* (1973) designed by Jørn Utzon. The initial freeform shapes sketched by Utzon were first approximated by surface segments extracted from spheres of varying radii, and were then subdivided into flat patches (figure 3.47). Triangulation is the most commonly applied form of planar tessellation. It was used, for example, in the glass roof of the *DG Bank* (2001) building (figure 3.48) that Frank Gehry designed at Parizer Platz in Berlin, Germany. The triangulated space frame was constructed from solid stainless steel rods that meet at different angles at six-legged star-shaped nodal connectors, each of which was unique and was CNC cut from 70 mm thick stainless steel plate. The frame was infilled by approximately 1,500 triangular glazing panels, which were also CNC cut. A similar production strategy was used in the glass roof of the *Great Court* in the British Museum in London, designed by Foster and Partners (figure 3.49). The irregularly-shaped and deformed "sliced" torus form of the roof was rationalized as a triangulated frame network consisting of 4,878 hollow rods and 1,566 connector nodes, all of them different from each other and all of them CNC cut. The frame was then filled with 3,312 glass panes, each of which was unique, due to the irregular geometry of the roof's perimeter.
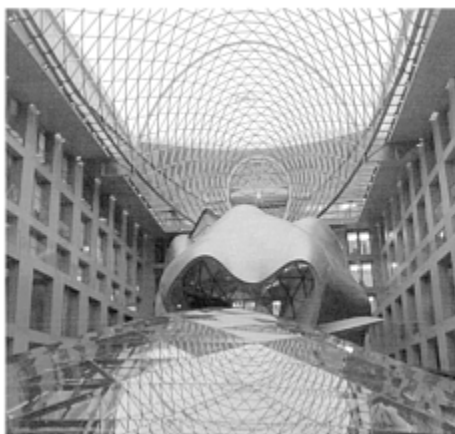
3.48. Triangulated complex surfaces in Frank Gehry's *DG Bank* (2000) building in Parizer Platz, Berlin, Germany.

In some of their recent projects, Foster's office has created designs with complex geometries that are based on parameterized, concatenated torus patches that smoothly transition to each other. As with complex curves, rationalizations based on the radial geometry of spheres, cones, cylinders or tori, are often deployed to approximate complexly-curved surfaces. The roof structure of the *Music Centre* (2003) in Gateshead, UK, designed by Foster's office, consists of a series of torus patches, which curve in both directions and are mutually dependent (figure 3.50). Each of the patches is subdivided into bands of identical four-sided flat panels, whose size can be parametrically varied to match the specific production and construction constraints.

3.49. The triangulated toroidal surface of the *British Museum Great* Court (2000), London, UK, architect Foster and Partners.

Other multi-sided tessellation patterns are also possible. More sophisticated modeling programs often provide a rich repertoire of tessellation options, allowing designers to choose not only the geometry of the patches but also their minimum and maximum size. By varying the tessellation parameters, designers could interactively explore various approximation strategies to match various cost and production scenarios. Other surface subdivision algorithms can be used to divide a complex surface into a collection of patches, which are not necessarily flat. Sometimes, custom surface subdivision procedures are developed, as was done by Dennis Shelden in Gehry's office for the definition of the geometry of some 21,000 different metal shingles on the EMP project in Seattle (figure 3.51).

Another method of "rationalizing" double-curved surfaces is to convert them into "rule-developable" surfaces. Ruled surfaces are generated by linear interpolation between two
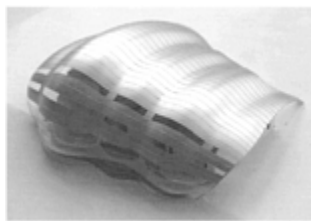
3.50. The toroidal geometry of Foster and Partner's *Music Centre* (2003), Gateshead, UK.

curves in space, i.e. by connecting pairs of curves with straight, "ruling" lines that are placed at regular intervals (figure 3.44). A wide variety of surfaces can be generated in this fashion. The simplest ones are cones and cylinders; the more interesting forms from an architectural point of view are saddle-shaped hyperbolic paraboloids (figure 3.52) and hyperboloids (figure 3.53), a common form for the cooling towers of nuclear power stations.

The ruled surfaces are fairly easy to construct using conventional construction techniques. Relatively simple formwork is required for concrete structures. Stonemasons, for example, have used templates to cut complex ruled surface forms out of stones for centuries. For some architects, such as the well-known Uruguayan architect Eladio Dieste, the ruled surfaces were a preferred means of architectural expression in a number of his building designs (figure 3.54).
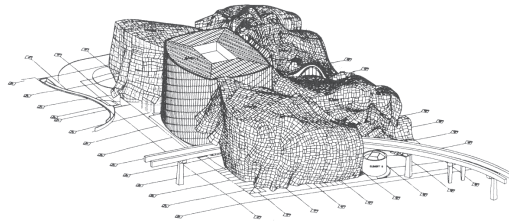
3.51. Surface subdivision of the exterior envelope in EMP (2000), Seattle, architect Gehry Partners.
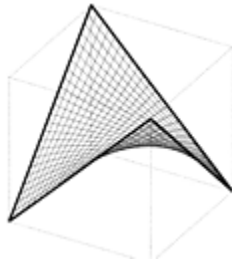
3.52. Ruled surface: hyperbolic paraboloid.

3.53. Ruled surface: hyperboloid.

Ruled surfaces are used extensively in contemporary architectural practice because they can be "developed," i.e. unfolded into flat shapes in modeling software (figure 3.46), and digitally fabricated out of flat sheets. "Developable" surfaces can be formed by rolling a flat sheet of material without deformation, i.e. with no stretching, tearing or creases. They curve only in one isoparametric direction, i.e. they are linear in the other direction (figure 3.55a–c), unlike the doubly-curved NURBS surfaces.

Frank Gehry's office relies extensively on the use of ruled, developable surfaces to ensure the buildability of his sinuous designs within reasonable schedule and budgetary constraints (figures 3.56a– b). Gehry physically models his conceptual designs by shaping into desired forms the "developable" strips of paper or metal. These forms are digitized and the resulting surfaces are then analyzed in CATIA software and converted into digitally developable surfaces.
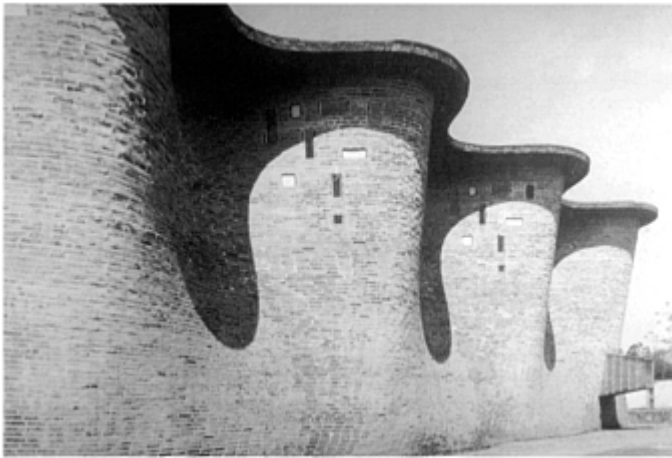
3.54. *Atlantida Church* (1958), Uruguay, architect Eladio Dieste.
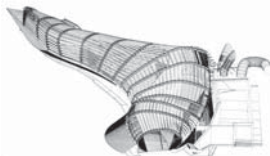
3.55a–c. Use of ruled surfaces in the *Water Pavilion* (1998), the Netherlands, architect Lars Spuybroek/NOX Architects.
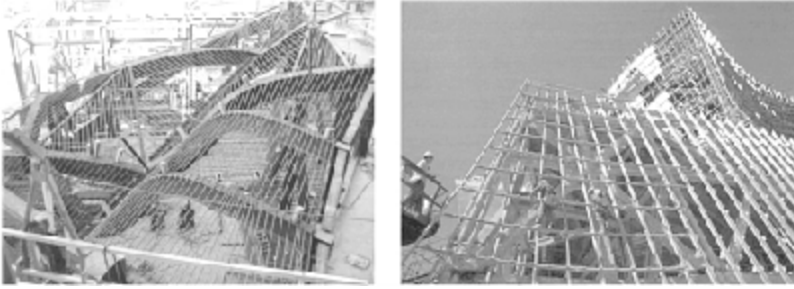
3.56a–b. Use of ruled surfaces in the *Walt Disney Concert Hall* (2003), Los Angeles, architect Gehry Partners.
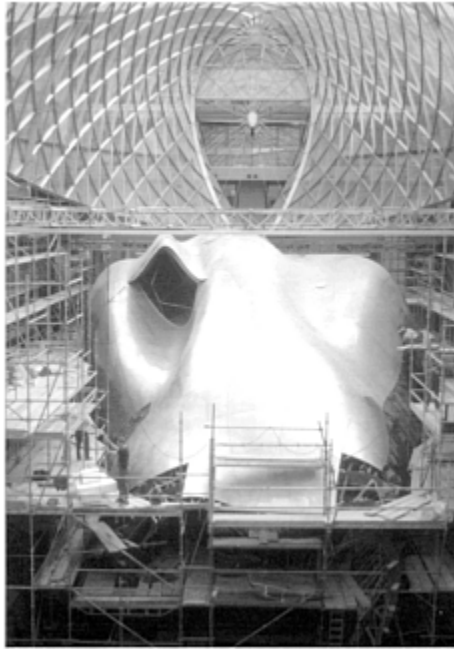
3.57. The doubly curved steel plates for the conference chamber of the *DG Bank* (2000), Berlin, Germany, architect Gehry Partners.

The fabrication technologies allow the production of non-developable doubly-curved surfaces, albeit at a higher cost. As discussed earlier, doubly-curved concrete elements can be formed in CNC-milled Styrofoam molds, as was done for the *Zollhof Towers* (2000) designed by Gehry in Düsseldorf, Germany (figures 3.17a–f). Glass panels with complex curvature can be produced in a similar fashion, by heating the flat sheets of glass over

CNC-milled molds in high-temperature ovens (figures 3.16a–d). CNC-driven pin-beds can be used to shape metal panels into doubly-curved forms. For example, the large stainless steel plates (2 m×4 m) for the conference chamber of the *DG Bank* (2000) building, designed by Gehry at the Parizer Platz in Berlin, were shaped by boatbuilders to produce its complex doubly-curved form (figure 3.57).

Whether a particular section of the building's envelope is produced as a developable or doubly-curved surface can be determined by applying the *Gaussian* analysis to the surface model. The Gaussian analysis evaluates the degree of curvature in complexly-shaped elements and produces a colored image that indicates, through various colors, the extent of the surface curvature—a blue color indicates areas of no or minimum curvature, red is applied to maximum values, and green is used for areas with a median curvature (figure 3.58). Developable surfaces, for example, have zero Gaussian curvature at every point on the surface, because they are linear in one direction (figure 3.59).

3.58. Gaussian analysis of a doubly-curved surface.

3.59. Gaussian analysis of a developable surface.

In designing the *Guggenheim Museum* in Bilbao, Gehry's office used the Gaussian analysis to determine the areas of excessive curvature (figure 3.60), as there are limits as to how much the sheets of metal could be bent in two directions—the same technique was used on other projects by Gehry. For example, Gaussian analysis was used in the *EMP* in Seattle to determine which of the apparently double-curved surface patches can be converted into developable ones (figure 3.61) and which ones need to be complexly shaped, thus providing Gehry's office with an important ability to determine and control the overall cost of manufacturing elements of a particularly complex envelope.
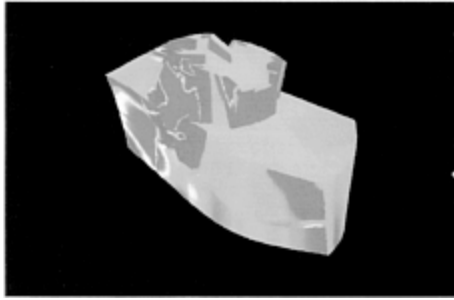
3.60. *Guggenheim Museum:* Gaussian analysis.
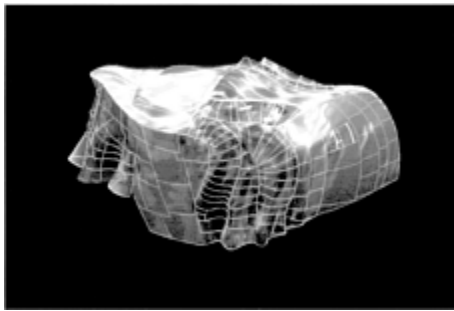
3.61. *Experience Music Project* Gaussian analysis.

NEW MATERIALITY

New forms of architectural expression and advances in material science have led to a renewed interest among architects in materials, their properties and their capacity to produce desired aesthetic and spatial effects. As was often the case in the past, a formal departure from the basic, normative geometries would often coincide with the development of new materials. Freely formable materials, such as concrete and plastics, have led, for example, to renewed interest into "blobby" forms in the 1950s and 1960s, as discussed in Chapter 1.

The contemporary emphasis on surface articulation is fundamentally related to the possibilities and resistances offered by the intended material composition. New materials for architectural skins are offering the unprecedented thinness, dynamically-changing properties, functionally-gradient composition, and an incredible repertoire of new surface effects. For example, the titanium sheets that cover the exterior of Gehry's *Guggenheim Museum* in Bilbao have the thickness of only 0.38 mm. But it is not this thinness that is driving the increasing interest in new materials. The building skins are also acquiring a new complexity as new digital and mechanical networks become embedded into their composite layers. Structural skins with dynamic behavior are challenging the prevalent assumptions about the tectonics and the permanence of the material conditions.

The old, familiar materials, such as brick, are today being used in novel ways, as shown by the sinuous masonry wall of the *Craword Municipal Art Gallery* (2000) in Cork, Ireland (figure 3.62), designed by Erick van Egeraat Architects, which emphasizes the new addition while adhering to the local vernacular. Van Egeraat's design is a contemporary version of the smooth, fluid forms of Eladio Dieste's buildings constructed from bricks and mortar (figure 3.54). Beneath the plastered, curving exterior walls in one of the three office towers designed by Frank Gehry in Düsseldorf, Germany, is a framework construction of CNC cut steel rules with in-fill masonry (figure 3.63), a distant contemporary antecedent of Erich Mendelsohn's *Einsteinturm* (1921, figure 1.4) in Potsdam, Germany, whose fluid shapes, conceived in concrete, were also realized in bricks and plaster.

3.62. *Craword Municipal Art* Gallery (2000), Cork, Ireland, architect Erick van Egeraat Architects.

3.63. Masonry walls in one of the *Zollhof Towers* (2000), Düsseldorf, Germany, architect Gehry Partners.

Conventional materials are being reconceptualized in new ways. For instance, the conventional steel rebar grid in reinforced concrete can be replaced with a non-corroding carbon fiber grid, producing concrete structures that are lighter and considerably stronger than steel reinforced concrete. Carbon fibers made from carbon *nanotubes* could even become the building material of the twenty-first century, replacing steel as the material of choice for the skeletal systems in buildings. Carbon atoms can create tiny spheres, which, with an appropriate catalyst, can form tiny, nano-scale edgeless tubes—"nanotubes" (figure 3.64)—that have very high strength and are much stronger than steel: a single nanotube (figure 3.65) can support more than a billion times its own weight! Once the bulk manufacturing of nanotubes becomes a reality in a decade or so, we will probably start to see some incredibly thin, but exceptionally strong, beams and walls. Nanotubes could form "gossamer structures that open up spatial realms far beyond anything we could imagine," according to Antoine Predock,[15] who says that "blobs would seem heavy-handed by comparison," as "nanoscale structures would be like clouds."

While new construction materials made of carbon nanotubes are still in the realm of the "not-yet" future, other commonly available materials, such as fiberglass, polymers and foams, offer several advantages over materials commonly used in current building practice. They are lightweight, have high strength, and can be easily shaped into various forms. For example, the physical characteristics of fiberglass make it particularly suitable for the

3.64. Digital model of a double nanotube.
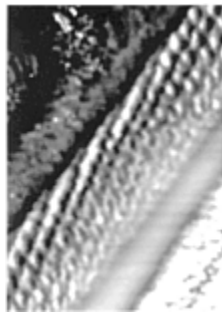
3.65. Microscopic image of a carbon nanotube.

fabrication of complex forms. It is cast in liquid state, so it can conform to a mold of any shape and produce a surface of exceptional smoothness—a liquid, fluid materiality that produces liquid, fluid spatiality, as manifested in Kolatan and Mac Donald's design for the *Ost/Kuttner Apartments* in New York (figure 2.26).

The "liquid" materials that have aroused particular interest among architects today are *composites* whose composition can be engineered precisely to meet specific performance criteria, and whose properties can vary across the section to achieve, for example, a different structural capacity in the relationship to local stress conditions and surface requirements. These layered materials, commonly used in automotive, aerospace, shipbuilding and other industries (figure 3.66), are experimented with for possible architectural applications, as they offer the unprecedented capability to design material effects by digitally controlling the production of the material itself.

Composites are actually solid materials created, as their name suggests, by combining two or more different constituent material components, often with very different properties. The result is a new material that offers a marked qualitative improvement in performance, with properties that are superior to those of the original components. A composite

3.66. Closeup of a bicycle frame made of a carbon fiber composite material.

material is produced by combining two principal components—the *reinforcement* and the *matrix,* to which other filler materials and additives could be added. The matrix is, typically, a metallic, ceramic or polymer material, into which multiple layers of reinforcement fibers, made from glass, carbon, polyethylene or some other material, are embedded. Lightweight fillers are often used to add volume to the composites with minimal weight gain, while various chemical additives are typically used to attain a desired color or to improve fire or thermal performance.

The actual components made from composite materials are usually formed over CNC-milled molds, as in boatbuilding, to produce boat hulls or large interior components, or in closed moulds by injecting the matrix material under pressure or by partial vacuum, as is done in the automotive industry for the production of smaller-scale components. In the building industry, composite panels are produced either through continuous lamination or by using the resin transfer molding.

Among composites, the polymer composite materials, or simply "plastics," are being considered with renewed interest by architects, primarily because of their high formability, relatively low cost, minimum maintenance, and a relatively high strength-to-weight ratio. Plastics were used with great enthusiasm in the 1960s and 1970s because of their novelty as a material and their ability to take any shape, but the poor weathering capabilities, the shifting aesthetics of the late 1970s and early 1980s, and the ubiquity of plastic products, led to their second-class status later on.

It is the *functionally gradient* polymer composite materials that offer the promise of enclosures in which structure, glazing, and mechanical and electrical systems are synthesized into a single material entity. By optimizing material variables in composites for local performance criteria, entirely new material and tectonic possibilities open up in architecture. For example, transparency can be modulated in a single surface, and structural performance can be modulated by varying the quantity and pattern of reinforcement fibers, etc.[16]

Other possibilities are opened up by materials that change their properties dynamically in direct response to external and internal stimuli, such as light, heat and mechanical stresses. Kolatan and Mac Donald are exploring, in their speculative projects, materials such as "plastics that undergo molecular restructuring with stress," "smart glass that responds to light and weather conditions," "anti-bacterial woven-glass-fiber wall covering" and "pultruded fiberglass-reinforced polymer structural components."

New skins begin to change not only their transparency and color, but also their shape in response to various environmental influences, as the *Aegis Hyposurface* project by Mark Goulthorpe shows. This project was developed initially as a competition entry for an interactive art piece to be exhibited in the Birmingham Hippodrome Theater foyer. The developed construct is a highly faceted metallic surface, which is actually a deformable, flexible rubber membrane covered with tens of thousands of triangular metal shingles (figure 3.67), and which can change its shape in response to electronic stimuli resulting from movement and changes in sound and light levels in its environment, or through parametrically-generated patterns. It is driven by an underlying mechanical apparatus that consists of several thousand pistons, which are controlled digitally, providing a real-time response. According to Goulthorpe, this project "marks the transition from autoplastic (determinate) to alloplas-tic (interactive, indeterminate) space;" it "utterly radicalize[s] architecture by announcing the possibility of dynamic form."

Goulthorpe's *Aegis Hyposurface* dynamic skin, a highly complex, electromechanical hybrid structure, whose sensors, pneumatic actuators, and computational and control systems provide it with what could be called "intelligent" behavior, points to a material

3.67. *Aegis Hyposurface* (1999), architect Mark Goulthorpe/dECOi.

future in which it could become a fairly thin, single "intelligent" composite material with a "neural" system fully integrated into its layers.

"Intelligent," "smart," "adaptive" and other terms are used today to describe a higher form of composite materials that have sensing, actuation, control and intelligence capabilities. These composites have their own sensors, actuators, and computational and control firmware built into their layers. According to another definition, intelligent materials are those materials that possess adaptive capabilities to external stimuli through built-in "intelligence." This "intelligence" of the material can be "programmed" through its composition, its microstructure, or by conditioning to adapt in a certain manner to different levels of stimuli. The "intelligence" of the material can be limited to sensing or actuation only. For example, a sensory material is capable of determining particular material states or characteristics and sending an appropriate signal; an adaptive material is capable of altering its properties, such as volume, opacity, color, resistance, etc. in response to external stimuli. An active material, however, contains both sensors and actuators, with a feedback loop between the two, and is capable of complex behavior—it can not only sense a new condition, but can also respond to it.

Some of the early "intelligent" materials, for example, were capable of sensing stress and temperature change through embedded sensors. The complexity, capacities, and utility of the "intelligent" materials, however, have increased dramatically over the past decade, with most of the research efforts concentrated on aerospace applications. Piezoelectric and optical sensors, for example, are embedded into composite material used as a skin in high-performance airplanes. These materially-integrated sensors continually measure stress and chemical changes within an airplane's skin, detecting damage and transmitting an

appropriate signal. Similar sensory mechanisms, for example, are being embedded into "smart" concrete via tiny optical fibers, to monitor stresses and to detect potential damage. By producing materials in a digitally-controlled layer-by-layer fashion, as in additive fabrication, it is possible to embed various functional components, thus making them an integral part of a single, complex composite material.

The developing materials and technologies of the twenty-first century will radically redefine the relationship between architecture and its material reality. Future digital architecture, in its conception and its realization, will respond dynamically to the internal logics and external influences of the environment. Designs are already "alive"—the buildings will soon be as well.

MASS-CUSTOMIZATION

The sparse geometries of the twentieth century Modernism were, in large part, driven by Fordian paradigms of industrial manufacturing, imbuing the building production with the logics of standardization, prefabrication and on-site installation. The rationalities of manufacturing dictated geometric simplicity over complexity and the repetitive use of low-cost mass-produced components. But these rigidities of production are no longer necessary, as digitally-controlled machinery can fabricate unique, complexly-shaped components at a cost that is no longer prohibitively expensive. Variety, in other words, no longer compromises the efficiency and economy of production.

The ability to mass-produce one-off, highly differentiated building components with the same facility as standardized parts, introduced the notion of "mass-customization" into building design and production (it is just as easy and cost-effective for a CNC milling machine to produce 1,000 unique objects as to produce 1,000 identical ones). Mass-customization, the post-Fordian paradigm for the economy of the twenty-first century, was defined by Joseph Pine[17] as the mass production of individually-customized goods and services, thus offering a tremendous increase in variety and customization without a corresponding increase in costs. It was anticipated as a technological capability in 1970 by Alvin Toffler in *Future Shock* and was delineated, as well as named, in 1987 by Stan Davis in *Future Perfect*.[18]
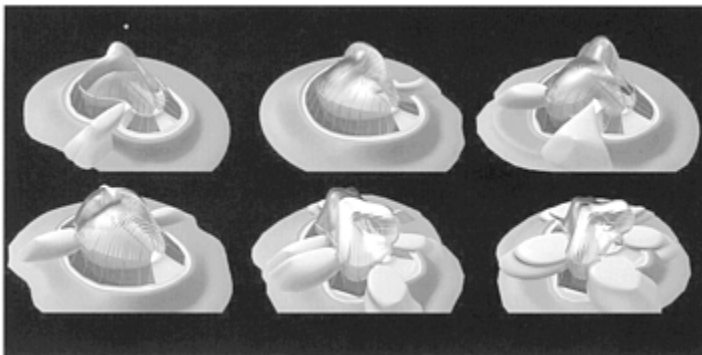
3.68. *Embryologic* Houses (2000), architect Greg Lynn.

Almost every segment of the economy, and industrial production in particular, has been affected by mass-customization, sometimes in very radical ways. Levi's, for example, offers customized jeans, manufactured from body measurements taken by a scanner in one of its stores, at a cost slightly more than a standard pair. Motorola's Paging Products Group lets its customers design their own pagers by choosing the desired frequency, tone, color, software, clips and other components (more than 29 million combinations are possible), and sells them at the same cost as their off-the-shelf predecessors. In Japan, Panasonic sells bicycles that are built to individual rider's measurements, with customized color combinations and other options (with some 11 million possible variations), creating truly mass-produced, built-to-fit, i.e. mass-customized machines.

Mass-customization is a particularly suitable production paradigm for the building industry, since buildings are mostly one-off, highly customized products. A "custom" house will become available to a broader segment of society. Eventually, the technologies and "customization" methods that are developed in the consumer products industry will be applied to building products as well. In buildings, individual components could be mass-customized to allow for optimal variance in response to differing local conditions in buildings, such as uniquely shaped and sized structural components that address different structural loads in the most optimal way, variable window shapes and sizes that correspond to differences in orientation and available views. The digitally-driven production processes will introduce a different logic of seriality in architecture, one that is based on local variation and differentiation in series. It is now possible to produce "series-manufactured, mathematically coherent but differentiated objects, as well as elaborate, precise and relatively cheap one-off components," according to Peter Zellner,[19] who argues that in the process the "architecture is becoming like 'firmware,' the digital building of software space inscribed in the hardwares of construction." That is precisely what Greg Lynn's *Embryologic Houses* (figure 3.68) manifest: mass-customizable individual house designs produced by differentiation achieved through parametric variation in non-linear dynamic processes.

For Bernard Cache, "objects are no longer designed but calculated,"[20] allowing the design of complex forms with surfaces of variable curvature and laying "the foundation for a nonstandard mode of production." His *objectiles* (figure 3.69) are non-standard objects, mainly furniture and paneling, which are procedurally calculated in modeling software and are industrially produced with numerically-controlled machines. For Cache, it is the modification of parameters of design, often random, that allows the manufacture of different shapes in the same series, thus making the mass-customization, i.e. the industrial production of unique objects, possible.

The implications of mass-customization for architecture and the building industry in general are profound. As Catherine Slessor observed, "the notion that uniqueness is now
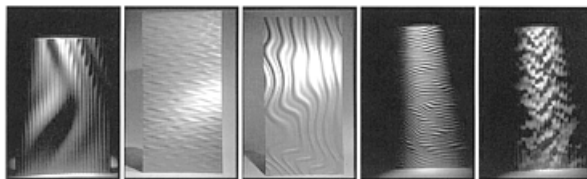
3.69. *Objectiles,* designer Bernard Cache.

economic and easy to achieve as repetition, challenges the simplifying assumptions of Modernism and suggests the potential of a new, post-industrial paradigm based on the enhanced, creative capabilities of electronics rather than mechanics."[21] In the Modernist aesthetic, the house was to be considered a manufactured item ("machine for living"). Mass production of the house would bring the best designs to a wide market and design would not no longer cater to the elite. That goal remains, albeit reinterpreted. The industrial production no longer means the mass production of a standard product to fit all purposes, i.e. one size fits all. The technologies and methods of mass-customization allow for the creation and production of unique or similar buildings and building components, differentiated through digitally-controlled variation.

NOTES

1　For more information about large-scale scanning, see Edward H. Goldberg, "Scan Your World with 3D Lasers" in *Cadalyst,* February 2001 (online at http://www.cadalyst.com/features/0201cyra/index.htm).

2　William J.Mitchell. "Roll Over Euclid: How Frank Gehry Designs and Builds" in J.Fiona Ragheb (ed.), *Frank Gehry, Architect*. New York: Guggenheim Museum Publications, 2001, pp. 352–363.

3　For more information about various fabrication technologies, see W. Mitchell and M.McCullough, "Prototyping" (Chapter 18) in Digital *Design Media,* 2nd edition. New York: Van Nostrand Reinhold, 1995, pp. 417–440.

4　W.Mitchell and M.McCullough, "Prototyping" (Chapter 18) in *Digital Design Media,* 2nd edition. New York: Van Nostrand Reinhold, 1995, pp. 417–440.

5　For more information about this project, see Thomas Rempen, *Frank O. Gehry: der Neue Zollhof Düsseldorf.* Essen, Germany: Bottrop, 1999; and Catherine Slessor, "Digitizing Dusseldorf" in *Architecture,* September 2000, pp. 118–125.

6　For more information about various rapid prototyping technologies, see Chee Kai Chua and Leong Kah Fai, *Rapid Prototyping: Principles & Applications in Manufacturing.* New York: Wiley, 1997; and Detlef Kochan. *Solid Freeform Manufacturing: Advanced Rapid Prototyping.* Amsterdam: Elsevier, 1993.

7　Behrokh Khoshnevis. "Innovative Rapid Prototyping" in Material *Technology,* vol. 13(2), 1998, pp. 53–56.

8　Annette LeCuyer. "Building Bilbao" in *Architectural Review,* December 1997, vol. 102, no. 1210, pp. 43–45.

9　Charles Linn. "Creating Sleek Metal Skins for Buildings" in *Architectural Record,* October 2000, pp. 173–178.

10　Annette LeCuyer. "Building Bilbao." op cit.

11　Joseph Giovannini. "Building a Better Blob" in *Architecture,* September 2000, vol. 89, no. 9, pp. 126–128.

12　*Ibid.*

13　S.Stephens. "The Bilbao Effect" in *Architectural Record,* May 1999, pp. 168–173.

14　Annette LeCuyer. "Building Bilbao." *op cit*.

15　See Erik Baard, "Unbreakable" in *Architecture,* June 2001, p. 52.

16 See Johan Bettum, "Skin Deep: Polymer Composite Materials in Architecture" in Ali Rahim (ed.), *AD Profile 155: Contemporary Techniques in Architecture*. London: Wiley, 2002, pp. 72–76.

17 Joseph B.Pine. *Mass Customization: The New Frontier in Business Competition*. Boston: Harvard Business School Press, 1993.

18 *Ibid.*

19 Peter Zellner. *Hybrid Space: New Forms in Digital Architecture*. New York: Rizzoli, 1999.

20 Bernard Cache. *Earth Moves: The Furnishing of Territories.* Cambridge: MIT Press, 1995.

21 Catherine Slessor. "Digitizing Dusseldorf." *op cit*.

4
INFORMATION MASTER BUILDERS

BRANKO KOLAREVIC

The challenges of constructability left designers of new formal complexities with little choice but to become closely engaged in fabrication and construction, if they were to see their projects realized. Building contractors, used to the current "analog" norms of practice and prevalent orthogonal geometries, were reluctant to take on projects they saw as apparently unbuildable or, at best, with unmanageable complexities. The "experimental architects had to find contractors and fabricators capable of digitally-driven production, who were often not in building but in shipbuilding. They had to provide, and often generate directly, the digital information needed to manufacture and construct the buildings. So, out of sheer necessity, the designers of the digitally-generated "blobby" architecture became closely involved in the digital making of buildings.

In the process, these architects discovered they have the digital information that could be used in fabrication and construction to directly drive the computer-controlled machinery, making the time-consuming and error-prone production of drawings unnecessary. In addition, the introduction and integration of digital fabrication into the design of buildings enabled architects to almost instantaneously produce scale models of their designs using processes and techniques identical to those used in the industry. Thus, a valuable feedback mechanism between conception and production was established.

This newfound ability to generate construction information directly from design information, and not the complex curving forms, is what defines the most profound aspect of much of the contemporary architecture. The close relationship that once existed between architecture and construction (what was once the very nature of architectural practice) could potentially reemerge as an unintended but fortunate outcome of the new digital processes of production. In the future, being an architect will also mean being a builder, not literally, of course, but by digitally generating the information to manufacture and construct buildings in ways that render present inefficient hierarchies of intermediation unnecessary.

The new processes of design and production, born out of the pragmatic ramifications of new formal complexities, are providing unprecedented opportunities for architects to regain the authority they once had over the building process, not only in design, but also in construction. The new relationships between the design and the built work place more control, and, therefore, more responsibility and more power into the hands of architects.

By integrating the design, analysis, manufacture and assembly of buildings around digital technologies, architects, engineers and builders have an opportunity to fundamentally redefine the relationships between conception and production. By reinventing the role of a "master builder," the currently separate disciplines of architecture, engineering and construction can be integrated into a relatively seamless digital collaborative enterprise, thus

bridging "the gap between designing and producing that opened up when designers began to make drawings," as observed by Mitchell and McCullough.[1]

HISTORY OF DISASSOCIATION

For centuries, being an architect also meant being a builder. Architects were not only the masters of spatial effects, but were also closely involved in the construction of buildings. The knowledge of building techniques was implicit in architectural production; inventing the building's form implied inventing its means of construction, and vice versa. The design information was the construction information—one implied the other.

The master builders, from the Greek *tekton* (builder), to the master masons of the Middle Ages were in charge of all aspects of buildings, from their form to the production techniques used in their construction. They had the central, most powerful position in the production of buildings, stemming from their mastery of the material (stone in most cases) and its means of production. As the palette of materials broadened and the construction techniques became more elaborate, the medieval master masons evolved into master builders (or architects) who would integrate increasingly multiplying trades into an increasingly more complex production process.

The tradition of master builders, however, did not survive the cultural, societal and economic shifts of the Renaissance. Leon Battista Alberti wrote that architecture was separate from construction, differentiating architects and artists from master builders and craftsmen by their superior intellectual training. The theory was to provide the essence of architecture, and not the practical knowledge of construction.

Paradoxically, the history of architecture's disassociation from building started in the late Renaissance with one of its most celebrated inventions—the use of perspective representation and orthographic drawings as a medium of communicating the information about buildings. The medieval master builder (architect) used very few models and drawings to test or communicate ideas, and relied instead on direct verbal communication with craftsmen, which, in turn, required continuous presence on site, but provided for a seamless exchange of information at all phases of building. With Alberti's elevation of architects over master builders came the need to externalize information (so it could be communicated to tradesmen) and the introduction of orthographic abstractions, such as plan, section and elevation, into the currency of building. Architects no longer had to be present on site to supervise the construction of the buildings they designed.

The rifts between architecture and construction started to widen dramatically in the mid-nineteenth century when "drawings" of the earlier period became "contract documents." Other critical developments occurred, such as the appearance of a general contractor and a professional engineer (first in England), which were particularly significant for the development of architectural practice as we know it today. The relationships between architects and other parties in the building process became defined contractually, with the aim of clearly articulating the responsibilities and potential liabilities. The consequences were profound. The relationship between an architect (as a designer of a building) and a general contractor (as an executor of the design) became solely financial, leading to what was to

become, and remain to this day, an adversarial, highly legalistic and rigidly codified process. It is the biggest obstacle to change today.

The late-nineteenth century New York firm McKim, Mead and White is often cited as another example of the power architects once had over the building process. As described by Howard Davis,[2] this architectural firm, in its quest for total control over the construction of each of their buildings, produced not only hundreds of drawings, but also had a final say over every detail, the quality of materials and workmanship, and over every payment to contractors and subcontractors. But this high degree of control was not without consequences. As architects placed more and more layers beneath themselves, the distance between them and the construction site increased. As Davis observes, "As the system evolved further, the role of the general contractor grew at the same time as the architect's connection to craftspeople lessened."[3] Although architects were at the apex of hierarchical control structure, increasingly the desired outcome had to be explicitly and precisely described in various contract documents. The architect's role on the construction site, instead of shaping the building (as master builders once did), became the contractual administration, i.e. the verification of the contractor's compliance with the given contractual construction documents. The design was split from the construction, conceptually and legally. Architects detached themselves fully from the act of building, unintentionally giving up the power they once had, pushing the design to a sideline, and setting the profession on a path of increasing irrelevance in the twentieth century.

The twentieth century brought increasing complexity to building design and construction, as numerous new materials, technologies and processes were invented. With increased complexity came increased specialization, and the emergence of various design and engineering consultants for different building systems, code compliance, etc. At the same time, the amount of time allotted for design and construction was shrinking. As the complexity of building increased and the design "time" decreased, the architects sought the need to limit their liability exposure. While the legal definition of their role was becoming progressively more defined, architects were, at the same time, increasingly losing control and the decision-making power over the building process, thereby formally dissolving the authority they once had and knowingly disassociating themselves from the rest of the building industry.

In the United States today, architects are prohibited from taking part in construction by the codes of practice established by the professional association, the American Institute of Architects (AIA). The standard contracts in use by the AIA state explicitly that "the architect will not have control over or charge of and will not be responsible for construction means, methods, techniques, sequences, or procedures."[4] This aversion to risk has, unsurprisingly, led to the further marginalization of architectural design, further contraction in services offered by the design firms, and further reduction in fees.

The outcome of this progressive disassociation of architecture from the rest of the building industry is a profession unsure of its role in contemporary society and its economy, and a profession unable to respond to the challenges and opportunities of the Information Age. Only by taking the lead in the inevitable digitally-driven restructuring of the building industry will architects avoid becoming irrelevant.

THE DIGITAL CONTINUUM

It is debatable whether the drawings emerged in the building industry because of the need to separate design and construction or whether their introduction produced the present separation. The lasting legacy is the legal framework within which building industry professionals operate today, requiring drawings, often tens of thousands of them, for a project of medium size and complexity.

Only the present divisions of responsibility make this production of drawings necessary. In other industries, such as shipbuilding, the designer and the builder are often one legal entity, so there is little or no need to produce drawings, i.e. to externalize design information. Many shipyards and boatyards have eliminated drawings by working directly with a comprehensive three-dimensional digital model from design to construction. The digital geometric data extracted from the model are used to drive the automated fabrication and assembly equipment.

Fortunately, the digital revolution that radically restructured the shipbuilding and other industries did not go unnoticed in architecture. Some architects were quick to exploit the design and construction opportunities that were opened up by the newfound ability to digitally generate and supply the manufacturing information to fabricators and contractors, and, in turn, their ability to reciprocate by providing accurate material and cost estimates. In these newly discovered mutually-beneficial processes of direct information exchange, the digital design information became the construction information, and vice versa, without the intermediate time-consuming and error-prone steps of drawing production. These digital processes, pioneered by Frank Gehry's office, represent a radical departure from the normative practices—they eliminate, rather than automate, the production of various construction documents as paper drawings. The digital data are passed on directly, i.e. in paperless fashion, to fabricators for cost estimation and fabrication.

The ability to digitally generate and analyze the design information, and then use it directly to manufacture and construct buildings, fundamentally redefines the relationships between conception and production—it provides for an informational continuum from design to construction. New synergies in architecture, engineering and construction start to emerge because of the use of digital technologies across the boundaries of various professions. As communication among various parties increasingly involves the direct digital exchange of information, the legacy of the twentieth century in the form of drawing sets, shop drawings and specifications, will be inevitably relegated to the dustbin of history. The need to externalize representations of design, i.e. produce drawings, will lessen as a direct consequence of the new digital possibilities for producing and processing information.

As production of the drawings declines, i.e. as digital data are increasingly passed directly from an architect to an engineer or a fabricator, and vice versa, so will the building design and construction processes become more efficient. By some estimates, there is a potential for building construction to become 28–40% more efficient through better (digital) information and coordination.[5] But for that process to begin, the legal framework of the building industry, in which the drawings establish the grounds of liability, would have to change. In other words, the nineteenth century building practices would have to change for architects to work directly with fabricators, i.e. subcontractors. This "disintermediation"[6] should bring new efficiencies. According to James Cramer, Chairman and CEO of

Greenway Consulting, architects will find themselves "moving from linear to non-linear changes—from information that is shared by teams, rather than individuals, and communication that is continuous, rather than formal and fragmented."[7]

In this scenario, the digital model becomes the single source of design and production information that is generated, controlled and managed by the designer. It encodes all the information needed to manufacture and construct the building. Layers of information are added, abstracted and extracted as needed throughout the design and construction, as architects, engineers, contractors and fabricators work in a collaborative fashion using a single digital model from the earliest stages of design.

Such a model of production requires that all tools for design, analysis, simulation, fabrication and construction be integrated into a single, cohesive digital environment that can provide information about any qualitative or quantitative aspect of building under design or construction. The challenge is (and has been for more than three decades of computer-aided design) how to develop an information model that facilitates all stages of building, from conceptual design to construction (and beyond, for facilities management), and provides for a seamless digital collaborative environment among all parties in the building process.

For Gehry's office, a digital model created in CATIA—the design and manufacturing software used mainly in the aerospace industry—is the single source of design and construction information. In a remarkable departure from the current norms of practice, the three-dimensional digital model is actually a key part of the contract documents, from which all dimensional information is to be extracted during the fabrication and construction of the building. In other words, the digital model takes precedence over any other construction document, legally and in practice, on the construction site. This is a radical, revolutionary change in building practice, for which Gehry's office will probably be remembered in future history books (and not only for the sinuous, curving geometries of the *Guggenheim Museum* in Bilbao, Spain).

The single, unified digital model, as envisioned by Jim Glymph, one of Gehry's partners, places the architect in the role of a "coordinator of information"[8] between the various participants in the design and construction of a building. The principal idea is to unify, i.e. to bring together in a single digital information environment, the hundreds of different parties involved in a typical building production, with the aim of overcoming the inefficiencies, resource-wise and information-wise, that result from the conventional divisions of responsibility and modes of production in the various professions.

Gehry's office first experimented with the "paperless" process of digital production in the late 1980s in the design and construction of the large fish-shaped pavilion at the entrance of a retail complex on Barcelona's waterfront (1992, figure 3.1). It was a watershed project for the office. As was the case with all of Gehry's projects later on, a physical design model was first generated and then translated into a corresponding digital surface model. The digital model was further refined; the wireframe model was extracted and used by structural engineers to develop the supporting structural frame. A physical scale model was machined from the digital version for comparison with the initial conceptual model. The digital model was then used in the full-scale construction to directly control the production and assembly of the components. For the first time, the construction drawings were not needed to erect the building. This process of project development and production, with

some variations, was used by Gehry's office on a number of projects. Particularly notable among recent projects are the *Experience Music Project* (2000) in Seattle (figures 3.9a-b), and the *Walt Disney Concert Hall* (2003) in Los Angeles (figure 8.1), whose design and construction represents the most complete use of digital technology by Gehry's office so far.

According to Gehry, particularly appealing is the newfound ability "to get closer to the craft"[9] by engaging the digital technology directly in the production and thus eliminating the many layers that exist between the architect and the act of building. To Gehry, that means one thing—"it's the old image of the architect as master builder," who now has control over the building process from beginning to end. Thus, the basic idea of the Bauhaus (of the unity of the craftsman and the artist) from the early twentieth century is reactualized at the beginning of the twenty-first century.

CHALLENGES

In the new digitally-driven processes of production, design and construction are no longer separate realms but are, instead, fluidly amalgamated. Builders and fabricators become involved in the earliest phases of design, and architects actively participate in all phases of construction. The fission of the past is giving way to the digital fusion.

This model of a digitally-facilitated collaborative continuum from design to construction, while opening up unprecedented opportunities for the building industry, faces a number of difficult, multifaceted challenges, which must be overcome for this new digital continuum to become a reality. The principal obstacles stem from the long-established social and legal practices in the industry. Its highly fragmented and differentiated structure, which facilitates a clear definition of the responsibilities, does stand in the way of new collaborative synergies emerging in the industry.

The sharing of digital data among various parties in the building process is, in fact, discouraged by the current legal codes of practice. Under the current definitions of professional liability, if an architect transmits a digital model or a drawing to a contractor or a fabricator, he or she becomes liable for any work resulting from the given digital data. The consequence is that each participating party in design and construction creates its digital data from scratch, i.e. from paper documents reproduced from the previously digitally-generated information. Needless to say, this process is not only highly redundant and utterly inefficient, but it also compounds any errors that could occur in interpreting the information exchanged on paper.

While uniting all the participants through a single modeling system, as discussed earlier, does hold a promise of a remedy for the present redundancies and inefficiencies, it makes the responsibilities of different parties far less distinct than is presently the case. If the building industry were to adopt this new modus operandi of shared responsibilities, it needs to clearly assess the legal repercussions and embark on a fundamental redefinition of relationships among various parties in the building industry, with the help of legal and insurance experts. A radical restructuring of the industry, while technologically possible today, is an enormously difficult task because of the tremendous social and cultural inertia of the firmly entrenched traditions, developed slowly over several centuries.

The transition then is likely to be evolutionary rather than revolutionary. Gehry's office, for example, relies on a "hybrid" system in which an owner-contracted consulting firm (called *C-cubed,* and led by Rick Smith) provides digital modeling services in CATIA to all members of the design and construction team, effectively coordinating the production of the shared digital model. Each team member extracts and adds information to the shared model as mandated by their expertise without crossing the traditional lines of responsibility and thus staying within the limits of liability established by the legal and insurance rules. Had Gehry's office assumed the responsibility for the development and data coordination of the digital model, they could have been liable legally as a professional architectural firm for the information provided by other members of the team.

While this solution protects the architect and creates an elegant legal "umbrella" for the rest of the design and construction team under the existing rules, it places significant responsibility on the owner-contracted consulting firm as a "data manager." This is an emerging role that needs a full and clear definition as challenges of accurate and integrative production of information become more and more demanding. It is this role—the information master builder—that represents the greatest opportunity for architects to return to their master-builder roots. The architectural profession will seal its fate if it abandons the overall process and information integration and management to construction and engineering firms, some of which have already realized that the emerging dynamic, geographically distributed, digital networks of design and production expertise are the future mode of operation for the building industry.

With greater responsibility comes increased liability, i.e. a greater assumption of risk, but also greater rewards. According to Jim Glymph, "both money and time can be eliminated from the construction process by shifting the design responsibility forward."[10] Glymph offers, as an example, the cost of producing the shop drawings, which far exceeds the architectural and engineering fees for a typical large-scale project. But if architects were to provide the information for the benefit of other members of the design and construction team, they ought to be compensated for that new role. The restructuring of the industry therefore requires not only professional and organizational adjustments, but also a rethinking of how various members of the team are compensated.

In the *Stata Center for Computer, Information, and Intelligence Sciences* (2003) at MIT, Gehry's office is breaking new ground by sharing the overall responsibility for the project with other members of the building team. The concept of shared liability is a remarkable departure from the current distributed liability of building practice. It is, perhaps, the most difficult challenge to overcome, as it represents a complete reversal of the present position by architectural professional organizations and insurance companies of minimizing the liability of architects in the building process. If they are to remain relevant as a profession, architects will have to learn to share responsibility with other members of the building team, as they once did.

Some architects have responded to the opportunities and challenges that come with shared responsibility by teaming up with contractors to create *design-build firms,* which serve as both architect and contractor to the owner, thus representing a single legal entity and a single point of responsibility. This change in the structure of building practices, and the resultant redefined legal framework that provides for shared decision-making, is one possible logical remedy for the present inefficiencies of a highly fragmented building

industry. By some estimates, one-quarter of all construction projects in England and one-tenth in the United States are now done as design-build.[11]

Design-build, however, is only one way of actualizing the emerging professional synergies of digitally-driven modes of production. A more interesting possibility is the structuring of building teams as dynamic, geographically-distributed digital networks of design and production expertise, which change fluidly as the circumstances of the project or practice require. Architects will increasingly find themselves working in an environment of multidirectional digitally-mediated exchange of knowledge among various members of design and construction teams. In the emerging fluid, heterogeneous processes of production, the digital data, software and various manufacturing devices will be used in different ways by different members of the building team, who will often operate in different places and in different time zones.

As architects shift their attention from drawing production to digital information authoring, the software industry has a very important role to play in the transition to emerging digital modes of practice. Instead of adopting a conservative stance, which calls for providing technologies based on prevalent modes of practice, it has to actively engage in developing the tools that support new modes of production. In partnership with the building industry, it must overcome existing social and cultural barriers to technological innovation and must aggressively promote a new culture of use based on a single building model.

Educational institutions are the ones who have the power (and, hopefully, the foresight) to prepare future generations of professionals for the emerging practices of the digital age. We need to start training architects to be master builders again, to understand and re-engage the processes of building through digital technologies.

THE INEVITABLE

As architects find themselves increasingly working across other disciplines, such as material science and computer-aided manufacturing, the historic relationships between architecture and its means of production are increasingly being challenged by the emerging digitally-driven processes of design, fabrication and construction. The amalgamation of what were, until recently, separate enterprises has already transformed other industries, such as aerospace, automotive and shipbuilding, but there has yet to be a similarly significant and industry-wide impact in the world of building design and construction. That change, however, has already started, and is inevitable and unavoidable. The obstacles are numerous but the rewards are compelling if architects can manage to liberate the profession from the anachronistic practices of the twentieth century.

If nothing else, eventually the sheer number of digitally-produced projects will bring about a new way of thinking about architecture and its proper place within the building industry. Many of the strategies and techniques of production, which are pioneered today by Frank Gehry and his numerous less-known but more adventurous, younger colleagues, will be commonplace tomorrow, just as the material and technological innovations of the nineteenth century eventually became mainstream in the twentieth century.

NOTES

1   W.Mitchell and M.McCullough. "Prototyping" (Chapter 18) in Digital *Design Media,* 2nd edition. New York: Van Nostrand Reinhold, 1995, pp. 417–440.

2   Howard Davis. *The Culture of Building.* New York: Oxford University Press, 1999.

3   *Ibid.*

4   AIA Document A201: *General Conditions of the Contract for Construction;* the AIA's oldest contract document in circulation.

5   James Cramer, 2000, http://www.greenwayconsulting.com/

6   *Ibid.*

7   *Ibid.*

8   Bruce Lindsey. *Digital Gehry: Material Resistance, Digital Construction.* Basel: Birkhauser, 2001.

9   "CATIA at Frank O.Gehry & Associates, Inc.," http://www-3.ibm.com/ solutions/engineering/ esindus.nsf/Public/sufran.

10 Andrew Cocke. "The Business of Complex Curves" in *Architecture,* December 2000.

11 Dana Buntrock. *Japanese Architecture as a Collaborative Process.* London: Spon Press, 2002.

5
DIGITAL MASTER BUILDERS?

MARK BURRY

BERNARD CACHE

BERNHARD FRANKEN

JAMES GLYMPH

MARK GOULTHORPE

BRENDAN MACFARLANE

WILLIAM MITCHELL

BRANKO KOLAREVIC

KOLAREVIC: This panel discussion will focus on the reemergence of the master builder paradigm. In contemporary circumstances, the master builder is someone who is fully involved in the making of the buildings, where the making means design, production and construction in an almost medieval fashion. As mentioned in the introductory remarks, the complexity of the blob-like forms is drawing architects back into being fully involved in the making of the buildings, that is, into assuming the role of the master builders. Most of the panelists did find themselves in that new role, perhaps out of sheer necessity to see their designs built for reasonable budgets. I would like to ask each of the panelists to provide their own views of that master builder reality in which they find themselves: is that something they are intentionally seeking out, or is that a necessity to have their work built?

GLYMPH: In our case, it is both. With what we do, which is really based on not taking the rationalizations steps described by Hugh Whitehead, we wind up with many highly-shaped, sculptural forms. That was a pursuit I think Frank Gehry wanted as a means of expression in his architecture, which was constrained by the cost and complexity of dealing with the geometric problems without computing. In the advanced computing world at the time we began doing this, it meant that you had to collaborate very, very closely with fabricators who were just beginning to enter the same world. This made it a necessity in order to execute that type of architecture, to establish a very strong bridge between us and the fabricators, the craftsmen, and the people executing the work, who are just being introduced to information technology. So, it was a necessity in that regard.

There is also deliberateness to it, because there is a philosophical stance in our firm that the architect needs to be able to deal with the tactile and sensual and the less easily quantifiable aspects of his art. To do that, he needs to get very close to the craftsmen, or to the fabricators, so that they become extensions of the gestural strokes that Frank Gehry will make on a model and collaborators in it. Philosophically, I think we are driven toward the notion that the barriers that have been established, particularly in North America, between

subcontractors, craftsman, and people working in the field and the architect himself need to be torn down. Architecture needs to return to a more direct association between the material, craft, the physical reality of the building and its own design process.

MACFARLANE: We started with ideas, not intending to get into the complexity of fabrication. We were not that interested in the fabrication of the project; it is about being more interested in the ideas than the concepts. My passion today is close to that of a "mason," working with the fabricator, taking that as a generating way back towards the idea, and reworking the idea. I never thought I would be in that position. It is exciting and very, very interesting. It is a subject that interests me a lot.

CACHE: In our case, it was very deliberate to be involved in fabrication. We would like to concentrate all the complexity in the software, so that building architecture can be just a gesture—as simple as putting a dowel into a hole. I think that building software is also part of the business in this field.

FRANKEN: We had a team of 75 people working on the last BMW project we did. It is not that the master is somewhere at the top and controlling everything; it is more like the role of a movie director. The movie director is a decision-making machine; he has to make sure he makes the right decisions as many times as possible. We are working with people whom we respect but, on the other hand, it is our position to control them, which makes the process difficult. We have to come up with control systems like the ones we saw at Foster's, having lists and seeing tolerances, etc. We need the possibility to remove people if they are not performing their part, often on the basis that isn't regulated by law. The whole question of liability when it comes to digital data exchanges is open. It is all new territory.

KOLAREVIC: I think what was just mentioned—the issue of control—actually uproots the existing hierarchies, in which architects give up the control of the project as soon as they pass the construction documents to the contractors. So how do you deal with risks, with the liabilities in these new modes of operations? We heard from Hugh Whitehead that they actually pass their models to the fabricators and say, well, it is your model now, you are making it, so therefore you are liable for it. So how do you in your practices deal with the issues of risks and liabilities?

MITCHELL: There are a number of interconnected issues. Technologically, we have a very fluid situation with developments happening in two domains that are being tied together. First, there is an amazing transformation happening in fabrication technology— the whole technology of computer-controlled machines, essentially robotic devices that make things. That technology is transforming amazingly fast at every scale, from the nanoscale at which we are assembling atoms directly, up through product-design scale to the upper end of the scale spectrum where architecture is. So, there are these amazing transformations happening in machines that make things together, with machines and processes for artificially positioning and assembling complicated things. Then there is considerable degree of innovation in what we tend to think of as CAD software—but it is really broader than that. It is the domain of computational support systems you use for exploring design ideas.

You end up with the situation where you have to marry these two worlds. As there isn't a standard way of marrying these worlds, you have to invent it. That is what makes it so exciting now—this constant process of inventing it, trying to fit these things together in ways that are not given, not locked in place. I would hope that it does not rigidify, that the kind of inventiveness and fluidity continues.

Then there is a question about risks. Architects have spent a long time backing away from liability and backed themselves into smaller and smaller corners in the process. This is very different from the way other professionals have behaved in the twenty-first century and the twentieth century, where you say you try to develop your competence to the point where you can take more risks. That is what defines you as a professional—the ability to move into situations where you can confidently deal with the risk factors that are involved. I really think this is what architects have to do—get away from this position of constantly backing away from liability and develop enough competence to responsibly manage risks in situations of high innovation and high uncertainty. That is what real professions do. I think it means a change in the way we think about education. It means a change in general professional attitude. I think it is very fundamental.

GLYMPH: In the Disney Concert Hall project, the risks were vastly increased by the process we used—the risks to the architect. In most cases, we look at the process as a risk reduction for everyone. We do hand off models and have people share data and continuously build on the same database. There are lines of responsibility that are drawn; because of the way you deal with computing systems, those can be extremely complex lines of responsibilities.

A better situation, which has occurred on most of our European projects, is to look at the whole problem in another way and collaborate very early with the team that will build the building. In that environment, we thought of ourselves as a bridge between those who have the real, direct responsibility to build the job (which isn't the general contractor) and the designers. To make that collaborative environment work, you have to take into consideration early in the design process the nature of the material, the craft, and the capability of the actual hands that will build the building—and forget about risk. You have to design a model that is not concerned with the legal structure; you have to see what the technology can do to bring those two groups together. If a project is established from that point of view, you normally find out that there are many devices everybody is willing to put on the table to manage the risk. It is pure problem-solving with the tool that allows new possibilities to designers on one side but also serves the people on the shop floor or in the field at the other end of the spectrum. Simply looking at the most efficient way to put   together the system, I think is the key to what we should be doing. And then we change the law.

GOULTHORPE: The fascinating thing with technology is once you have a sense of what it can do it fills the imagination. I am a sort of hopeless case of being like a monkey with a stick poking into an anthill. But one realizes that the essence of technology is not in the stick—the stick is just a stick—it is in the desire for ants that it propitiates! This is the real point at Issue for a cultural discourse. And the curious thing is that another monkey without a stick who sits watching the first monkey can also become ant mad—this is the proliferation of the effect of technology. And that seems to me is what is happening at present.

Offices like mine, which obviously can't invest in expensive software, are still ant mad. We are investing a lot of time in creating liaisons with people who do have those skills, which is creating a whole new type of practice. I think of dECOi really as three or four people in a traditional office structure in France, but then there is a network of affiliates— mathematicians, programmers, robotic engineers—who are globally dispersed and whom we call upon for their specialist skills.

That said, I think there are fascinating potentials for new spatial possibilities and new material possibilities; I am particularly fascinated by the new tactilities that one might begin to arrive at a geological rather than geographical potential of form.

Currently we are working on an apartment project where we are machining and casting every basin, every door handle, every light switch—an entirely non-standard production. We are casting in bronze and aluminum, so I had a crash course in nineteenth century founding technologies! I have spent about 30% of my time finding sufficiently skilled people to help us begin to realize new material possibilities in this realm. That extended beyond bronze-casting sculptors and aluminum welders to robotic engineers in Australia. If I spend 30% of my time finding them, and 30% understanding them and the constraints of a kiln in a particular factory (and how you cast a half ton chimney piece in bronze and what really are the constraints of that), it really is coming back to trying to be some sort of master builder, but with a digital communication possibility. In such work a vast network of different skills are called into play, which is fascinating—which is actually terrifying! (If the fireplace cracks, it is going to be my fault!)

If architects want to realize the potentials which seem to be in the offing with this fabulous new technology, I think we have to move back into a realm of taking responsibility and reinvesting in understanding fully every aspect of digital praxis, from bronze casting all the way through to robotic engineering. I think that probably does demand a shift in education and a huge shift in apprenticeship, in the manner in which people are coming through practice.

BURRY: The real innovation required where I live, in Australia, is social innovation, in the sense of how the process is driven. The architect seems to be able to garner all the resources required to do the kinds of things we have been talking about. In the environment where I live, however, the population is not specifically asking for this kind of innovation, but will accept it begrudgingly if it appears not to cost too much of the taxpayers' money.

In my view, the real enemy for the architects who attempt to innovate are the contracting organizations. It seems to me the more the architect and the team innovate and decrease the risk of going over cost, the more they risk going over cost because the contractor decides it is an innovation which might be risky and prices accordingly. So, we seem to have a paradox.

I think the most exciting thing about the idea of the master builder is the whole issue of authorship. I think that sole authorship—the designer being the master builder—is no longer relevant. It is not synonymous with the way we might have been encouraged to think, particularly in the 1990s.

KOLAREVIC: What would it take for these practices to enter the mainstream of the building industry in this century? I think the obstacles are very difficult and I think it would take

quite a bit of time—perhaps a few generations—to actually make a serious change in our industry.

GLYMPH: Technically, it could be done overnight. Socially, which I think is Mark Burry's point, it could take a few decades. That is because you are really going back to when there wasn't even an architect and the gothic master builder worked with the craftsman (which is sort of the master builder reference that resonates). That is realizable technically, but it will take down a set of processes and procedures, roles and responsibilities, and laws and standards that have been in place and have developed for over at least a century, if not more. It will take some time to take that down. It will only come down if benefits can be shown early—and there is the conundrum, because the process is expensive now and it is not proving anything unless you are trying to do something extraordinary. It is not proving things to the ordinary yet.

We have to come up with completely different ways of contracting, building and relating to each other. We have to have a different attitude about liability, responsibility and risk, and how it is shared. But it is possible. We are doing a project at MIT that has a project liability policy which includes fabricators, their engineers, and architects under one umbrella. So, you can make progress… Those kinds of environments create whole new possibilities.

MITCHELL: I totally agree with all those things Jim just said. How do you do it as a matter of practical strategy? How do you get started? I think there are a couple of basic things. One is energetic innovative research and education. Just producing a generation of people who are good and committed at doing some of these things—that is how you make a change. You begin with people. I think it is a major responsibility of the schools to provide an environment where this sort of thing can happen. It is difficult to do, but I think that is fundamental.

The other thing is that it is very important to have brave models of innovative practices. You can't change the whole industry overnight. It is a massive, complicated thing, but you can make enormous amounts of progress by showing alternative models, by just doing it. Getting the concrete alternative models up, making the wonderful projects, is what in the end, I think, catalyzed change.

If you look at the difference between the construction industry and the computer industry, you see a very interesting thing. Take something like the World Wide Web, which was an invention that swept over the world in the blink of an eye. It happened because there wasn't a big established structure in place it had to fight with—it was just this new thing that could take over. What we have with the construction industry is a huge, rigidified established structure. We can't expect the kind of instant takeover as with the World Wide Web, but we can do it in education, producing the people. We can do it with alternative practice. I have lots of faith that we will eventually accomplish very radical change.

CACHE: We are a very small practice, two designers plus the back office of programmers and other people, but we want to be small and to remain small. I am glad to hear that much bigger offices are facing the same type of problems we have. A couple of months ago I had to go to one of our contractors and prove to him—on the machine—that the origin of the

machine was not where he believed it was. As a result, we decided to buy machines. We have our own workshop, because it is very difficult to find a collaborative combination that works.

We develop software, we make every effort to produce the same products more efficiently each time, but the manufacturers keep their margins unchanged. That was becoming comical… We tried for ten years to establish a relationship by which we measure the time of production for each new piece we do, and we never succeeded. That is why we are about to set up our own production unit.

KOLAREVIC: I don't think that will be the model for offices like Gehry's and Foster's, where they would actually engage in the making of buildings themselves.

GLYMPH: Sure we would… One of the things that gives us the hope of actually pushing a lot of change right now is the Design Build Association of America, which is looking at these same issues and does not have the constraints architects   have. They have decided to take full responsibility. They are going to take off with this technology. And they are going to put architects who are not working in design-build out of business.

The construction industry is messy, dirty, unruly… It is the last place where you can go to have an adventure of high risk. The risk is unavoidable, but the industry is aware of its problems. In the last decade or two, while the overall productivity in the economy has been going up because of the impact of technology and different business practices, it has dropped 15% in the construction industry. They know they have a problem. There are many people searching for solutions. There are many owners and major clients who are searching for solutions to get out of this messy "Wild West" environment of building buildings. They are open to new ideas, so we do have an opportunity to advance. If we advance the technology quickly, we have an opportunity to lay out examples that work better, that have better results, that can create momentum towards making social, legal and business changes. Many people will be put out of business. Certain roles will disappear; others will be created. This is a major upheaval for an industry, and it has to be motivated. And I think it can be motivated because it is the only industry going in the wrong direction.

JERZY WOJTOWICZ (from audience): What are the implications of this curious condition for architectural education today? We witness certain preferences for certain modes of working -you call it master builder, but maybe it is a digital craftsman—but schools seem to operate largely along conventions developed over generations. We see introduction of non-rational geometries to design that are frequently uncritically endorsed by students who do not have the grounding of the people who sit across this table (and who certainly don't have a grounding of Gaudí).

GLYMPH: I think you have to make a distinction of process and imitating Frank Gehry or others who have highly developed eyes, in a strong sculptural sense, and took 45 or 50 years to get there. Students can't be there. Designing on the computer with blob generators doesn't produce architecture. It is even more important now that the critical side of design be imposed on students. The quality of design from an aesthetic standpoint is even more important now, I think. At the same time, I think we need to bring back what I think

most schools have moved away from, which is the training in how things are built and engineered and how they work. The architect is supposed to have both of those. I think the schools have abandoned the responsibility for one of them.

BURRY: Just one question that I have never had a satisfactory answer to… When I studied, it was the late 1970s, we spent a lot of time hatching—I remember spending at least several days hatching on my final project! There has been an incredible productivity gain through CAD, but what are we doing instead with the time we have saved in studio? I am sure there is a deeper and richer body of theory including technology that could be added to the syllabus. But at the schools I have taught at, the syllabus is effectively still the same. Subjects like communication have changed to become some sort of CAD thing; there might be some business studies that might not have been as prominent in my course. There must be a lot of room for a completely renovated architectural education.

MITCHELL: I agree with that completely. I really think we have to loosen up a great deal and realize that in a moment of rapid transformation that kind of authoritarian mode of education is never a good idea. It is particularly a bad idea in this kind of context. We have to create environments that allow exploration, innovation, and finding of directions in ways that I think really good, research-based universities can do. They involve putting together new combinations of things that allow critical exploration of ideas to develop.

A number of us at the table are involved this term in a studio operated jointly at MIT. There is a group of students and faculty at MIT, a group of Mark Burry's students at RMIT in Melbourne, and then Jim Glymph and a number of talented people in Gehry's office. It is all tied together electronically,   with traveling back and forth, and so on. The reason we are doing that is not because we want to demonstrate the capabilities of video conferencing— far from it. To create the kind of experimental, critical environment that we want, it is just necessary to put together that sort of mixture, which is essentially outside of traditional education and research structures. You have to put together a collection of intellectual resources that you need to do real serious experimental work. I think you only get a critical work by doing experimental work, not by sitting around and talking in a seminar room, but by actually doing the design work and being really rigorous about it, getting into the critical discussions that arise out of doing the work. I think that has to be the strategy—a difficult one, but the right one.

MACFARLANE: I have a sense of concern when I hear a lot of people talking about fabrication techniques, and I think to myself, where did the concept go? Where did the critical discussion go? For myself, I am not worried, because I think we are interested in that—we come from that. I think I see in the schools right now a push towards this territory of both representation and fabrication from representation. That is where the energy really is, where the discussion really is, and that is partially why we are here today. Have we lost critical analysis along the way or have we lost an architectural culture along the way? I don't think so at all.

GOULTHORPE: I think in our office we are facing a couple of problems. Finding people capable of doing the work is always an issue. I have been very fortunate to have a stream of Mark Burry's students coming through, so I think I have benefited enormously from the rigor of Gaudí's work and Mark Burry's work—I hope they benefit from coming into our practice and get a thorough apprenticeship. Generally, students are coming with programmatic skills or parametric skills and they are teaching us something.

I think the university does have an incredible role to play in allowing the necessary accumulation of skills to come into offices. Students after five years of university education should be coming out as useful. One would hope.

We always face the problem of losing students. People come to the office for six months with a skill in 3D Studio MAX or Maya. Somehow, there seems to be a sense among the generation of school leavers that because they have mastered a software, they are sufficient as architects, and they almost immediately seem to be leaving to set up their own practice, which usually turns into a graphics company for websites very quickly. There seems to be an enormous problem in convincing this generation of digital talent that there is a deeper and more profound body of knowledge to acquire, which they will only get through apprenticeship. Perhaps there is some link between university and practice that needs to be reinforced somehow.

I want to point out that the people whose work I mentioned, many of them here, are philosophers, and this technological change is properly speaking a philosophical one: Bernard Cache, Greg Lynn, Lars Spuybroek… They are all thinkers from other fields or have had deep exposure to other fields. They are actually thinking the technology, rather than simply using it. I think we should be encouraging a properly philosophical reflection on the nature of this transition, which again I don't find in many schools. It is almost a training program for technicians. I don't think it is adequate—I think there is a much profounder reflection that needs to take to place.

PAUL SELETSKY (from audience): How do the panelists view the implications of technology on the future role of the "architect of record?"

GLYMPH: Sometimes referred to as the "executive architect?" In projects where we work with executive architects in foreign situations, where we cannot be the architect of record, they have to ride into the process with us, and that has the same implications for them. But what has been interesting about that is that it depends on where you are in the world. There are great models in the world for doing it differently. How it is done in North America is by no means even close to the right way of doing it. So, I would   suggest you look at executive architects working in Germany and in some cases in Spain. We have a couple of organizations we are working with. They are actually moving even closer to the role of being construction manager as well.

Once you have this technology and you master the database, the role of the contractor becomes logistics. Management can almost be done as a continuous process, as part of the design process. I think executive architects have evolved towards a design-build role or at least a project management role. We have a number of firms we worked with that have actually made that transition by adopting our process and seeing an opportunity. That is a hole people aren't willing to step into. Contractors in the US have pulled away from that

role as well. What is interesting is they don't do coordination anymore either. So, there is a gap, there is an opportunity. I think there is technology out there that can give you the edge. I think a few are looking at that and having some success with it.

KEVIN KLINGER (from audience): There has been a lot of talk today about the necessity to enter into programming to achieve the things that you want to achieve, particularly with Mark Burry's work and Bernard Cache's work. Back to the issue of the master builder, could you address what you see as the role of the software developer as a part of that relationship?

MITCHELL: First, the issue of what software really is and who makes software… It used to be in the early days of computation (in the way Microsoft likes to think about these things) that the software is a packaged up, standardized product that somebody sells to you and then you are a user. The terminology tells you—it is really just horrifying as a way of thinking about it—it is like something you do in a back alley with a syringe. But in fact what is happening, of course, it is like learning that you were speaking prose all your life.

When you make a parametric model, in fact, you are programming. You are doing a sophisticated piece of programming. You are declaring entities that are going to be part of what happens, you are establishing relationships, you are assigning values to parameters, you are doing all the things that programmers do. Now, it is in a very different style from what people think of as coding, but nonetheless it is programming. I think there is no alternative if you really want to have your hands on what is important, if you really want to innovate, if you really want to do the sorts of things that were shown so beautifully today, you just have to learn to do them. I think it is fundamental to anybody who wants to seriously think about design or technology today to have those sorts of programming capabilities. What I don't mean is knowing the syntax of some esoteric programming language—that is trivial—you can pick that up very quickly. What I think is crucial, is to have the intellectual skills of abstraction, definition of relationship, all of these sorts of things that parametric modeling demonstrates.

ROBERT AISH (from audience): On the issue of software I think the problem is that the software engineers producing the initial CAD software looked at what they thought real designers were doing, and made the incorrect assumption that the process of design was all done through the direct manipulation of geometry. The software engineers got into the typical Microsoft approach of creating an application which was a metaphor of what was previously done. In fact, in a deeper analysis of the architectural design process, we find that it has both an intuitive and a formal component. These can be more effectively combined in a computational design tool that allows the designer to be progressively more programmatic if he wants to be and as the design problem requires. I think that Bill Mitchell is absolutely right. My view is that a CAD application is in fact more like a visual programming environment.

6
DESIGN WORLDS AND FABRICATION MACHINES

WILLIAM J.MITCHELL

Intuitively, it seems obvious that some buildings are simpler than others. Most of us would agree, for example, that a standard commercial office tower is a far less complex object than Frank Gehry's Bilbao Guggenheim (figure 6.1). How might we quantify this difference? And what are the implications of this difference for design and construction?

6.1. *Guggenheim Museum* (1997), Bilbao, Spain, architect Frank Gehry.

TYPES AND ALGORITHMS

The process of constructing a three-dimensional digital model provides a clue. Any experienced CAD modeler will immediately note that the office tower consists of repeating parts arranged in regular grids and arrays. There is a floor grid, a column grid and a ceiling grid. The curtain wall consists of standard panels arranged in rows. And whole floors repeat vertically. So, the efficient way to construct a complete model is first to construct the standard parts, then to use repeat operations to produce the complete composition. In other words, you can put a relatively small amount of information in to get a much larger amount of information out.

If you want to be a little more sophisticated, you can write an algorithm that is executed to expand the input data into a complete model.[1] You begin by writing parameterized procedures to generate the various standard parts. Then you specify parameterized loops to create the necessary rows, grids and vertical stacks of these elements. Once you have made this intellectual investment, you can quickly generate the complete model by entering a few key parameters, then executing the procedure. If you are clever, you can write the procedure so that, with different parameters, it generates numerous different instances of the tower—with differently proportioned plans, different heights, and so on—as appropriate to different circumstances. More technically, the code of your procedure specifies the essential properties of a particular type of office tower, the parameter values that you enter specify the accidental properties, and execution of the procedure with these parameter values generates a three-dimensional digital model of the corresponding instance.

Creation of code, in this fashion, is an investment of intellectual effort, time and money in the expectation of a future payoff. If you can exploit your insight into the regularities of a building type to write concise code that expands a few parameters into a lot of explicit detail, then the investment is a good one; a relatively small amount of coding time saves you a large amount of model construction time. The investment is even better if you use the code repeatedly, to generate varied instances as required in different contexts. But the investment is less attractive if the code itself is lengthy and complicated; the coding may require more effort than the savings in model construction time.

Now consider, by contrast, a free-form building without repeating parts or layout regularities. In this case, there is no way to write concise code that creates all the explicit detail. The shortest description is something approaching a point-by-point, line-by-line, surface-by-surface enumeration of the geometry. This relates to the theory of random numbers. A random string of integers is often defined as a string that is its own shortest description. By contrast, a string such as "1212121212…" has a very concise description. If you think of a string of integers as a string of coordinate values in a three-dimensional digital model of a building, there will normally be some repetition and structure reflecting the regularities of the design. If not, the model describes a random heap of random shapes.

In summary, the complexity of a building type can (roughly speaking) be defined as the length of the shortest procedure that can expand parameter values into explicit instances. Simple types, such as standard office towers (particularly when they are to be instantiated repeatedly) repay investment in coding. Complex types (particularly when instances are not widely repeated) provide less attractive opportunities to achieve such payoffs.

INSTANTIATION PROCESSES

Now imagine that you have access to a procedure that constructs, in a computer-aided design (CAD) model, instances of geometric primitives, building elements, or even complete buildings. Independently of the internal elegance or otherwise of the code, the process of specifying instances may itself be simple or complex. It is a very simple process, for example, to specify a straight line segment; you only need to provide the coordinates of two endpoints (or the equivalent). It is slightly more complex to specify a circular arc; now

you need to provide the coordinates of three points. And, for a complicated spline, you may need to provide the coordinates of many control points.

To specify a rectangular beam, you need to provide length, width, height and position parameters. For a T-section or an I-section, there are more section parameters to establish. If the beam can be curved rather than straight, there are additional parameters to account for that, and so on. The more geometric freedom you have as a designer, the more parameters you need to control.

Much the same goes for entire buildings. Where they are completely standardized, as with prefabricated army huts or farm sheds, the designer only has to locate a predefined object on the site—that is, to choose position parameters. If there is a need to vary the size of the building in response to different sites and programs, the designer might have control of a few dimensional parameters as well. In a customizable standard house, there might be tens or hundreds of parameters to vary.

There is, then, a tradeoff to consider. Procedures that construct instances of geometric primitives, building elements or complete buildings allow users to freely assign values to some design variables (the parameters), then they compute values for the rest. If there are few parameters under the control of the designer, and a great many computed values, then the design process is an efficient one, but the designer's freedom is limited. Conversely, if there are many parameters under the designer's control, and fewer computed values, then the design process is more laborious, but the designer has more freedom.

This tradeoff between efficiency and design freedom can be balanced in different ways to serve different purposes. In software intended to allow unskilled users the possibility of customizing standard house designs, for example, it makes sense to build many design rules into the software and to provide only a small number of parameters.[2] But, in CAD systems for use by highly-skilled designers, who may want to pursue innovative ideas, it is appropriate to maximize control at the expense of efficiency.

It is often helpful, as well, to transfer implicit design rules out of a designer's head and into the code. If a designer wants to always work with rectangular parallelepipeds, for example, it makes little sense to require explicit input of every coordinate of every vertex; this adds labor, and creates the possibility of error. It is better to require the input of length, width, height and position values, and to allow the code to compute vertex coordinates from these—thus automatically maintaining the property of rectangularity. But, if the designer may want to work with irregular quadrilaterals and skewed shapes, the code obviously should not enforce a discipline of rectangles and boxes. If you build into code the right rules for a particular designer in a particular context, you gain efficiency and accuracy with no downside, but if you build in the wrong rules, you impose artificial and unwelcome constraints.

DESIGN WORLDS

In general, CAD and similar software systems allow designers to model instances of certain types of artifacts. The essential properties that characterize the type, and are common to all instances of that type, are encoded in the software. The accidental properties that pick out particular instances, and distinguish them from one another, are established when the user inputs parameter values. The software performs the task of expanding

parameter values into detailed, explicit CAD models of instances. In other words, CAD systems establish well-defined design worlds—domains of possibilities that designers can explore in responding to design problems or in speculating about design ideas.[3]

If we want to define a design world and create software to explore it, we can begin by establishing a shape vocabulary—that is, a "given" set of shapes that will simply be assumed at the start of a design process, and not constructed from other shapes. Historically, architectural shape vocabularies have comprised the point, the straight line segment, and the circular arc. This is, of course, the shape vocabulary of Euclid's geometry. It is explicitly introduced in Renaissance architectural treatises, and it is embodied in traditional drafting instruments—straightedge, dividers and compasses.

Next, we can define the geometric transformations that will be used to create instances of vocabulary elements. Architects, traditionally, have worked with translation, rotation, reflection and scaling. Technically, shape vocabularies, together with geometric transformations, establish shape algebras.
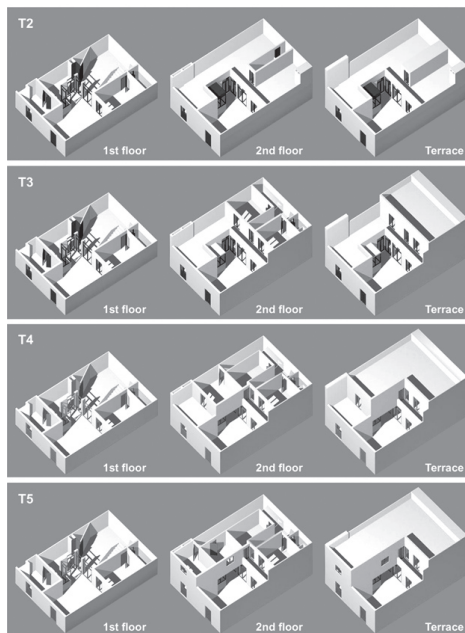
6.2. The design derivations of the shape grammar modeled after Alvaro Siza's Malagueira housing project in Portugal.

We also need combination operations, so that we can build up more complex shapes from the simple ones in the vocabulary. So, in addition to providing primitive shapes and geometric transformations, CAD systems allow users to insert and combine vocabulary elements, then recombine the results, and so on. Thus, two-dimensional CAD drafting systems provide extensive facilities for creating constructions of straight lines and arcs, and

three-dimensional solid modeling systems provide union, intersection and subtraction operations for sculpting complex solids.

If we want to make more specialized and restricted design worlds, we can begin with a more specialized vocabulary, such as that of some particular architectural style or component building system. And we can restrict transformations and combinations by establishing syntactic rules. Thus, Palladio's *Four Books* describe the vocabulary and syntax of Palladian villas, and the treatises of Durand and Guadet informally specify *Beaux-Arts* architectural languages. Today, shape grammars enable the rigorous specification of specialized architectural languages—much as similar formalisms, such as BNF (Backus Naur Form), enable the rigorous specification of programming languages.[4]

DERIVATIONS

Once a design world has been implemented in the form of CAD software, a user can derive designs in that world by applying available operations and rules to shapes in that world. Figure 6.2, for example, illustrates the derivation of a house design in the style of Alvaro Siza's Malagueira houses.[5] The software to enable this was based upon a shape grammar for such houses, and has been implemented as an online design site.

It is often useful to think of derivations as multilevel instantiation processes. You instantiate and combine geometric primitives to construct architectural vocabulary elements, you do the same with these vocabulary elements to create subassemblies, then subassemblies to create still higher-level subsystems, and so on.

Such derivations need not be straightforward, linear processes; they may involve extensive searching, in which the designer moves back and forth among options to find ones that meet the design goals. Furthermore, they may require little computational work or a lot. One of the properties of traditional, Euclidean design worlds is that they require relatively little computational work to derive designs; operations are generally quick and easy to execute, and manual drafting instruments have long sufficed for the exploration of such worlds. But, in design worlds that involve curved surfaces, computations such as constructing the lines of intersection of arbitrary curved surfaces, and so on, the computational work is much greater, and we need high-powered computers to facilitate the process of deriving designs. And, if derivation of designs requires searching large spaces of possibilities, the computational demands may become still higher and may grow exponentially with the size of the problem.

More technically, we can say that design derivation tasks may be of low- or high-computational complexity. In the past, architects were limited to derivations of relatively low-computational complexity. Now, with fast, inexpensive computation, and sophisticated CAD software, it is possible to execute derivations of much higher complexity. Thus, the derivation of a design such as that of the Bilbao Guggenheim, which would have been prohibitively slow, laborious and expensive in pre-CAD days, is now well within the bounds of possibility. As a result, we are seeing some designers, such as Frank Gehry, shifting their focus to design worlds that entail high-complexity derivations.[6]

6.3. The Stratasys deposition printer.

CAD/CAM FABRICATION MACHINES

Once a design has been digitally modeled, through some derivation process, it is ready for fabrication. We can think of a fabrication machine as a device that automatically translates a digital object in a design world into a material realization. For example, a deposition printer (figure 6.3) translates a solid model from a CAD system into a correspondingly-shaped piece of plastic. A multi-axis milling machine might produce much the same result, but the sequence of operations would be very different.

From a computational perspective, we can describe the process of design development as one of translating a digital model from some design world into a sequence of instructions for some particular fabrication machine.[7] In order for a deposition printer to produce a design physically, for example, the associated design development software must first slice up the digital model into thin, horizontal layers. Then, for each of these layers, it must develop a scanning sequence for deposition of tiny pellets of plastic to create the layer. Eventually, the complete design is fabricated in layer-by-layer fashion. In other words, before physical fabrication actually takes place, design development software translates the digital solid model into a very different representation; this software produces a very long sequence of instructions for depositing pellets of the material, then the fabrication machine executes these instructions, one by one.

6.4. The non-repeating sheet-metal panels on the *Experience Music Project building* (2000), Seattle, USA, architect Frank Gehry.

We might produce the same shape on a laser cutter, water-jet cutter or CAD/CAM router. In this case, the design development process is very different. Here, the task is to decompose the solid into surface polygons, and to describe each polygon as a sequence of movements of the cutting head. The cutting device quickly chops the polygons out of some sheet material, then they must be assembled by hand.

With CAD/CAM fabrication, the crucial efficiency considerations are, first, the number of operations that must be executed to physically produce a given design, and, second, the speed with which each operation can be executed. As the time taken to execute an operation decreases, the number of operations executable in a given time increases. This means, in general, that you can feasibly fabricate shapes and objects with greater complexity of detailing. With a fast laser cutter, for example, cutting a complicated filigree shape is little more difficult than cutting a circle.

In recent years, the growing availability of fast CAD/CAM fabrication devices has opened-up new geometric possibilities to architects. In Frank Gehry's Experience Music Project (EMP) in Seattle (figure 6.4), for example, the exterior sheet metal is made from non-repeating panels. Each one of these panels was efficiently produced, from a digital model, by a CAD/CAM cutting device.

CONCLUSION

CAD/CAM design and construction processes require three types of intellectual investment. First, you must invest in creating or acquiring code that establishes a design world for exploration. This code may be concise or extensive, the investment that it represents may be high or low, and it may provide you with great freedom or impose many design restrictions. Second, you must invest in deriving a digital model through application of this code. This derivation process may require you to control few or many parameters, and it may be of low- or high-computational complexity. Third, you must invest in the design development for a particular CAD/CAM fabrication machine—the conversion of a digital model into a sequence of instructions for that machine. The payoff, when you have finally produced such a sequence of instructions, is that you can execute them at high speed—often to produce results that could not be achieved in any other way.

Today, architects are increasingly able to take advantage of accumulated investment in code, fast computers that support complex derivation processes, and CAD/CAM fabrication machines that make it highly advantageous to invest in the production of digital information. They can exploit the resulting opportunity for more efficient exploration of familiar design worlds. Or—far more interestingly—they can seize the chance to open up new, previously inaccessible worlds.[8]

NOTES

1 William J.Mitchell, Robin S. Liggett and Thomas Kvan. *The Art of Computer Graphics Programming.* New York: Van Nostrand Reinhold, 1987.

2 William J.Mitchell. "Dream Homes" in *New Scientist,* no. 2347, 15 June 2002, pp. 38–42.

3   William J.Mitchell. *The Logic of Architecture.* Cambridge: MIT Press, 1990.

4   George Stiny. "Introduction to Shape and Shape Grammars" in *Environment and Planning B,* vol. 7, 1980, pp. 343–351.

5   Jose P.Duarte. *Customizing Mass Housing: A Discursive Grammar for Siza's Malagueira Houses.* PhD thesis, MIT Department of Architecture, 2001.

6   William J.Mitchell. "Roll Over Euclid: How Frank Gehry Designs and Builds" in J.Fiona Ragheb (ed.), *Frank Gehry, Architect.* New York: Guggenheim Museum Publications, 2001, pp. 352–363.

7   William J.Mitchell. "Vitruvius Redux: Formalized Design Synthesis in Architecture" in Erik K.Antonsson and Jonathan Cagan (eds), *Formal Engineering Design Synthesis.* Cambridge: Cambridge University Press, 2001, pp. 1–19.

8   William J.Mitchell. "A Tale of Two Cities: Architecture and the Digital Revolution" in *Science,* vol. 285, no. 6, August 1999, pp. 839–841.

7
LAWS OF FORM
HUGH WHITEHEAD

7.1. The *American Air Museum* (1987–1997), Duxford, UK, architect Foster and Partners.
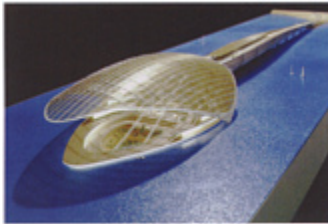
7.2. The model of the *Dubai Cultural Centre* (1995–98), architect Foster and Partners.

7.3. The model of the *Sage Music Centre* (1997–2003), Gateshead, UK, architect Foster and Partners.

7.4. The model of *Albion Riverside* (1999–2003), London, UK, architect Foster and Partners.
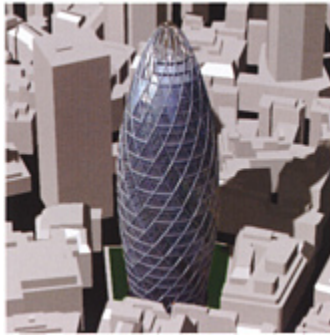
7.5. The model of the *Swiss Re* (1997–2004) building, London, UK, architect Foster and Partners.

Foster and Partners is a practice well known for its many completed buildings, but this chapter will focus more on the process of design, which is less often described, and in particular on the work of the Specialist Modelling Group. The chapter aims to convey some of the atmosphere of working in the Foster studio and, as such, it is a personal view rather than a corporate one.

The Specialist Modelling Group (SMG) was established in 1998 and, to date, has been involved in 63 projects. We have had the opportunity to see many of them progress from concept design through to fabrication and on-site construction. The group currently consists of four people, who support approximately 400 architects in the studio—a demanding ratio, but one that provides a stimulating source of new challenges. All the members of the group share a common architectural or engineering background, but have very different specialities and diverse interests, which range from aeronautical engineering to air-supported structures.

The SMG's brief is to carry out research and development in an environment that is intensely project-driven. This provides a sharp focus for development, while forcing us

to examine fundamental, or even philosophical, questions. For example, we must decide whether geometry is really the essence of form, or just a convenient means of description. Producing a form that can be built requires definition of the relationship between geometry and form in terms of a particular medium. Therefore, it is significant that designers in the studio work with many different materials and in a wide range of media.

The use of digital media has an influence that could be described by analogy. One of the best materials for sculpting is clay, but the results are free form and have no descriptive geometry. However, when clay is placed on a potter's wheel, it inherits geometry from
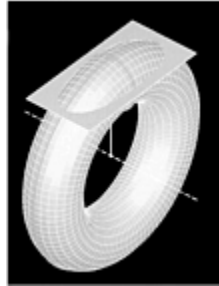
7.6. A torus patch.

the mechanism that drives the wheel and a highly geometric form is produced. Digital techniques are also mechanistic and can have a similar effect. At the same time, they enable us to cross the boundaries between different media, while expressing the same design intent. The use of rapid prototyping technology closes the loop in a digital design process by recognizing the fact that key decisions are still made from the study of physical models.

Analytical studies, on the other hand, are becoming an increasingly important part of our work. This discussion features two projects, *City Hall* (1998–2002), London, and the *Chesa Futura* (2000–03), St Moritz, in both of which analytical studies have had a profound effect on our methodology.

Panelization Theory

Foster and Partners has designed a number of buildings in recent years that were based on toroidal geometry. Each has extended the envelope of design and increased our knowledge of how to construct buildings based on sculptural forms. The following projects illustrate that radically different architectural expressions can be generated from the same simple geometric principle: the *American Air Museum* (figure 7.1), the *Dubai Cultural Centre* (figure 7.2), the *Sage Music Centre* (figure 7.3), *Albion Riverside* (figure 7.4), and the *Headquarters for Swiss Re* (figure 7.5).

In order for comparative performance studies to inform the design process, we required very precise control of geometry. As a result, we became particularly interested in exploring different combinations of torus patch constructions as an approach to the panelization

of curved surfaces. A torus is a solid ring of circular section, generated by revolving a circle about an axis outside itself but lying in its plane, such as a donut or a tire (figure 7.6). A torus patch is interesting from an architectural point of view because it has a natural flat panel solution, due to the fact that a constant section revolved around a constant centre produces a surface without twist. As ongoing research, we continually explore other constructions, such as ruled surfaces or hyperbolic paraboloids, which produce

7.7. The competition image showing *City Hall* (1998), London, UK, next to Tower Bridge, architect Foster and Partners.

surfaces with natural flat panel solutions. While a curved surface can always be triangulated to produce flat panels, this approach does not offer any repetition of panel types and creates difficulties with partitioning and space planning requirements.

The two projects described in detail—*City Hall* and the *Chesa Futura*—have required radical new solutions to the control of geometry and the architectural expression of curved surfaces. In this respect "radical" is an appropriate word because it literally means "back to the roots." The idea that returning to "first principles" is the only way to be original has always been part of the Foster design culture.

CITY HALL, LONDON

Soon after the SMG was formed, the studio entered the competition to design *City Hall* in London, which occupies a strategic position on the south bank of the River Thames adjacent to Tower Bridge and directly opposite the Tower of London (figure 7.7)—a World Heritage Site. The brief presented an opportunity to produce an iconic, signature building that would be sensitive to environmental issues while making a statement about public involvement in the democratic process. Having won the competition, the team was encouraged to extend the conceptual boundaries during the development of the scheme.

Three years later the building has just been completed. It houses the assembly chamber for the 25 elected members of the London Assembly and the offices of the Mayor and 500 staff of the Greater London Authority (GLA). It is a highly public building, bringing visitors into close proximity with the workings of the democratic process. The building is set

within the new Foster-designed *More London* masterplan on the south bank of the Thames, bringing a rich mix of office buildings, shops, cafés and landscaped public spaces to a section of the riverside that has remained undeveloped for decades.

A large sunken outdoor amphitheatre paved in blue limestone leads to a public café at the lower ground level, beyond which is an elliptical exhibition space directly below the assembly chamber. From this space, a half-kilometer-long, gently rising public ramp coils through all ten stories to the top of the building, offering new and surprising views of Lon-don, and glimpses into the offices of the GLA

7.8. The serrated profile of the *City Hall*.
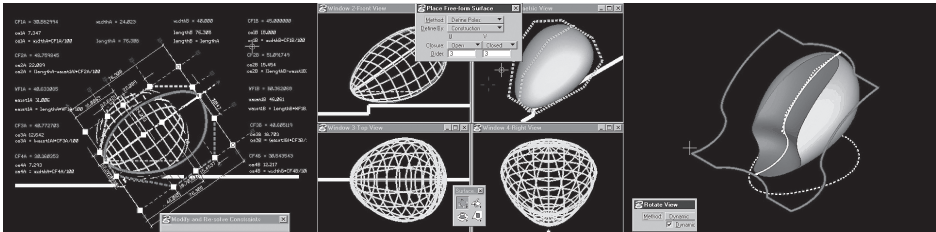
7.9a-c. The "parametric pebble"

staff. The ramp leads past the Mayor's Office to a public space at the top of the building known as "London's Living Room." This day-lit space, with external viewing terrace, can be used for exhibitions or functions for up to 200 guests.

Design Studies

In retrospect, one of the most interesting aspects of the *City Hall* project was how the design evolved from the initial ideas at the competition stage to become a form that had an integrated energy solution and a rationale which would enable it to be built. Originally, the concept was to create a large "lens" looking out over the river, with a set of floor plates attached at the back in a serrated profile, which resulted in a "pine cone" glazing effect (figure 7.8). At first sight, the inspiration for the form may seem somewhat arbitrary, which

was, in fact, how it began; as the team started work on the project one of the partners was heard to say, "We are doing something by the river. I think it is a pebble."

We took up the idea and attempted to create a "parametric pebble." The problem we faced was how to formulate a "pebble" in descriptive geometry. Our first thoughts were to start with a sphere, which has a minimal ratio of surface area to volume, and then explore how it could be transformed. This could have been achieved using animation software, but
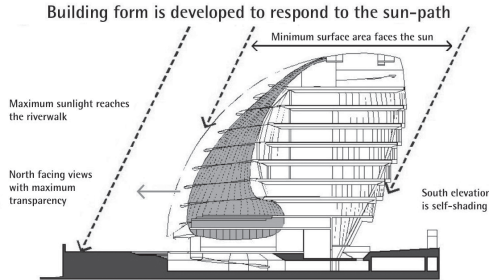
7.10. The sun illumination diagram for the *City Hall*.

we chose to develop it in Microstation, the office standard computer-aided design (CAD) system, because the results could immediately be passed to the team for use as a design tool. Having first derived a "minimal control polygon" for a sphere, we connected it to a parametric control rig, so that the form could be adjusted by using proportional relationships (figure 7.9a-c). The creation of a set of variational templates for direct use by the design team has now become a typical part of our brief. While it may take several hours for our group to produce a custom-built parametric model, it is often used for several months by the team to produce alternatives for testing during design development.

A proportional control mechanism allows designers to dynamically fine-tune curves by hand and eye, while the system precisely records dimensions. Once an appropriate shape is found, the control polygon is extracted and used to produce a solid model for further development. The pebble-like form, created in this way for *City Hall,* had some remarkable properties. If the main axis is oriented towards the midday sun, the form presents a minimal surface area for solar gain, which became very important as the design progressed (figure 7.10). The side elevations were also curved, presenting a minimal area to the east and west, where the façades face a low sun angle. The resulting form, as seen from the north, has an almost circular profile, exploiting views across the river.

Behind the giant "lens" is an atrium, a spectacular plunging void that descends to a debating chamber that is open to the public. The initial shape of the atrium was created using simple curve manipulations to generate a trimming surface, which was then used in a Boolean operation to cut away the front of the building. Although this early solid model more closely resembled a piece of product design than a building, the form had strong aesthetic qualities and already carried special properties, which would lead to an energy efficient solution.

By slicing the solid model with horizontal planes, a set of floor plates was extracted to be used as the basis for space planning studies, checking the brief, and computing net-to-gross ratios, with the results being fed back into the parametric model to improve performance. The slicing of floor plates revealed further interesting characteristics of the form.
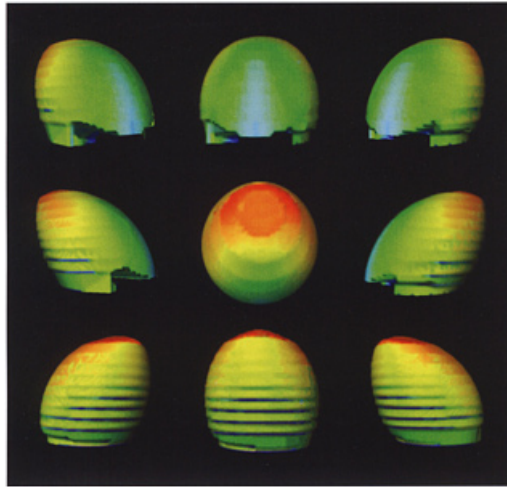
7.11. Solar studies for the *City Hall* building.

The floor plates were found to be elliptical, with the long axis of the ellipse shortening to become a circular floor plate, and then lengthening in the other direction in a transition towards the top of the building. Almost by accident, we had discovered something that could be used to generate the form through a rational transformation.

A number of detailed studies followed, with intense thought and effort applied to the glazing of the "lens." These studies relied heavily on the CAD system and its link to the CNC (computer numerically controlled) machine, because every one of the diamond-shaped panels would have unique dimensions. By applying a diamond grid to a torus-patch surface, the advantage had been lost because the panels inherited different twist and different dimensions. However, the team liked the appearance and saw potential in this design option. To eliminate twist, the panels could lift off the surface, which would allow the possibility of introducing vents around the sides. In order to test this geometry in a physical model, panels were cut using the CNC machine and then glued onto a frame. They all fitted perfectly, which was, in itself, a remarkable achievement. The result gave us confidence that by scaling the techniques to digital fabrication technology, the result would be deliverable as a built form.

The dialogue between the design team, the SMG, and the model shop created an information flow that raised further interesting questions, such as how to draw in non-Cartesian space. The designers dealt with that challenge in a very pragmatic way, sketching with a felt tip pen directly on a vacuum-formed surface, which had been produced in the model shop from the computer-generated design surface. So now, when teams want to explore non-Cartesian geometry, a digital solid model is contoured to produce a tool for a vacuum

form, on which the designers sketch ideas—why draw on flat paper when we can draw on any surface? CNC machines are also commonly used to cutout floor plates and to quickly assemble basic physical models; by stretching tape strips across them, the designers found they could rapidly explore ideas for panelization and glazing systems. Some designers were even more direct in their work methods—molding a piece of plasticine and then etching the surface with a pen. As these examples illustrate, a variety of digital and non-digital means were combined during the detailed exploration of options for the diamond grid and the "lens."

The Energy Case

Analysis of the energy studies had a major impact on the scheme development. From the earliest stage, we intended the building to be energy efficient and that its form would have special properties from an energy point of view. Arup's engineers did a solar study of the proposed design, and produced a remarkable image in which they color-coded the surface according to the total amount of energy that each cladding panel would receive during one year. They also provided irradiance figures in a spreadsheet format, so that the distribution could be analyzed in detail. Although these figures were informative, they did not provoke as much in the way of design ideas as a digital fly-around sequence of the form, color-coded with the irradiance data (figures 7.11 and 12). From this, it was immediately clear that the south façade was performing as expected—it was self-shading, as shown in the image by the blue overhang areas. The east and west surfaces were green, indicating that the oblique angles of incidence were indeed limiting solar gain. But to the north, where the atrium glazing would be, there was only a thin strip of light blue. The protected area was not large enough for the "lens" that had been envisioned—there was a conflict between the design and the outcome of the energy analysis. The solar study showed us that the glazing system had to change and, so, in this case, the color-coded diagram actually led to the glazing solution. The same study also showed a very localized hotspot at the top as an ideal position to mount solar panels.
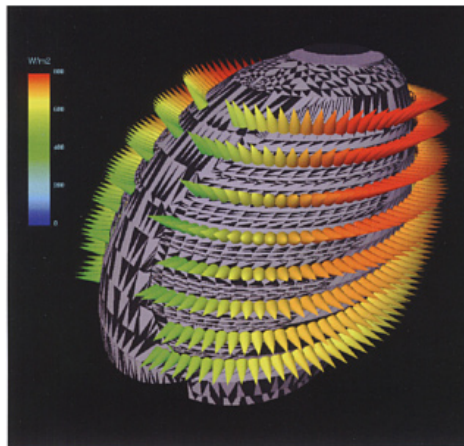
7.12. Solar study for the *City Hall* building.
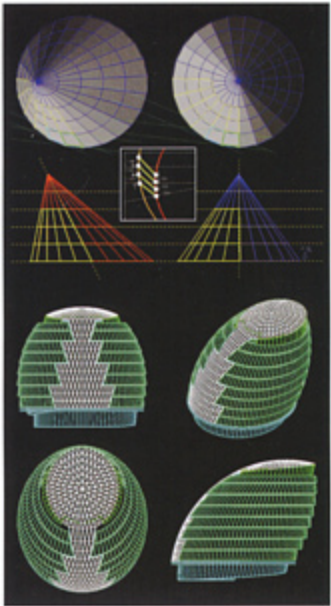
7.13. The glazing solution for the *City Hall* based on a stack of sheared cones.
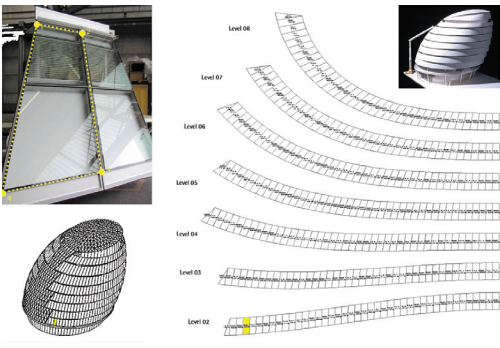
7.14. Flat-patterned drawing of the glazing solution for *City Hall*.

		Corner 1			Corner 2			Corner 3			Corner 4		
Panel ID		X1	Y1	Z1	X2	Y2	Z2	X3	Y3	Z3	X4	Y4	Z4
P_002_001		38.526778	71.225110	15.700000	37.240670	70.447647	15.700000	37.187501	71.182021	11.900000	38.478968	71.962724	11.900000
P_002_002		37.240670	70.447647	15.700000	36.007043	69.589343	15.700000	35.948733	70.320140	11.900000	37.187501	71.182021	11.900000
P_002_003		36.007043	69.589343	15.700000	34.830971	68.653727	15.700000	34.767761	69.380625	11.900000	35.948733	70.320140	11.900000
P_002_004		34.830971	68.653727	15.700000	33.717292	67.644648	15.700000	33.649441	68.367342	11.900000	34.767761	69.380625	11.900000
P_002_005		33.717292	67.644648	15.700000	32.670585	66.566256	15.700000	32.598373	67.284456	11.900000	33.649441	68.367342	11.900000

7.15. A computer-generated spreadsheet with data for each glazing panel.

The final solution required a radical change (figure 7.13), so that the design of the glazing system would literally fit the energy analysis produced by Arup. Without the "lens,"

a torus patch solution was no longer appropriate for the atrium, while the office cladding required flat, trapezoidal glass panels, triple-glazed with louver systems and blinds in precisely controlled areas. The geometric solution was to post-rationalize the surface into a stack of sheared cones. Applying this principle, we found that by glazing between circular floor plates, regardless of their size or offset, the panels remain planar if they follow the shear. We then developed a software macro that enabled programmatic generation of the glazing solution using this technique. The result produced a dynamic visual effect as the frames for the glazing fan backwards with the rake of the building. To estimate the cost of such a solution, the original macro was extended to lay out the glazing panels in a flat pattern (figure 7.14), automatically scheduling all areas of the technique has become very important in our work. When a flat-façade, and listing panel node coordinates (figure 7.15). This patterned drawing is given to fabricators or contractors, regardless of the complexity of the form, they immediately recognize it as something that can be priced, manufactured and assembled on-site.
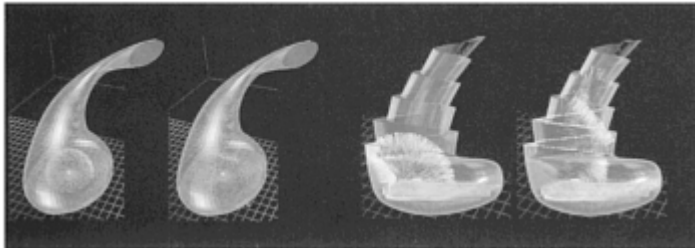
7.16a–b. Acoustic analyses of alternatives for the *City Hall* debating chamber.

Form and Space

A further important element of the *City Hall* was the internal glazing to the atrium, which separates the offices from the public space. The shape of this surface resembles a glass chemical flask, with the debating chamber at the base (figure 7.10). As shown in the schematic section, the building already had a strong rationale for its external geometry. The inclined form allows maximum sunlight to reach the riverfront walkway, the roof presents the minimum surface to the sun, and transparent glazing is restricted to the north-facing atrium, while the south façade is self-shading. The form of the "flask" needed to have an equally strong rationale for its definition, construction, and performance.

A digital model was created so that the shape of the flask could be transformed through a morphing sequence, allowing the team to explore the spatial requirements for the chamber. Starting with a symmetrical flask defined as a surface of revolution, the plan shape was transformed from a circle into an ellipse. The centre of gravity was moved down towards the bottom of the flask, while the neck of the flask was gradually bent to fit the curve of the north façade. The morphing sequence was produced by "key framing" the three different transformations, so that they could be executed in parallel to produce a wide range of alternatives. By setting up two extremes, the sequence was used to generate intermediate

versions and so find the most appropriate blend of characteristics. For example, in a time-based morphing sequence of 100 frames, i.e. different states, the designer could choose number 67 as the preferred solution.

Arup's engineers performed an acoustic analysis of the proposed geometry of the debating chamber, and determined that this dramatic shape would be difficult to treat acoustically because all the sound reflected straight back towards the speaker (figure 7.16a). Surprisingly, the breakthrough came from a parallel study of the public circulation. The office had recently completed the *Reichstag*—the *New German Parliament Building* in Berlin, which features a spiral ramp in the glazed cupola above the debating chamber as a remarkably successful element in making politics a public process. A similar spiral ramp was wrapped around the "flask" and, as a consequence, the glazing leaned outward, causing the sound to reflect in a totally different way. Further acoustic analysis on the altered geometry of the "flask" (figure 7.16b) showed the results to be ideal. The sound performed as required—it was scattered and reflected up the neck of the "flask." It could also easily be dampened by applying a sound-absorbing surface to the soffit of the ramp.

Devising a flat-panel solution for the geometry of the "flask" proved even harder to resolve than the external cladding surface. First, the form was elliptical, second, the ellipses reduced progressively in size at varying offsets, and, third, the surface was helical. Just as we had found a solution and tested it in a physical model, another lateral shift in thinking resulted in a decision to move the ramp inside, so that the glazing could be detached and moved outwards to span simply from floor to floor. The glazing was still inclined and had the same acoustic properties, but the ramp was no longer outside the "flask"—it had moved inside to become part of the space.

A sudden lateral shift in thinking is something that often arises when working with design teams and consultants on many different projects. As a group, we design tools, techniques and workflow, but with detachment, being interested in the process of providing solutions for other people to work with. This requires the group to integrate very closely with project teams, so that whether we work with them for a day, a month, or a year, we are part of the team. As the design evolves, a very large number of physical scale models is produced, sometimes being collected together as a "model graveyard" which shows the history of the design development.

Different alternatives are digitally analyzed for their performance, as in the solar study by Arup (figure 7.12). This startling image tells a very important story, because it illustrates the distribution of irradiance values for every panel. The cones show the orientation of each panel, while the color is a visual code for the irradiance value. The image produced from the analysis showed the team where to focus its design effort—on the solar protection systems. These examples illustrate that the synthesis of form is considered from many different viewpoints—functional, spatial, sculptural, structural and environmental. In trying to combine all these aspects in an optimal solution, we have to build tools that cannot be found in off-the-shelf software.

Everything in the studio is done from first principles, and so even the tools we need have to be built from first principles. Custom-developed software utilities provide ways of exploring design intent by directly driving the geometry engine behind the CAD system. This is leading towards a system that supports programmable model-building, and which records design history in an editable form.
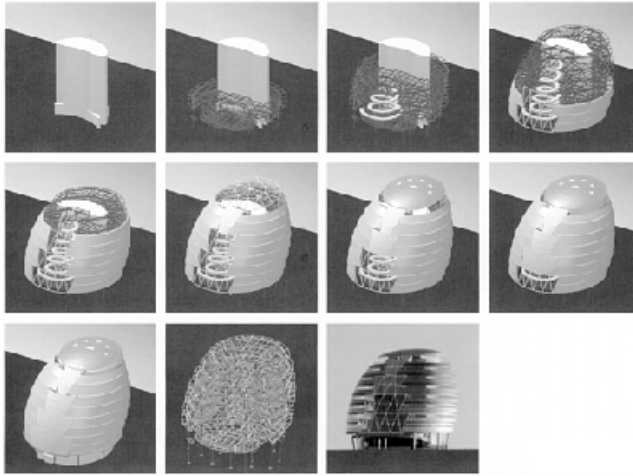
7.17a-k. The construction sequence of the *City Hall*.

Design Rationalization

Before a building such as the *City Hall* could progress to construction, the design process had to be taken apart and reassembled as a sequence of procedures. This meant that the whole building was reanalyzed as a set of construction components. There is a concrete core, a steel structure, the ramp, the atrium, the entrance glazing, the front diagrid, and the office side cladding, resulting in a complete component model (figures 7.17a-k).

Geometry Method Statement

Separate trades and different contractors were responsible for each component, so, in order to coordinate construction, we had to assist the contractors in understanding the building's geometry. A further analysis of the form was undertaken as a post-rationalization of the geometry, referred to by the team as "Nine Steps to Heaven" (figures 7.18a-i). The final form was described as a sequence of nine dependent stages, using only rational curves for all the setting out, and this was issued as a Geometry Method Statement.
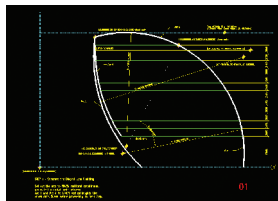
7.18a. Generating the diagrid lens cladding. Step 1: set out the arcs to given radii and coordinates; generate horizontal joints between arc 1 and arc 4 to given vertical heights; use check dimensions given before proceeding to next step.
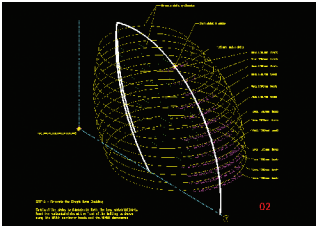
7.18b. Generating the diagrid lens cladding. Step 2: construct the circles by diameter to form the lens horizontal joints; facet the horizontal circles at the front of the building as shown using the given number of facets and the given dimensions.
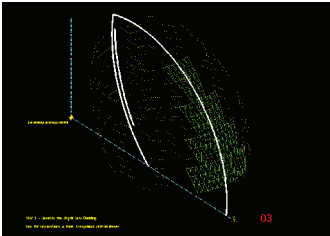
7.18c. Generating the diagrid lens cladding. Step 3: join the intersections to form the triangulated shell as shown.
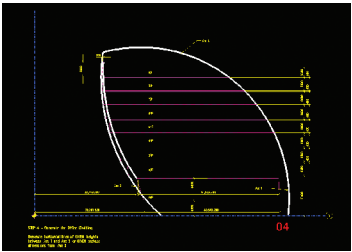
7.18d. Generating the office cladding. Step 4: generate horizontal lines of given heights between arc 1 and arc 3 or given setback dimensions from arc 3.
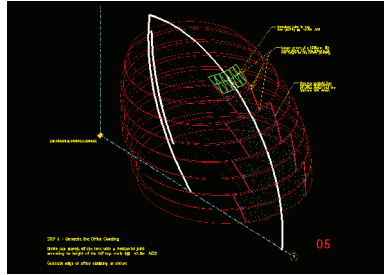
7.18e. Generating the office cladding. Step 5: divide top panels of the lens with a horizontal joint according to the height of the ninth floor top circle (@43.8m AOD); generate the edge of office cladding as shown.
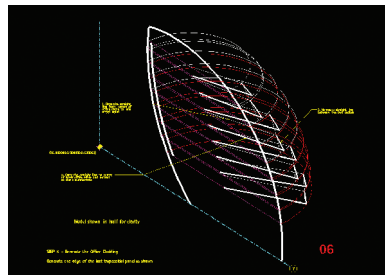
7.18f. Generating the office cladding. Step 6: generate the edge of the last trapezoidal panel as shown.
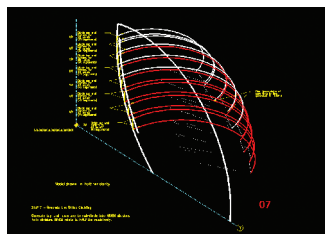
7.18g. Generating the office cladding. Step 7: generate top and lower arcs to subdivide into given dimensions.
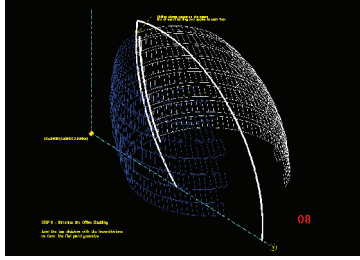
7.18h. Generating the office cladding. Step 8: join the top divisions with the lower divisions to form the flat panel geometry.
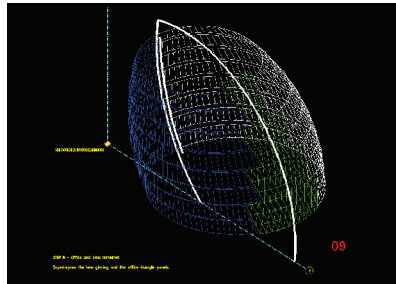
7.18i. Office and lens combined. Step 9: superimpose the lens glazing and the office triangle panels.

It may be asked why the reduction to arc-based geometry was necessary when computers can work easily with free-form curves and surfaces. The reason for this decision comes from extensive experience of the realities of building. Construction involves materials that have dynamic behavior, although their digital definition is static. They have real thickness that varies, and they move and deform, which requires a strategy for the management of tolerances. From a construction point of view, everything about the design, particularly the cladding and the structure that supports it, depends on the control of offset dimensions. CAD systems can work with free-form curves and surfaces, and produce offsets that are accurate to very fine tolerances. However, these are not precise and because the system generates more data with each successive operation, processing limits are rapidly exceeded and the system becomes overpowered. Offset dimensions can be simply controlled by specifying radii because an arc has only one center. High precision is required only in defining the coordinates for the arc centers, which leads to a dramatic reduction in problems, both in the factory and on site.

It may seem counterintuitive that in order to build a complex form, originally generated as a free-form surface, we embarked on a long and difficult process of post-rationalizing the design to arc-based geometry. However, the real benefits lay in achieving reliable data

transfer between independent digital systems. By following the Geometry Method Statement issued to contractors, we were able to describe the *City Hall* geometry in terms of basic trigonometry. This was entered as a set of expressions in Excel spreadsheets, which programmatically generated cladding node coordinates for the entire building (figure 7.15). This has now become a form of information that can be used directly by manufacturers on their production lines. However, coordinates computed in the Excel spreadsheets had first to be compared with those from the Microstation model produced by the design team.

A similar checking procedure was then used with the fabricators and contractors. They were instructed to build digital models by following our Geometry Method Statement on their own CAD system, so that coordinates could be compared by overlay and any discrepancies noted. Closing the data loop in this fashion has a number of advantages. By requiring contractors and fabricators to develop their own models from first principles, the problems that typically occur in data translation between different CAD systems were avoided. More importantly, the process transfers accountability from the design team to the suppliers, because each works with a digital model built specifically to fabricate and assemble their own components. It is a deliberate strategy of education that works for all parties; the contractors and fabricators come to understand all the subtleties of the building as a logical consequence of the underlying principles of the design.

Tolerance Management

The construction sequence had to be ordered in a very specific way. Because the structure of the building leans backwards, it progressively deflects as it becomes loaded with additional floors. This transformation could not be predicted reliably and, therefore, it had to be monitored and measured on site. There also had to be a strategy to deal with the implications of movement, particularly to monitor deflections and manage tolerances, so that different trades could work with each other and not clash.

Warner Land Surveys, who were appointed initially by the client to be responsible for setting out on site, undertook this pivotal role. They were then appointed independently by the steelwork contractor to advise on all aspects of the control of steel fabrication. With a further appointment by the client to monitor the assembly of the cladding system, they effectively took control of every aspect of the delivery process, which converted complex geometry to built form. Warner is a technically advanced company, who used the latest surveying equipment to monitor deflections as the structure was progressively loaded. The way Warner used their technology integrated perfectly with our design process. Like the fabricators, they built their own digital models of the project, but their checking procedures required three different versions—the design model as a basis for comparison, a fabrication model to manage tolerances, and a construction model to monitor deflections. Owing to the eccentric loading, the deflections became increasingly significant towards the upper floors of the building, as can be seen in the Sway Diagram (figure 7.19).
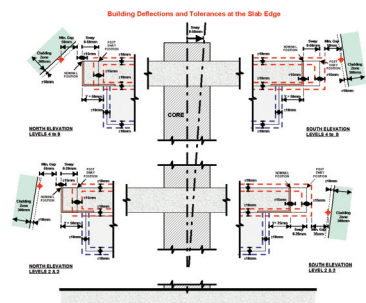
7.19. The Sway Diagram of the deflections stemming from the eccentric loading.

7.20. Digitally-driven laser-surveying equipment was used for precision control of the assembly of *City Hall.*

7.21. Installation of the cladding panels on the

7.22a–b. Testing of the cladding system.

7.23. The diagrid structure was prefabricated and assembled on-site. *City Hall* building.

At the top of the building, there was a 50 mm sway, to which 50 mm tolerance was added, plus a further 50 mm as a minimum gap, requiring a total of 150 mm between the edge of the floor plate and the cladding. A system that could accommodate that kind of variation was required for attaching cladding panels. In order to control positioning during construction, Warners marked every piece of steel structure with holographic targets in the factory. By recording coordinates for each target in a database, they were able to track every piece from the factory to its installation on-site. Using laser-surveying equipment, XYZ coordinates could be measured during installation to an accuracy of 1 mm anywhere on the site. For example, as a beam was lowered down into position, they could precisely track its position until it was placed in its intended location (figure 7.20).
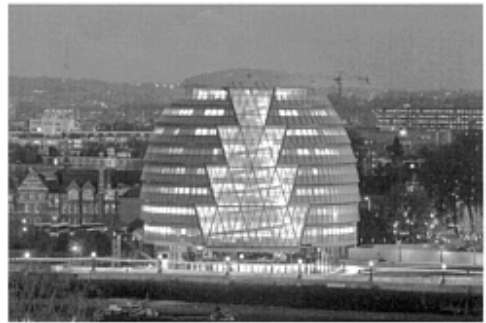
7.24a–d. Interior and exterior views of the completed *City Hall* building.

Every cladding component was barcoded, to enable accurate tracking during both the production and the assembly process. Even cladding components that varied in size by less than a tenth of a millimeter still had different barcodes. The cladding was fixed on-site panel by panel (figure 7.21), using bespoke connections resembling a ball and socket joint, except that the ball fitted into a square box. The connection system was designed to accommodate a wide range of movements and adjustments, providing for a perfect fit of the whole system. The assembly of cladding panels was tested in the factory, where three adjacent panels were placed side-by-side on a rig that could be adjusted hydraulically to simulate floor-plate configurations anywhere in the building. Each panel was checked in turn before leaving the factory to ensure a proper fit on-site. Weather tests were carried out by subjecting panels to a strong wind generated by an aero-engine and destruction tests were performed by swinging large boulders at them (figure 7.22a–b).

The final design for the atrium glazing also required special prefabrication of the diagrid structure (figure 7.23), which was generated from the Geometry Method Statement and used digital fabrication techniques to ensure a precision piece of engineering. The completed building (figure 7.24a–d) was delivered on time and on budget. It attracted 10,000 visitors during the first weekend after the opening ceremony.

7.25. The digital model of the *Chesa Futura* (2000–2003), St Moritz, Switzerland, architect Foster and Partners.

ST MORITZ—CHESA FUTURA

The second project discussed also involves complex geometry and high-tech construction methods, but is different in every other respect, particularly because it is made of wood. The *Chesa Futura* apartment building is in the popular skiing resort of St Moritz in the Engadin Valley in Switzerland. It is situated among dramatic landscape at 1800 m above sea level. It fuses state-of-the-art computer design tools and traditional, indigenous building techniques to create an environmentally-sensitive building. It combines a novel form with traditional timber construction—one of the oldest, most environmentally-benign and sustainable forms of building.

The building is raised off the ground on eight legs and has an unusual pumpkin-like form. This is a creative response to the site, the local weather conditions, and the planning regulations. The site has a height restriction of 15.5 m above its sloping contours. If the building were built directly on its sloping site, the first two levels would not have views over the existing buildings. Elevating the building provides views over the lake for all apartments and maintains the view of the village from the road behind the building. Raised buildings have a long architectural tradition in Switzerland—where snow lies on the ground for many months of the year—avoiding the danger of wood rotting due to prolonged exposure to moisture.

By sculpting the building into a rounded form, it responds to the planning regulations. A conventional rectilinear building would protrude over the specified height. Because the ground and first floor levels are not utilized, the three elevated stories are widened to

achieve the desired overall floor area, but do not appear bulky due to the building's rounded form. The curved form allows windows to wrap around the façade, providing panoramic views of the town and the lake (figure 7.25).
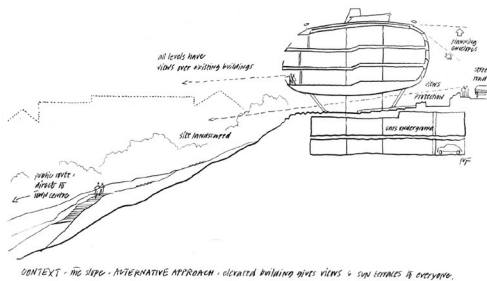
7.26. The design sketch of the *Chesa Futura* by Norman Foster.
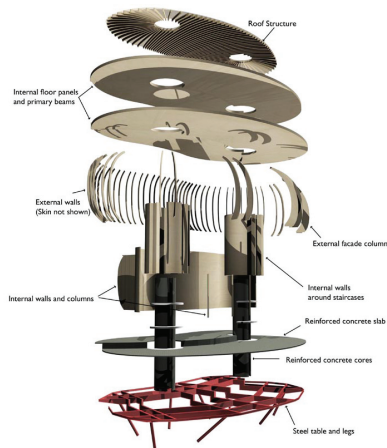
Development of the Form

The curved form resulted from responding to the potential of the site, while conforming to its constraints. The initial design sketches were interpreted and formalized as a parametric model (figure 7.26), which the team then referenced so that changes could be tracked in both directions. A parametric version of the section (figure 7.27) went through many months of changes, which were also informed by simultaneous planning studies. The constraints were such that a two-degree rotation of the plan resulted in a 50 m² loss of floor area, while a two-degree rotation of the section reduced headroom by 100 mm at each level.

Although it appears to be a relatively simple form, for every combination of plan and section, there were endless possible approaches to surfacing techniques. The key to controlling the form was to slice it with two sloping planes at a three-degree inclination (figure 7.28). The idea of using parallel slice planes, which separate the wall element from the roof above and the soffit below, may seem a fairly obvious proposition but it had surprising additional benefits. We started to think of the wall as a shell, which had a polar grid associated with it (figure 7.29). The polar grid is an ideal way of locating elements, such as windows, whose positions are based on radial setting-out geometry. We defined four sectors and a number of subdivisions within each sector, so that every subdivision could be either a window location or a rib position. This gave us great flexibility and control, and also provided a convenient coding and referencing system. Having placed the window reveal surfaces as cutters, we then applied Boolean subtractions to create a perforated shell (figure 7.30). The insertion of floor plates resulted in a form that related to the section, with a step in each floor plan to maximize the view (figure 7.31).

The initial modeling process is described only briefly, because the interesting part of the project was the way in which the many different generations of model, both digital and physical, were used by the engineers to develop the construction process (figure 7.32).

7.27. Parametric definition of the section for the *Chesa Futura*.

7.28. The initial surface model with the slice plane.

7.29. The model of the exterior wall as a shell, with associated polar grid.

7.30. The perforated design surface shell.
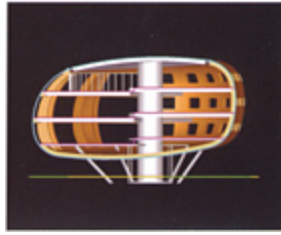
7.31. Addition of the floor plates.

7.32. The construction process and phasing strategy

Construction Strategy

Owing to the severe winter weather conditions in St Moritz, there are only six months of the year when building work can be undertaken. The planned construction sequence was therefore first to erect a steel table with a concrete slab, and then to prefabricate the whole wall system during the winter, when no work was possible on-site. The following spring, the frame, walls and roof could be rapidly installed, and the shell completed and made weather tight before winter, when the interiors could be finished (figure 7.32). This became the strategy that made construction possible, but meant that precise phasing of the work was absolutely critical.

Information Strategy

In order to rationalize the geometry of the shell and develop it as a parametric model, we explored the idea of relating plan to section as if on a drawing board (figure 7.33), but

generating constructions by using software macros. The macro uses a "ruler," driven by the polar coordinate system, to scan the sectors of the plan drawing and record measurements projected onto track curves on the adjacent section. This, in turn, builds parameter sets, which are passed to a rule-based wall section, causing it to adapt to any location on the shell (figure 7.34). The macro has two modes of operation: it can output a design surface shell as a solid model with associated ribs for the structural frame, or a matrix of drawing templates to be used for detailing or shop drawings.
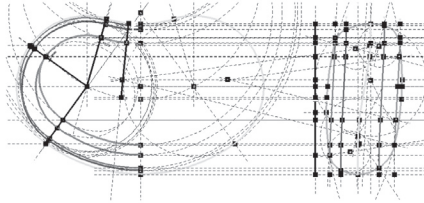
7.33. The parametrically-linked plan and section.
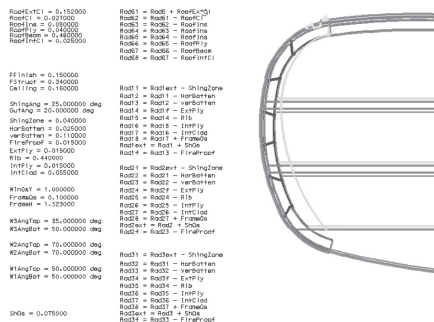
7.34. The parameter set for the wall section.

As the design progressed, each team member became responsible for a different set of parametric offsets, determined by the thickness of materials used in construction. One team member would work on the roof, another was in charge of structure and finishes, a third was in charge of the wall zone with battens, fireproofing and plywood cladding, while a fourth was responsible for all the window details. By having access to the same parametric templates, the team was able to respond to design direction and to coordinate development of the project, each making their own changes while responding to the implications of changes made by others.
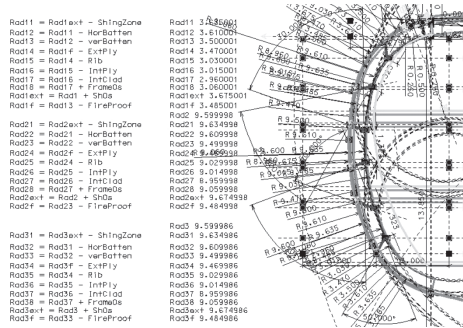
7.35. The parametrics were all arc-based, as shown by the radii.
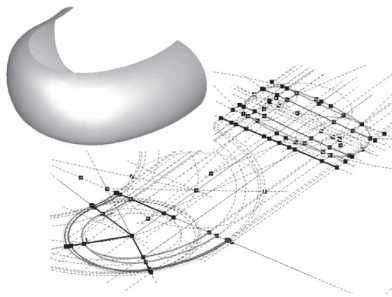
7.36. The resulting analytical surface is made of patches that have perfect tangency across arc boundaries.

As with *City Hall,* the parametric geometry was deliberately arc-based but for entirely different reasons (figure 7.35). The prefabrication strategy required a solid model that would be capable of driving advanced CAD/CAM machinery in a factory in Germany to precision engineering tolerances. In order to use this technology successfully, we had to understand the solid modeling process at the level of the underlying mathematics used by the software. Although the surface has free-form characteristics, it is, in fact, an analytical surface made up of patches, which have perfect tangency across boundaries that are always arcs (figure 7.36).

   An analytical surface is ideal for working with most solid modeling kernels—the software is able to calculate offsets with precision, giving results that are fast, clean and robust, which is particularly important during intensive design development. The ability to make rapid and reliable surface and solid offsets without suffering any CAD problems allowed us to share digital models with our engineers in Switzerland and fabricators in Germany. Choosing to pre-rationalize the design surface by making it arc-based achieved a degree of control that allowed us to simplify and resolve many complex issues of design and production. The software macros developed could derive all the arcs from rule-based constructions and then place them in three-dimensional space, automatically generating shell,

frame and rib geometry based on parameter values entered for the offsets. The result was a shell with a precise rational definition, which became the design surface that was signed off to the engineers.

At this point we made a commitment to make no further alterations to the design surface, although offsets were continually varied throughout the year as the project evolved (figure 7.37). We could locate any component by choosing a position on the polar grid, creating a plane, and intersecting it with the design surface to determine the radial offset for placing the component. In addition to being able to accurately model and place components in space, we could generate a matrix of sections, drawn for each rib position and thus produce templates for all the shop drawings. When both the plan and section were still changing, even at a late stage in the project, we could programmatically regenerate the design surface shell in a way that was consistent and reliable. Software tools were evolved that allowed the design to become a cyclic rather than a linear process. The freedom to explore multiple iterations of a design proved to be the key to optimization.
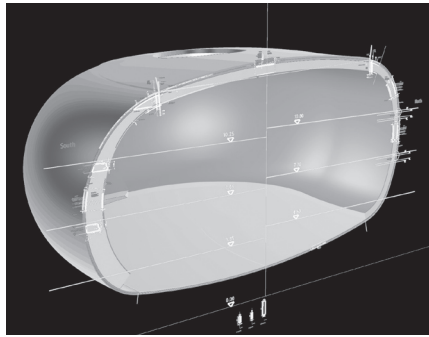
7.37. Design details were developed on the principle of a fixed design surface with variable offsets.
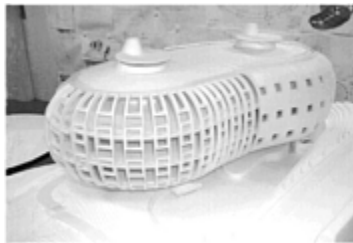
7.38. A physical model produced from CNC-cut parts.

7.39. A wide variety of media and modes of representation are used in project reviews.

Assembly Strategy

In the Foster studio, most of the key design decisions are still made from the study of physical models. In fact, the CAD system was introduced initially to the studio to provide shop drawings for our model makers. Digital technology now allows us to begin with he digital models, which are then passed to the model shop for fabrication using CNC machines (figure 7.38). There is a constant dialogue between drawings, computer models and physical A typical project review uses every possible medium—hand drawings, CAD models, rendered images, hidden-line models, CNC-cut models and sketch models (figure 7.39).

The next generation of the *Chesa Futura* model was based on realistic components, designed to test the actual assembly process of building, as envisioned by Arup and developed by Toscano, the Swiss engineers (figure 7.32). This model was created from the ground up—beginning with the steel table with hangers for the soffit (figure 7.40), the concrete slab, the ribs and C-columns for the front balconies (figure 7.41), then the spandrels, and finally the ring beam at the top (figure 7.42). This corresponds to the slice plane used to define the initial geometry, which became expressed as an inclined gutter marking the change of materials from wall to roof (figure 7.43). The windows are all identical, standard 1.4 m "Velux" sealed double-glazed units, which give the best performance in the severe
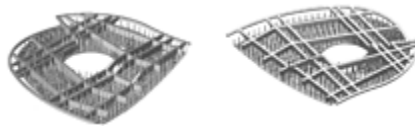
7.40. The digital model of the steel table with hangers for the soffit.
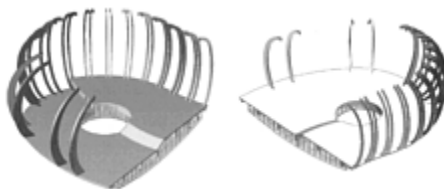
7.41. The concrete slab, the ribs and C-columns for the front balconies.
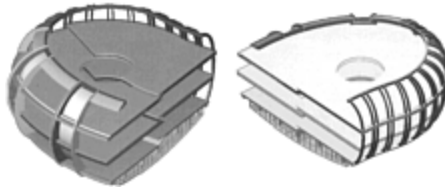
7.42. Addition of the spandrels and the ring beam at the top.

7.43. The complete shell, with all the window reveals.

local weather conditions. The reveal for each window is different and custom made, but the cost savings are far greater from the repetition of window type.

7.44. The coursing diagram for the timber shingles.

7.45. The digital model, showing the timber shingles.

7.46. Shingles modeled in etched brass.

Each generation of digital model led to the next physical model, as increasing levels of detail were explored. At this stage, there was a need to study how to control the coursing of the timber shingles in relation to window openings. The coursing lines were produced by software macros as flat patterns, cut by CNC machine, and then assembled on the model. To represent timber shingles at this scale of model required a high level of precision and many hours of patient work by the model makers. There was a coursing diagram (figure 7.44), worked out on the digital model, which showed how the skin was to be battened (figure 7.45), because it is the timber battens that control the shingle layout on-site. The shingles were modeled in strips of etched brass (figure 7.46), which were applied on the course lines and then painted over. Due to the level of detail achieved, this model allowed us to rehearse all the key aspects of the full-scale assembly process and to discuss points of detail with the craftsmen involved.

7.47. Lamination of the ribs.

7.48. CAD/CAM machinery used for prefabrication of the timber frame.

7.49. The hand-cutting of the shingles with an axe.

When it came to factory production, the full-size ribs were CNC fabricated from glue-laminated beams—thin layers of wood glued together under pressure (figure 7.47). This is a wonderful material because it has the strength of steel, the malleability of concrete, the lightness of timber, and exceptional fabrication possibilities. The fabricators, Amann, specialize in producing remarkable buildings that use glue-laminated beams. They have a very advanced CAD/CAM machine with an impressive array of 20 tools, which descend from racks in their prescribed order to cut, drill, rout or bore at any angle, with any curvature (single- or double-curved), on a piece of laminated timber up to 40 m in length (figure 7.48).

After designing a shell to engineering tolerances, it is a delightful irony that it will be clad with timber shingles, cut with an axe by an 80-year-old local expert (figure 7.49), and then nailed on by hand by the rest of his family.

The final generation of building model resolved all the junction details between finishes (figures 7.50a-d). At this stage, a most useful technique was to illustrate details using hidden-line sectional perspectives. These are cut-away views of the solid model with architectural drawings applied to the cut surface (figure 7.51). They successfully communicated process, assembly and final appearance in a single image.
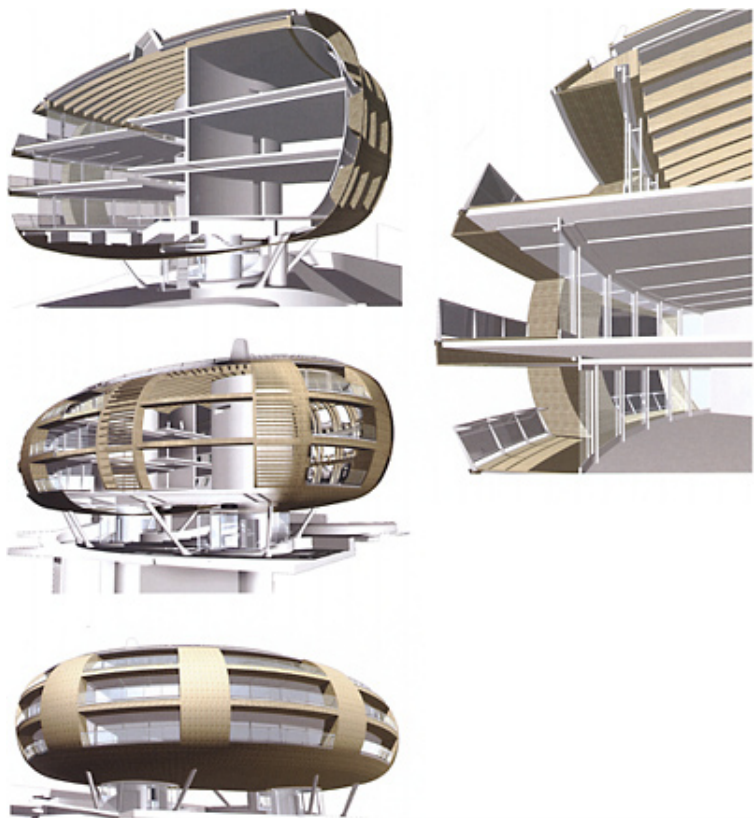
7.50a-d. The detailed digital model of the building.
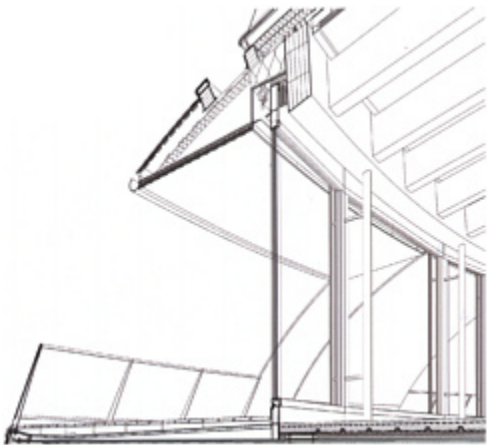
7.51. The sectional perspective cut through the solid model.

Full-scale Prototype

The detailed design was put to the final test in a life-size mock-up of a typical part of the shell, comprising a single window with the surrounding reveals and supporting ribs (figure 7.52). This was erected on-site and marked an important moment in the development of the project, when everybody started to believe that the building was achievable. As construction progressed on site, it was remarkable to see how a building with such an unusual combination of form and materials sat so naturally in its context (figure 7.53). While the skin of the building (figure 7.54) is made from a local, natural and traditional material—with timber shingles—the very high-tech frame that supports it, justifies the name *Chesa Futura*—House of the Future.

7.52. Prototype of the window section, clad with timber shingles.

7.53. Digital simulation of the *Chesa Futura* in its context.

EVOLUTION

There are common themes in the two projects discussed and in the way our use of technology has evolved to support them. Through the experience of *City Hall* we learned the importance of being able to post-rationalize building geometry. In the case of the *Chesa Futura,* we were able to embed the rationale in the tools used to create the form. The

development of customized utilities is now based on a function library, which extends with every project undertaken and is structured to allow functions to be combined by the user without having to prescribe the workflow.

Most designers already think programmatically, but having neither the time nor the inclination to learn programming skills, do not have the means to express or explore these patterns of thought. Conceptually, designers have outgrown conventional CAD packages, which in order to be useful in design terms, must now include systems for describing the structure of relationships, the behavior of physics and the effects of time.

Since its formation, the SMG has been collaborating with Robert Aish, Director of Research at Bentley Systems, to specify and test a new development platform. The results of the first evaluation cycle were shown at a research seminar at the 2002 Bentley International User Conference. This platform will be object based and aims to use new technology to promote learning and the sharing of expertise through a more symbiotic relationship between designers and the systems they use.
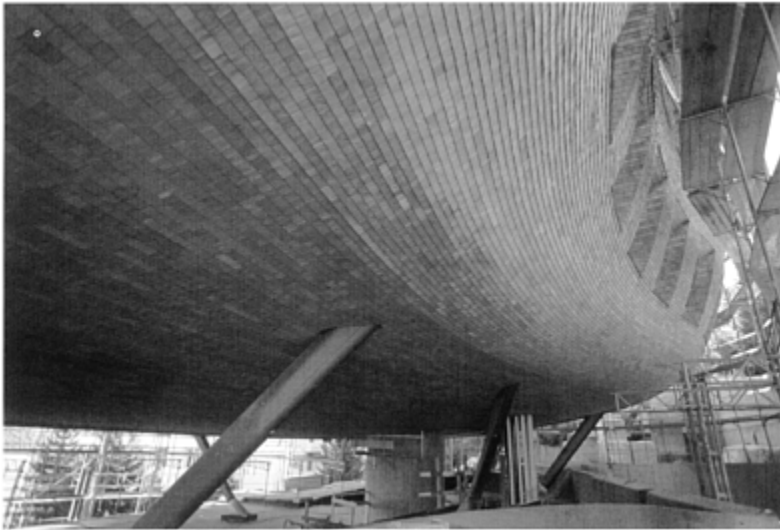
7.54. The *Chesa Futura* under construction.

8
EVOLUTION OF THE DIGITAL DESIGN PROCESS

JIM GLYMPH

At the risk of being repetitive, I thought it might be interesting to go back to the beginning of computing at Gehry, to the late 1980s, and take a look at the last dozen or so years as they relate to one project—that project being the Walt Disney Concert Hall (figure 8.1)—and weave in some of our experience from other projects.

There was a design competition in 1988 for a new concert hall on the Los Angeles Music Center site next to the Dorothy Chandler Pavilion, an opera house that the Los Angeles Philharmonic uses. As opera houses do not make very good acoustical halls for symphony music, Lillian Disney, Walt Disney's wife, began this competition with a gift of $50 million to the County of Los Angeles, which was intended to fund the project. The competition design that Frank Gehry did (figure 8.2) consisted of the concert hall itself, backstage support spaces, administrative offices for the Philharmonic, a chamber music hall, and a public space that was housed in a large, glass pavilion that was to be a "living room" for the city. As in most competitions, when the competition was completed and Frank Gehry had been selected, the owner and users sat down to talk about what they wanted to do, and what that might cost, and they quickly realized that they were short of about $100 million to build a concert hall of any sort. To make the project viable they added a hotel, which was to bring revenue to the project, help fund that portion, and pay for a substantial portion of the parking, with the balance of the parking and the land being provided by the Los Angeles County.

8.1. *Walt Disney Concert Hall* (2003), Los Angeles, USA, architect Frank Gehry.
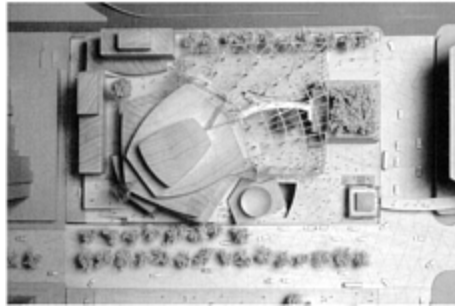
8.2. Frank Gehry's competition winning design for the *Walt Disney Concert Hall*.

The concert hall development group (WDCH1) also selected an acoustician for us to work with. This selection and its influence on the project is an aspect of the project that Frank Gehry has often talked about. We did numerous studies of different concert hall configurations, trying to understand what was correct for this symphony hall, creating an array of models that are either examples of existing halls or designs morphed from those examples (figure 8.3). The range thus created was an attempt to find the "single" perfect solution for acoustics, as there was no agreement among acousticians as to what would be the correct form of the hall. The assumption in the competition had been that the concert hall would be set up with the stage in an "in-the-round" configuration. The classical "shoebox" is supposed to perform equally as well, although differently.

We were developing a new design at that time, working with the concert hall in the round, with the hotel next to it. There was a central space between the chamber music hall and the concert hall, with the entrance off to the corner, so that it opened to the corner and the Dorothy Chandler Pavilion, creating an appropriate connection to the Music Center. This basic relationship of the parts was retained from the original competition model. The modified "shoebox" in-the-round design for the hall was incorporated into the design, with a 350 room hotel.

What is interesting about this point in the development of the project is where the office was, technologically, in 1989. At that time, we would create an AutoCAD drafted, hand-cut model to look at the relationships within the project. Even though the model is elementary, one could very quickly understand how the building was organized. Our acoustician, Dr. Toyota, was doing ray-tracing studies (figure 8.4) and looking at what we called a modified "shoebox." Volumetrically, a classical symphony hall normally holds about 2/000 people, but the Philharmonic wanted 2/400 seats. In order to adjust the volume of the room, we developed tilted walls on the box to maintain the greater capacity in the same acoustical volume, and then performed basic acoustical tests to position reflective acoustical surfaces
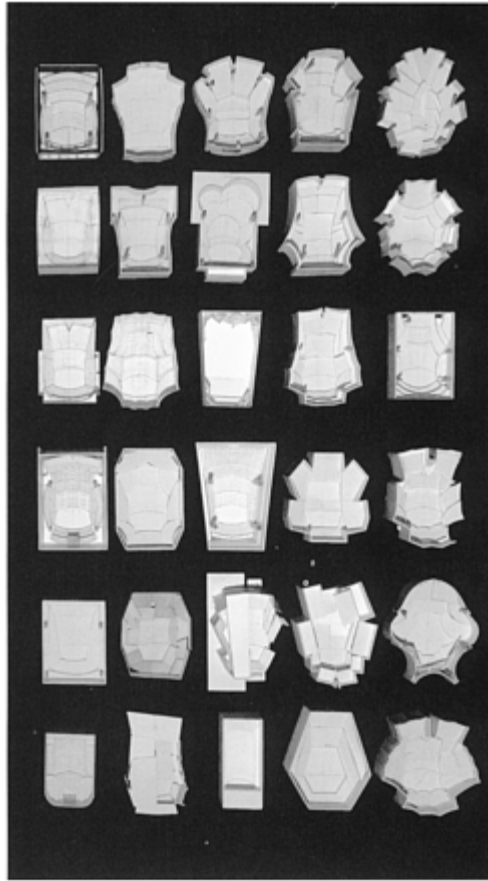
8.3. Studies of different concert hall configurations.

within the hall. As those were the early days of acoustical ray-tracing programming, Dr. Toyota also took actual laser measurements from physical models (figure 8.5). This approach was very compatible with the way Frank Gehry was working at the time. There were no robust computer models. He would install reflective surfaces on a physical model—the idea was to develop an ideal acoustical shape as the form generator for the building. Using this approach, we developed an initial seating tray arrangement with 2,400 seats around the orchestra, with none more than 60 feet away from the conductor, in a volume that is a theoretically correct volume for the symphony hall.
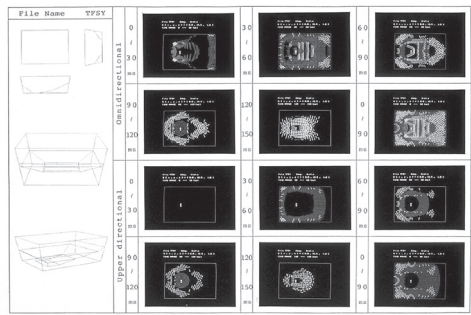
8.4. Acoustical ray-tracing studies (1989) by Dr. Toyota.

The forms emerging in the exterior in the study models of the time were corresponding to the forms generated in the acoustical studies for the interior. Frank Gehry was beginning to look at an aesthetic where the curves that were being generated on the inside became reflected on the exterior of the building. Gehry's working style is clearly manifest in these early models. As this project was developed soon after the American Center in Paris, there is a stacking of objects against each other as a starting point for the design process, and then the adding of paper or plastic cups and whatever else we found lying around the office. Study models were generated very quickly, spontaneously, around the basic ideas of the project. The development of sail-like forms and that kind of imagery was all done in physical models. There was no computer modeling at all; in fact, at that time there were no computers in the office.

That was where the project was in 1989. Looking at those forms then, one of the first questions was: how do we build this, from what materials and systems? As we were developing our second design with a hotel, the hotel operator decided to withdraw from the project over a dispute with the county on union operation. The hotel disappeared from the project, and in the next design we were left with the concert hall "flower" that sat with its chamber music hall in the center of the site, still trying to hold onto that original "living room" public space between the two halls. After this scheme was priced and compared with the realities of fund raising at the time, the chamber music hall disappeared from the project. We were back to the basic original program, without the chamber hall, so it no longer made any sense to have a "living room" in its original corner location. We had nothing to contain the space. At that point the


8.5. Acoustical studies of the concert hall using laser measurements from physical models (1989) by Dr. Toyota.

concert hall was rotated, so that the corner would face the corner entry from the Music Center; one would now enter on the axis, with this acoustical box, and then move through lobby areas that wrap around the sides of the acoustical box of the hall. This basic configuration of the box exists in the hall that is under construction today.

As we were completing the fourth schematic design for the project, we were invited to exhibit the design at the Venice Biennale. We were concerned about how we were going to build the concert hall and the need to provide a proof of concept for the construction. The client group wanted the building to be made out of stone; they did not want any "Frank Gehry chain-link, mesh, or metal," which seemed to be the biggest concern they had about hiring Gehry. For that reason, we developed all exterior walls as stonewalls. This requirement and the geometry intended in the design forced some real breakthroughs to happen.

Because forms on the models were becoming more gestured, and unique, Frank Gehry spent a lot of time struggling with the line between sculpture and architecture. The functioning and urbanism of the building remained paramount and the formal language that was evolving was free flowing and interesting, but not what one would expect in a building. At the same time, we had to start figuring out how we were going to build it using emerging computer modeling and CAD/CAM technologies.

Using a digitizer arm, we digitized the previously built model (figure 8.6), rationalized it to a degree in the computer, and then rebuilt it from templates to look very specifically at the surfaces that were to hold stone. The stone surfaces were modeled with rational breakpoints to create curves and arcs in some cases, and in other cases we left the natural form since we knew we were going to be milling. It was not critical that we completely
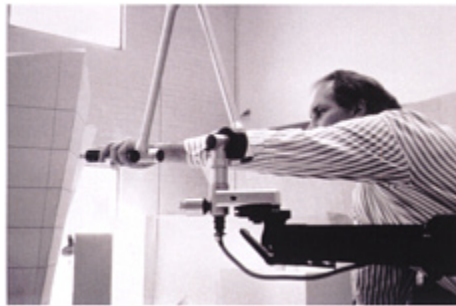
8.6. Digitizing one of the early models of the *Walt Disney Concert Hall.*

rationalize the geometry. We developed a stone pattern of standard block sizes and then we worked with fabricators in Italy to develop machine paths directly from our computer model to CAD/CAM fabricate the stone. We produced a mock-up for the Biennale as a proof of concept for the construction of the stone walls (figure 8.7).

By the time we reached the Biennale, we had a CAD/CAM fabricated stone wall, we had integrated a new acoustical ceiling into the hall, and we had finalized the basic design of the interior. While all that was going on in Italy, our acoustician was back in the office to build a one-tenth scale model for testing the acoustics of the hall (figure 8.8). This model

was constructed from templates out of our three-dimensional computer model. This process of generating models, by digitizing physical study models, developing a refined computer model, and regenerating physical models from templates, or by CAD/CAM methods, was beginning to be used on all our projects. This studio process was a direct outgrowth of our experience in stone at full scale.

What the acousticians were concerned about were the effects of echo, which they could not measure based on the reverberation time computed by the ray-tracing program. Echo is a fairly critical component to the whole operation of symphony music. The hall was meant to have completely natural acoustics, with no adjustable reflective surfaces. In this design one can adjust absorption, but we cannot adjust the shapes—they are fixed, so we put a great deal of energy into testing the acoustics by building the scale model and filling it with nitrogen to reduce the density of the air in it using high-frequency sound. We essentially built a tenth scale acoustical environment to take readings from and to develop the final adjustments to the surfaces of the interior. The various acoustical models established the

8.7. Full-scale mock-up of the exterior stone wall that was digitally fabricated from the computer model data.

location and geometry of the reflective walls. The ceiling shapes were particularly critical. The ceiling was raised slightly off the walls, and that generated internal forms—the "boat," the arc that one sits in with the orchestra to experience with the hall. Based on the mock-up produced for the Biennale, we were reasonably confident that we had taken every precaution available to make all of that work.

At that point, in the office we were producing iterative models using a three-dimensional digitizer, manually constructing surface shapes, interior and exterior, and then regenerating physical models to make modifications. Modifications to form made in the computer were not made for the purposes of aesthetics—they were made for the purposes of a system fit. The aesthetic modifications were all made on physical models.

We also started using very heavy watercolor paper when making the models, which would stretch so that we were not really working with "paper" surfaces. We knew we could do that because we were going to mill the stone. We had gathered from our experiments that geometry really did not matter a whole lot, that a lot of the rationalization we were doing was not that important because the costs of fabrication, sorting and delivering

remained the same regardless of whether we were doing more complex curves or whether we were doing simple geometric curves.

A CATIA model was completed for the entire stone and glass exterior as well as for the interior (figure 8.9). We made more iterations, modeling stone patterns as well. There were rules of breaking on a curve and setting-up radiuses and arcs on the various flips on the sail-like surfaces, so that we would get repetition in the stone along those lines to address some breakage issues. As Los Angeles is in a seismic zone, the building had all horizontal shear

8.8. One-tenth scale model for testing the acoustics of the hall.
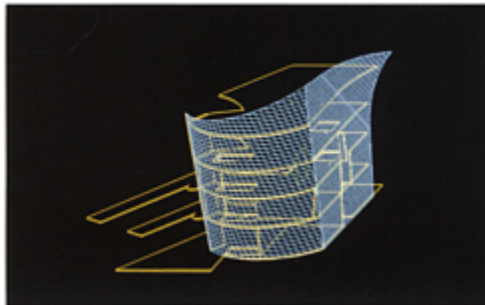
8.9. One of the early CATIA models of the exterior stone walls.

joints to allow a fair amount of movement in an earthquake. We developed the stone pattern and the masonry connection system where every stone was supported independently, so that every joint would be a movement joint; that way we could accommodate the movement of an entire wall without having to create large joints to break up the continuous surface. That was tested and then the final model was developed. We ran a bid competition based on providing computer data to a number of different fabricators, most of them in Italy. Several mock-ups were produced, in which the highly complex pieces were cut by CAD/CAM using machine paths generated directly on the architect's surface model.

The concert hall died very soon thereafter. We had developed a detailed budget that was broken down by component. The stone was fully developed in the computer and it was

on budget. We had an executive architect at the time, responsible for developing the basic building and working in traditional two-dimensional methods. As drawings got from 85% complete to 86%, to 86.5% complete, we started to realize they were never going to be finished successfully using traditional methods. At the same time, the fundraising was not going very well. The Disney family, with Lillian Disney's daughters also contributing, had given $100 million to the project, but none of the other fundraising had taken place. The combination of worrying about the feasibility of construction and the ability to complete the documentation for all of the "normal" portions of the building, the cost overruns on the more traditional elements of the construction, and the slow fundraising brought the project to a halt with only the parking garage completed.
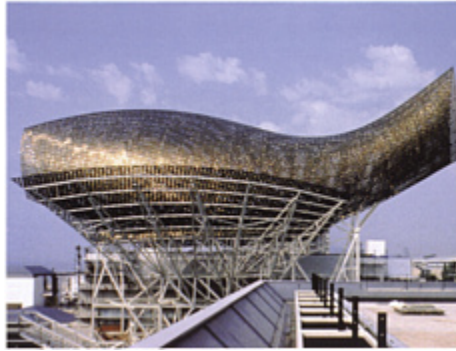
8.10. The fish-like structure at the entrance to the *Vila Olimpica* complex on Barcelona's waterfront (1992), architect Frank Gehry.
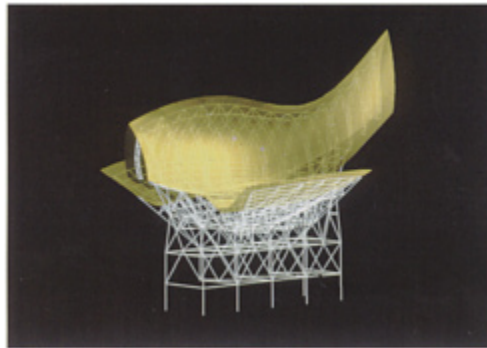
8.11. The three-dimensional model in CATIA of the Barcelona "Fish."

8.12. The *Nationale Nederlanden* building (1996), Prague, Czech Republic, architect Frank Gehry.

8.13a–b. Milling of Styrofoam molds for the casting of reinforced concrete panels (*Zollhof Towers,* Düsseldorf).

8.14. Concrete panels were precast in CNC-milled Styrofoam molds and installed on site.

It was an interesting process trying to get what were very reputable, very well-established architects and engineers to try to work in a three-dimensional environment to scale back in 1991. It was such a taboo that we had a very hard time getting anybody to have faith in it. In spite of the fact that we may have proved something with the stone, there were just too many layers of coordination in the two-dimensional not-to-scale drawing process—too much perceived risk.

   At the same time that we were doing the concert hall, we did a number of projects that made us believe that we were on the right interior. The various acoustical models

8.15. *Zollhof Towers* (2000), Düsseldorf, Germany, architect Frank Gehry.

established the x was done very early as a paperless project using CATIA (figure 8.11). It was relatively simple-cladding on the structural steel. It was all coordinated through the computer model. There were about six drawings by hand and a computer model for the entire process. The computer model was used for tracking parts, design and the layout of

the system. Through that project we became familiar with downloading information to laser cutters from a three-dimensional model and working with a contractor on the layout in fabrication from a single database that we all shared. We also did a project in Prague (figure 8.12) in the same timeframe, or soon after the concert hall was stopped. It was a complex metal and glass construction, modeled in the computer and then templated for what looks like a nineteenth-century construction of the steel but is, in fact, all computer-templated. We also had this notion that we could mass-produce, using a CAD/CAM process, individual precast concrete wall panels that were all slightly different, but the Czech labor rates were so low that we wound up simply templating directly from the computer to craftsman, who would build wood forms and then ultimately complete the wall.

Things were changing fast. Those two projects were both nearly in place at the time the concert hall stopped, but we were not in the position to continue the hall since we were, essentially, the design architect and not the architect of record, and the funding was not in place. We continued our exploration of milling in a project in Düsseldorf, where we collaborated very closely with a German contractor from early in the design phase. At that point, we were experimenting with laser-cut and milled models, and we were becoming
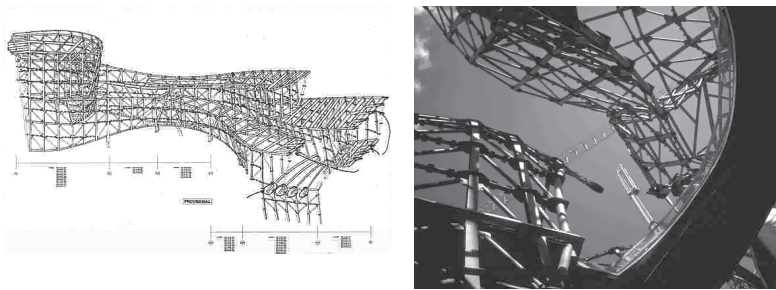
8.16a–b. The steel structure for the *Guggenheim Museum* (1997), Bilbao, Spain, architect Frank Gehry: carried out in Bocad steel-detailing program.

very familiar with iterating models directly from the computer and developing fairly sophisticated computer models that begin to integrate different elements of the project. In Düsseldorf, unlike Prague, we managed to find a contractor courageous enough to go out and buy some equipment. They built a CAD/CAM machine that mills large foam blocks (figures 8.13a– b), which were then used as molds to cast individually unique concrete pieces that were installed on the site (figure 8.14) to ultimately build the building (figure 8.15). (All the material for the molding was recycled.) It was an extremely efficient process.

And then, after the concert hall stopped, we had the miracle in Bilbao. It was a miracle, I think, because we were very lucky. At that point we were committed to trying to prove that what we wanted to have done on Disney could be done. We began a process with the same kind of exchange between physical and computer models, with the notion that we would build a CATIA model that would be able to control all the major elements of construction. The structural concept, developed by Hal Ingar of SOM, took advantage of the curves in

the design to stabilize the structure, and the walls were developed from a standard detail that was morphed into various shapes. Our first stroke of luck was that Bocad, a steel-detailing program that also runs CAD/ CAM equipment, had just been completed, and a local steel fabricator had just installed it on his production line. The steel structure was fully developed in Bocad, with a great degree of detail (figures 8.16a–b), and gave us the opportunity to show that, in fact, we could have done the steel structure on Disney.

The building in Bilbao had a lot to do with the Disney project coming back. Two things happened: it was successful because we were lucky about the available technology and that it had emerged in the region. It was successful because it was a point of regional pride and all the contractors worked in harmony for that reason. It was successful because they wanted to prove it could be done and they assumed we knew what we were doing. It was the power of positive thinking. We also had a recession in Spain, which kept prices low, and the Russians dumped a lot of titanium on the market, which reduced its price. It was successful because we had a strong relationship between the City as developer, the Guggenheim as operator, and the architect. All those stories are true, and, without them, the principal story, which is that CAD/CAM saved the day—and that is why the building was not expensive—would not have been told. It had a lot to do with the way people used the computing tools, rather than the tools themselves, and the way people collaborated using the tools.

With the successful completion of the *Guggenheim Museum,* back in Los Angeles, they again wanted to build the concert hall. They now believed that it would be buildable, but there had been the Northridge earthquake, which cracked some of the moment-frame structures in Los Angeles and threw the engineers off in terms of what would work. Moment-frame construction had been popular in Southern California for over a decade before the Northridge earthquake, but many buildings built on it failed. As we were trying to get the project started again, we had new and completely different seismic criteria to work with, and a great deal of uncertainty about whether the moment-frame structure that we had had previously, or any other moment-frame structure, would work. We were looking at that

8.17. The *Experience Music Project* (EMP) (2000), Seattle, USA, architect Frank Gehry.

problem, and the fact that the garage had already been built to hold a moment-frame based on old loading criteria. We also discovered that our clients were not quite so adverse to Frank Gehry using metal after the *Guggenheim Museum* was built. In the interim, the construction costs had only increased, so we chose to lighten the building; those forms thought of in stone had to be done as metal surfaces. One can work with relatively simple metal

surfaces, but one also needs an ability to unfold and develop the metal. We now had a sheet metal problem to solve.

The project in Seattle, the *Experience Music Project (EMP)* (figure 8.17), was an exploration of what we could do with sheet metal and how it performs on various surfaces. On that project we had been collaborating, much like in Bilbao, but on a fast track, with two or three different fabricators and the general contractor, with some very heavy surveying involved, using the computer model as the primary source of information for the construction of the building. There was a major cultural transition that everybody had to go through, to get used to the notion that one no longer measures things with a ruler and a tape, and then runs offsets from specific points, and that the entire building actually works from one zero point. There was a considerable uncertainty about the sharing of data, which was a very tough process to get through with American contractors. The project kept moving

8.18. Free-form curves of the café at the EMP in Seattle.

forward, I think, largely because of Paul Allen's support. But at some point, it seemed like everybody on site "got it."

It was presumed the irrational, complex curvilinear forms we were building would be the most expensive forms to build. When Paul Allen asked us, at the last minute, to design the interior for the café and also a wood façade, we made it polygonal. We thought that would be the inexpensive way to do it, as there was very little time; the building was well into construction and not that far from opening. When we talked to the contractors about building the polygon grid, they said it would cost much less if we just did the free-form curves (figure 8.18) and, since we had no time, it would be much faster if we did not bother with shop drawings. We had three different trades working out of the same computer model without shop drawings, fabricating their components directly from the computer model, and everything fitting together on the site with rather complex geometric forms without mock-ups. That part of the building was built in just four weeks. At that point, everybody

understood "it"—the contractors in the field understood "it"—there were no drawings and that was the least expensive way to do the project. That was a very important transition in the project. What made it possible was not the software so much—obviously, that is the tool—but a cultural change that took place on the building site. The contractors started out with the normal divisions between various participants, but they had all been working from a three-dimensional database long enough that they actually trusted it more than the architects and engineers did, and they drove the project to such a solution.

The concert hall has a curvilinear surface as well, which was reconfigured in metal (figure 8.19). The forms have changed in many ways, because we had to rationalize them to deal with how metal flows across a surface. The interior of the hall remained unchanged in the new design—all we had to do was to design a new structure between an interior that did not change and an exterior that was slightly modified, and change the structure from a brace-frame to a moment-frame under higher loading criteria but without changing anything else. That process led us to produce much more detailed steel models than we had done in the past, so that we could establish the basic framework for the steel structure. The concept was to have a central brace-framed box with its walls as the lateral support for the entire building, including everything that was to be hung on it (figure 8.20). That wall was also the acoustical wall that separates lobbies and the exterior from the interior hall itself. We had the same original "shoebox" of the same volume that we generated six or seven years earlier. The Santori Hall had been completed in Japan, which operated on similar

8.19. The Curvilinear metal surfaces of the concert hall.

acoustical principles, and was designed with the same acousticians. They were compiling databases that combined their scale-model measurements, what is now computer model measurements, laser measurements, and then similar measurements done on the completed building, so that they could correlate the data in an effort to create a reasonably accurate acoustical analysis software, which, after ten years, they are not sure that they are any closer to, but they keep collecting the data and refining the process. They did discover some anomalies in the Santori Hall, and so we did some minor modifications; we created a few new reflective walls to correct what we thought would be a few substandard seats.

We were using a different process for the concert hall from the one we had used in Bilbao. Where in Bilbao we provided less information to the Spanish contractor who developed the steel in Bocad, here in the United States, for the concert hall, we provided a lot of information to the steel detailers. We questioned whether the process used in Bilbao would work in the American construction industry culture. We tried to collaborate with them early on, rather than simply providing them with the wire frame of all the primary and secondary structure. They considered using the Spanish steel fabricator we used in Bilbao, but opted for an American operation that would use XSteel steel-detailing software. They developed connection details in XSteel, which we would then overlay on our original CATIA model and wire-frames to check for dimensional control and interferences. Their detailed drawings done in XSteel were intended to provide final detailing for all connections directly out of the computer model (figure 8.21); they even have the fillets for the welds in the model. The problem was that the original steel detailer went bankrupt soon after beginning the project. There was an Australian firm with a group that was going to do the steel detailing in CATIA in the Philippines. After going through the introduction to the process and establishing protocols for exchanging data, and the development of some preliminary models, they folded. That left the contractor with a serious problem, because he had to find detailers in a very hot market. They wound up splitting the job between three different detailers, one doing manual drafting, one working in two-dimensional AutoCAD, and two working in XSteel. This created a complex, often out of sequence process—the collaborative tools did not work very well in that environment. Consequently, they fell very far behind schedule, and steel became a schedule-driver for the whole project.
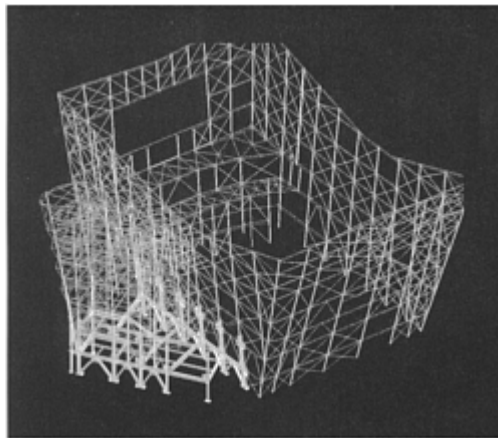
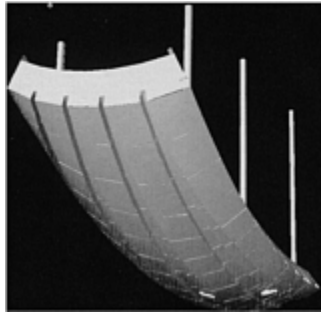8.20. The central brace-framed steel "shoebox" for the concert hall.
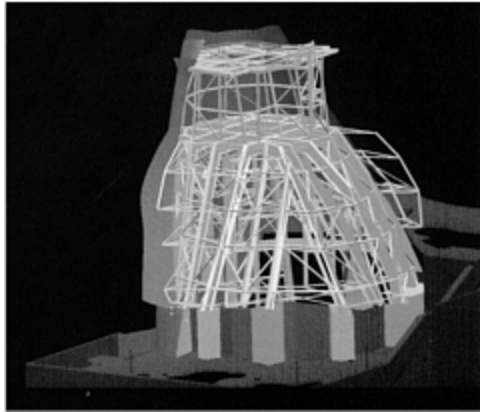
8.21. Part of the detailed model for the steel structure of the concert hall.
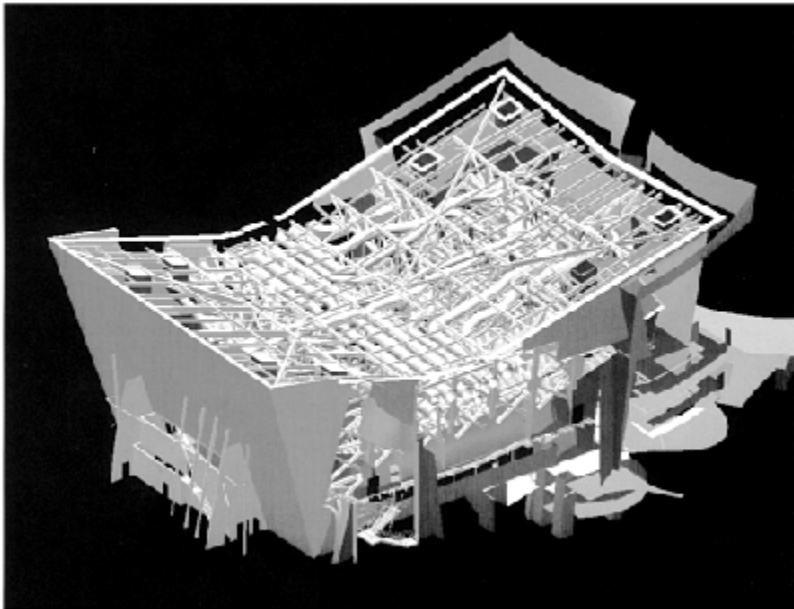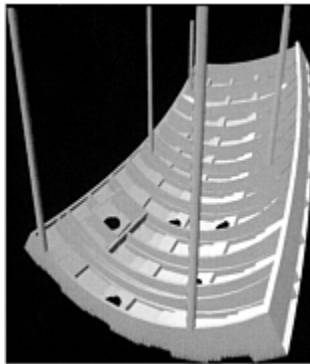

8.22. The coordination model for the concert hall.
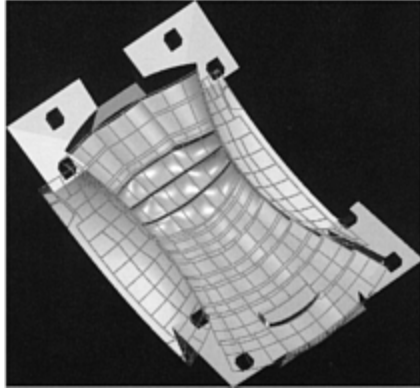
8.23. A digital model of the ceiling panels for the concert hall.

8.24. A digital model for one of the ceiling wood panels.

8.25. A digital model of the support structure for one of the ceiling wood panels.

Part of the problem was that the group was working in the litigious environment of Southern California, with a construction tradition that made the group reluctant to accept the notion of collaboration as it occurred in Bilbao and Seattle—that they could build on each other's models. People would start over or go backwards; they would avoid taking part in the collaborative process that we had working so flawlessly five years earlier in Bilbao. Even though there were advances in the way we did the modeling, advances in the software and in CAD/CAM technology, traditional claims building attitudes made collaboration extremely difficult. That cultural barrier to the sharing of information and ideas is the really difficult issue. But what did work the same in both Bilbao and the concert hall was that, in spite of its complexity, the steel fitted accurately—it was very carefully put together.

By this time, we were building models digitally in three dimensions and with a great deal of detail. We were also building a model for coordination (figure 8.22), working on the problem of squeezing the walls we cannot move on the inside and the outside, and trying to find a way to have a brace frame through the structure. We had modeled the surfaces of the ceilings (figure 8.23), which had to be put in to complete the acoustical envelope of the building. The question was how to build them. Each panel had three different levels of wood that are all curved and twisted (figure 8.24). At the EMP project in Seattle, we had similar exterior shapes in metal; we worked with the fabricator, the Zahner Company, to have automated CAD/CAM fabrication of steel and aluminum ribs for each panel. They were using ProEngineer at the time, and we were using CATIA, and we exchanged data successfully. They had a robotic punch that would shape the metal off a nested program, and we would then use a standard serrated "T" that fitted on the top and bottom to give it structural strength. Through a rather complicated analysis of the surface at EMP, we figured out how to get the appearance of compound curves with a little bit of controlled dimpling. That process informed the way the framing support for the wood ceiling at the *Disney Concert* Hall would be designed and manufactured. We thought we could mount it on the same kind of metal support system (figure 8.25). It could be CAD/CAM designed and fabricated. Working with the contractor, it was determined that we could leave the complexity in it, use the computer's develop function to develop the templates for all the wood members, panelize the entire ceiling, model light fixtures and other penetrations through it, and develop individual panels and hang-points and connections for adjustment. Using technology similar to that used at EMP, we could have the precision of one-sixteenth of an inch or less for nesting the pieces back together. We worked with our acousticians and the fabricators to work out all the "bugs" so that we could set up an automated process for all of the panels.

The area above the acoustical ceiling panels is the most complicated part of the concert hall. There are primary structure supports that go to the panel hang points; we had to bring all the mechanical services systems through them. As they are very low velocity large-scale systems, the catwalks had to have clearance running through them and around the duct work, resulting in the composite model of a very dense piece of construction (figure 8.26). (Earlier in the project, people would often comment that we had all that wasted space above the ceiling!)
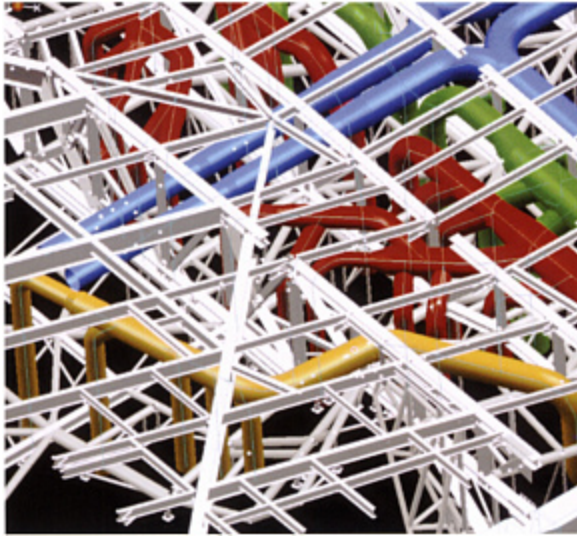
8.26. A composite model of the above ceiling systems.
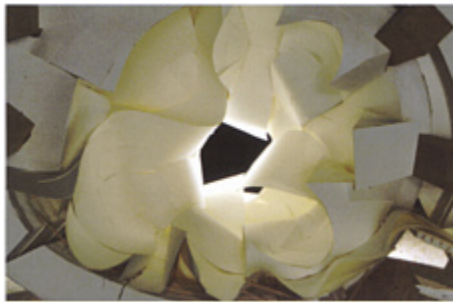
8.27. Scale model of the freeform surfaces of the Founders Room interior.
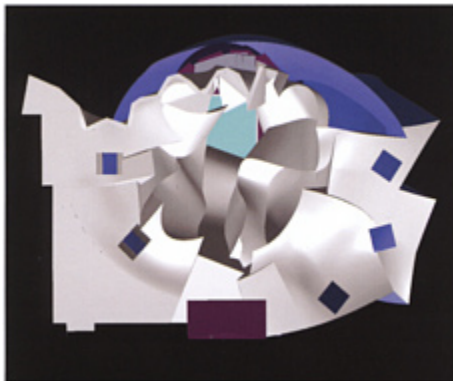
8.28. Digital model of the freeform surfaces of the Founders Room interior.

8.29. The Gaussian analysis of the Founders Room interior.

The steel walls were set out using no tape measures, nothing but surveying devices working with control points taken from the CATIA model. The entire hoisting pattern for the panels and the path of delivery, and the sequencing of the construction of all of those pieces, was done in a four-dimensional scheduling model, which the contractor derived from the original CATIA model.

In the concert hall building there is a part called the Founders Room, which Frank Gehry wanted to differentiate from the metal shapes around it as a feature to soften the stainless steel sail-forms (figure 8.27). In working out the geometry of the polished stainless steel of the Founders Room, we relied on paper (developable) surfaces once again and then cheated them slightly into "puffed" forms. The Founders Room is a bit of a building "in limbo," because we had fixed base-plate locations from the original design. All of our structural landing points had to remain the same, because it would be rather expensive to reinforce the garage underneath. We accepted the original base-plates in the Founders Room area and developed completely independent interior and exterior sculptural forms, the exterior form being the paper surface and the interior form being a free-form surface (figure 8.28). We also performed a Gaussian analysis on the surfaces of the interior (figure 8.29) to prove the obvious—that they will not unfold.

At the Case Western Reserve University building (figure 8.30), we used only developable paper surfaces (no "puffed" or "pillowed" forms like in Bilbao, Seattle or the Founders Room). Virtually everything on the building's exterior, with the exception of about
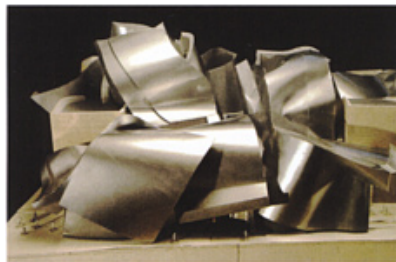
8.30. The exterior of the building at the Case Western Reserve University was built using developable paper surfaces.

10 or 12 square feet, was a ruled, developable surface, yet it created a complex architectural form with a sense of movement. We used very stable paper as a rapid way of producing the approximately correct model. Next, we digitized that model and rationalized it, so that it was constructed of ruled surfaces and was developable. We would then offset the geometry to create a structure of an irrational form.
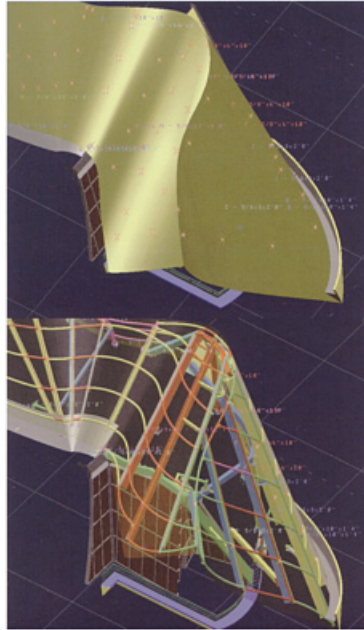
8.31a–b. Detailed CATIA model of the exterior surfaces at the Case Western Reserve University building.

We decided to build a very precise structure on this project, without any adjustment to the final surface to achieve the form. We decided to build the surface back as a ruled surface in the same way that it was done in CATIA (figure 8.31a–b). We developed a stainless steel shingle system that was pressure equalized and was designed to ride over the top of the entire structure. Since these systems went onto strictly developable surfaces, the metal panels have a smoothness instead of the "oil-can" texture of the titanium in Bilbao. The ruled developable surfaces were applied to the interior too. Special corners and attachments were fabricated from computer templates; much of the rest was standard studwork framed at angles to create the complex shapes.

We used a different approach at the EMP project in Seattle, where we had a shotcrete shell on a prefabricated steel structure, primarily because of the schedule. We knew we could not have the metal skin there quickly enough for the schedule of building. It was a fast-track job, and we wanted to build both the interior and the exterior at the same time. We had a primary steel structure (figure 8.32a) with extensions that penetrate the shotcrete shell (figure 3.33). The primary structure was a freeform structure of what the fabricator called "spaghetti" steel (figure 8.32b). The fabricator was from Oregon, and they have done

three of our projects since then. They have all the automated equipment that they built for the EMP job, and they can produce almost any planer-shaped built-up member in steel.

On the project in Berlin, we have an interesting contrast between the irrational, free-form steel on the "Horse's Head" conference room and a very rationalized form of the skylight above it (figure 8.34). In the latter case, we have the rigorous geometry and, in the former, the free-form geometry done in a quarter inch stainless steel. Those are two different ways of approaching the problem of geometry and tectonics, and both are equally valid. One does not need arcs and rationalized geometry to build those shapes.

The Bard College building was another project on which we used the paper surfaces. What we learned on all those projects gave us a number of different ways to build the Founders Room. We could not use the Case Western method for steel framing, since we had the issue of having to work with the original structure in the garage below. To
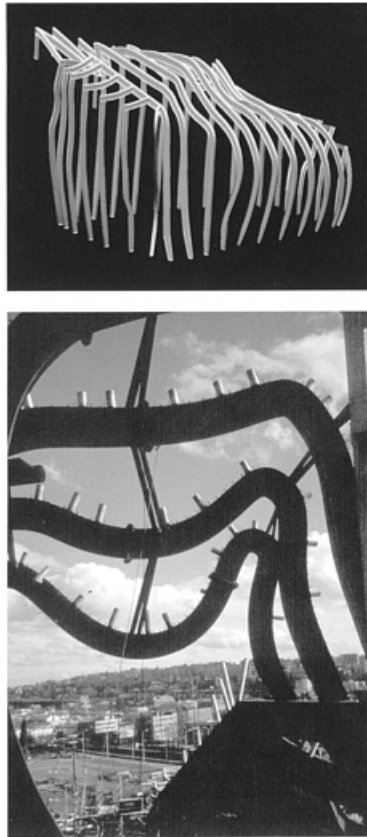
8.32a–b. The primary steel structure for the EMP project in Seattle.

8.33. The shotcrete shell at the EMP, with prefabricated panels on top of it.

build yet another structure, which was precisely where the metal panels were to be, did not work out. So, for the cladding, we had to fall back on what we did on the EMP project. We would have a shotcrete shell, and then prefabricated panels on top of it. We had to choose between two completely different systems; there is no rule, no right answer as to which one is better, which one is more appropriate. That depends on whom we are working with, where we are in the project, and what they think about particular issues that need to be re-solved. The "spaghetti" steel from Seattle found its way back into the Disney project. The Disney project benefited from a number of other projects we did during its 13-year history.

By 2001, when the steel structure was finally finished, the concert hall project was behind schedule. While the steel was being done, a fabricator from Italy, called Permasteelisa, had been working on the cladding; the Disney project was their fifth job with us. They were very confident about working with digital data. While waiting for the steel structure to be completed, they would invest their time in very detailed engineering and fabrication of what is essentially a stick-built cladding system, hoping they could recoup the increased design cost by being more productive in the installation. They imported into CATIA the approved model of the structural steel done in XSteel, so they knew what they were connecting to; we had given them a surface pattern (figure 8.35) and a curtain wall concept for developing it. The stud frame system was used to create the ruling lines; the spline-shaped aluminum extrusions were bent in space on-site —they were not preformed (figure 8.36). They were engineered in such a fashion as to be heavy enough to perform their structural role and were sufficiently light to be bent into spline shapes.
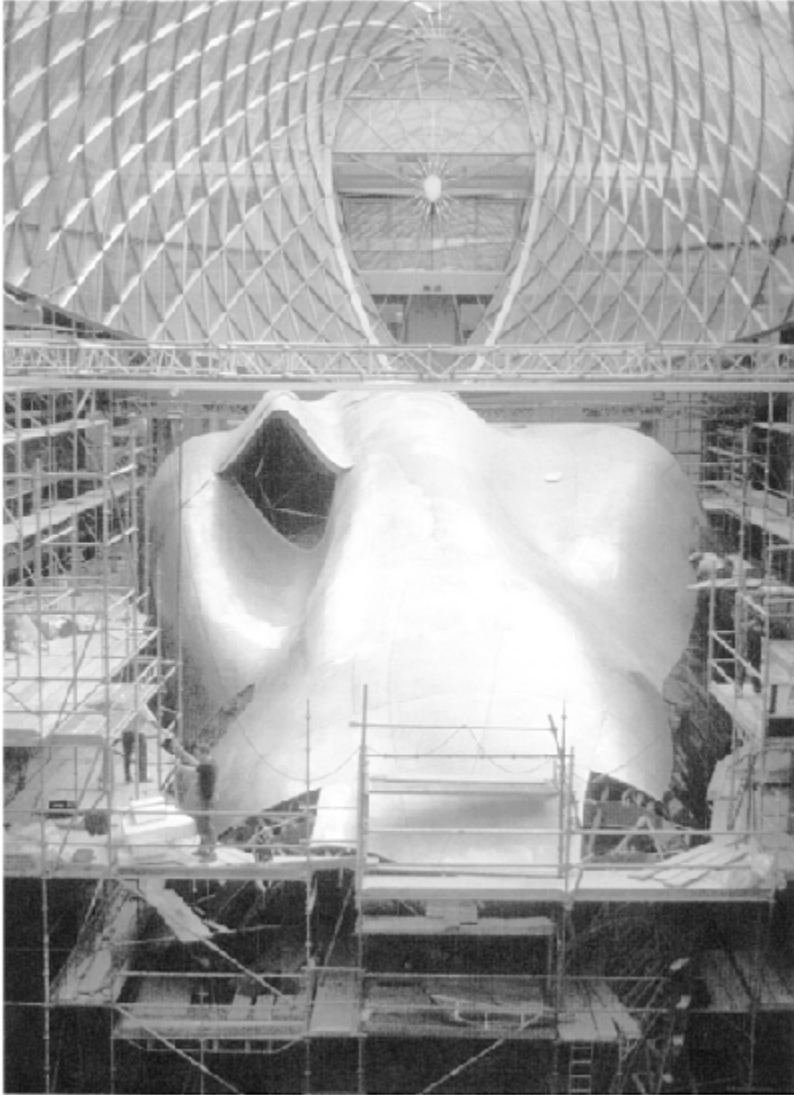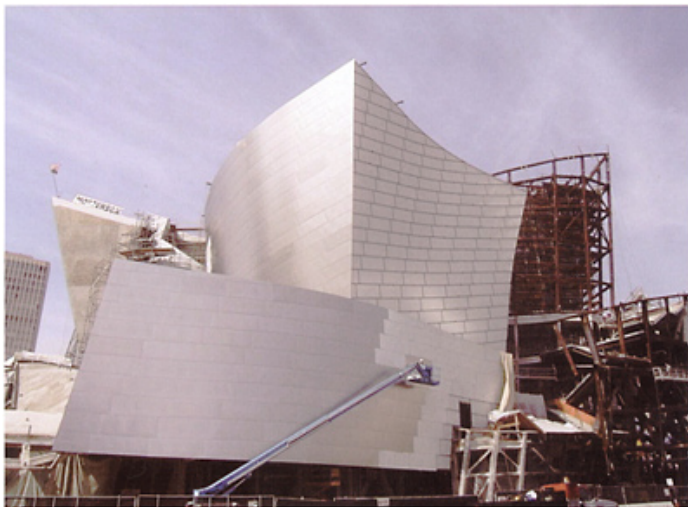
8.34. The "Horse's Head" conference room in the glass covered inner court of the *DG Bank building* (2000), Berlin, Germany, architect Frank Gehry.
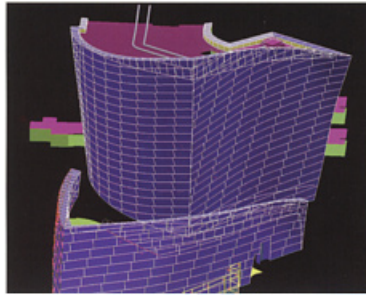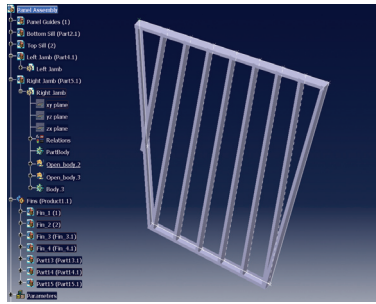
8.35. The surface pattern done in CATIA for one part of the concert hall.
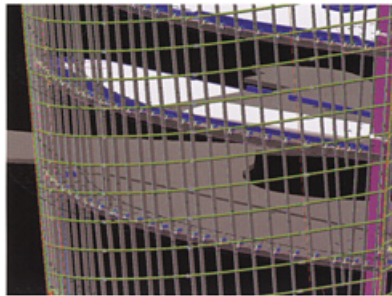
8.36. The detailed digital model of the stud frame system for cladding on the *Disney Concert Hall*.

8.37. Installation of the cladding on the exterior of the concert hall.

8.38. Digital model of a metal system for the *Stata Center* at MIT.

Every piece of cladding was detailed in the model. The connection points were surveyed directly into the concrete slab for location. They had ample room for adjustment in all of the connectors, but they did not use very much of it. All horizontal rails have a back pan as an infill. All the back pans were all pre-cut individually, numbered and bar-coded. The exterior panels were also pre-cut, even the edges. The panels were mounted on the rails, with rails forming the perimeter of the back pan and gutters for the system. It is a true curtain wall (figure 8.37); it was not only the sheet metal anymore—we had finally done a true free-form curtain wall. The wall itself is pressure equalized. Permasteelisa was installing it fast in most areas, so fast that in some cases they were running over trades working in front of them, so that schedules had to be adjusted. Their productivity rate in installation was better than they thought it would be, but it is not clear at this time if it will be fast enough to recoup the considerable amount of time spent on the precise engineering.

   Each of the buildings described so far, which we had done over the past dozen years or so, contributed something to the *Disney Concert Hall* project. There are several other projects that need to be mentioned briefly. We are currently doing the project for the *Stata Center* at MIT, in which we tried to develop, in CATIA Version 5, a parametric model of the metal system. When Zahner Co., the metal fabricator, was working on the EMP project, they used parametrics in Proengineer for the engineering of the metal panels and their layout. We challenged Zahner's team to develop a parametric model in CATIA V5 of the metal


8.39. The segmented glass surfaces on the *Guggenheim Museum* in Bilbao.

system for the MIT project (figure 8.38). There are actually three metal systems on that building. Several different standard panel types are parametrically defined and can be deformed to meet existing conditions. The parametric definition enabled us to modify and regenerate the geometry and reengineer the framing as needed, and then output the building material quantities, the shop drawings, or machine instructions. They are still working on the process. For example, the end pieces are still done manually, so the system is not fully automated yet. Zahner, the fabricator, however, is now producing panels for the MIT building with CAD/CAM fabrication, using automated layout and automated engineering computed off the surfaces, i.e. off the geometry we give them. This production process is going well; we are waiting for the concrete work to be completed so that they can start putting the metal system on and we can test the results.

We used several different approaches in working with glass. In Bilbao, we had basically segmented the glass, that is, we broke it through the curves. That is the position we were at when we did the glass for Bilbao, and it was also the aesthetic we wanted to achieve (figure 8.39). In the project in Berlin, we developed the form (figure 8.34) in collaboration between Schleich, the engineer, and Frank Gehry. Frank Gehry worked with Craig Webb and Schleich's structural rules, but was pushing Schleich to deform things in a more radical way. Schleich's approach was to have the same length for all members of the framing system; he was not particularly concerned about the changing geometry of the connections. We experimented with different forms and went back and forth between computer and physical models, as we always do. We had the basic frame, made up of solid, stainless steel bars; the mullions were the substance of the shell structure. We started with a design for a flexible connection between the pieces that would take a range of movement as angles changed. The fabricator, Gartner, found that it was cheaper to CAD/CAM fabricate each connection piece out of a solid block of stainless steel than it was to build an adjustable apparatus.

With the project we are doing in Jerusalem, we once again want to challenge the notion that it is necessary to resort to rational geometry or arcs to make the complex geometry buildable, on schedule and on budget. For that project, we developed an optimization program for patterning the quadrilateral pieces across a given surface, which corresponds to a manual method we used in the office. As the form changes, the pattern is regenerated automatically. There is also a scaling version of the rules that permits members to change in length and density as curvatures become larger or smaller, giving us more possibilities for matching the shapes that Frank Gehry was looking for aesthetically with Schleich's shell structure rules. The optimization program, which runs in CATIA, takes as its input the design surface and the ruled-based surface created by Schleich's engineering team, and it runs until the two surfaces are as close as they could be (figure 8.40), based on the parametric rules. Then it automatically creates the patterning layout for the system. An interesting debate in the office centered on whether the manual development process or the optimization is faster. The two are fairly close but, so far, the manual method, which allows intuitive intervention by the architect, appears faster at getting to an acceptable aesthetic solution.
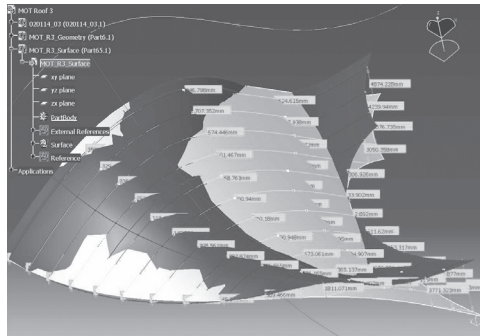
8.40. The patterning optimization program in CATIA.

This brief overview shows various influences the evolution of computing in construction has had on the design and production of the *Walt Disney Concert Hall*. We had about 13 or 14 projects so far that we have done using three-dimensional computer modeling, largely with CATIA. We have four of them that are complete or nearing completion in North America; each experience has been different. I have come to believe there is a real difference between architects and contractors and how they work with each other in the United States and in Europe. In many European cultures, craftsmen and subcontractors are often respected professionals, just like the architects. In my view, the construction process over there is much better grounded, they are less competitive within teams, they have a tradition of collaboration, and everything seems much easier to do there than it is in the United States. The construction industry, particularly the United States industry, has not yet seen the productivity gains that the rest of industry is seeing from the application of technology. Progress is being made, but things change slowly. As in so many other fields, the cultural changes evolve much slower than technology. The lessons learned on the *Walt Disney Concert Hall* inform our current work, not just in design and computing, but also in planning, contracting and communicating.
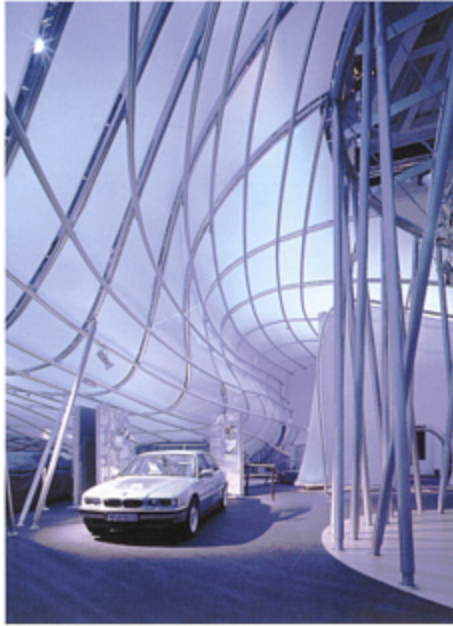
9
REAL AS DATA

BERNHARD FRANKEN

9.1. The *"Bubble,"* BMW's exhibition pavilion at the IAA '99 Auto Show in Frankfurt, Germany, architects Bernhard Franken and ABB Architekten.
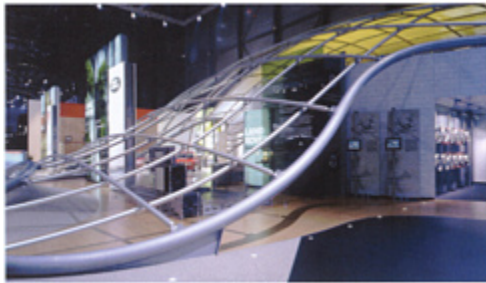
9.2. The *"Brandscape,"* BMW Pavilion at the 2000 Auto Show in Geneva, Switzerland, architects Bernhard Franken and ABB Architekten.

9.3. The *"Wave,"* BMW Pavilion at the Expo 2000 in Munich, Germany, architects Bern-
hard Franken and ABB Architekten.

In comparison to the shipbuilding and aerospace industry, the building construction field
in general appears somewhat archaic. While the digital technologies have revolutionized
other industries, the impact in building design and production has been minimal so far.
They all had information technology introduced into their respective design and production
processes at about the same time, albeit to a different extent and to different ends. Obvi-
ously, while others have managed to do things differently and in better ways using digital
technologies, little has changed in the building industry. We would argue that although
there are significant differences between the design and production of buildings and the
design and production of ships and airplanes, there are some interesting similarities that
merit closer scrutiny by architects. We have quite a bit to learn by looking at what others
have done, especially in the shipbuilding and aerospace industries.

Our design projects for BMW (figures 9.1–9.5) have a certain similarity to the develop-
ment of a racing yacht or an airplane but, surprisingly, not so much to the production of a
car. Although the automotive industry uses similar software and has a comparable empha-
sis on research, its end goal is mass-production, whereby the high development costs are
recouped by large sales figures. Buildings, on the other hand, can be characterized as pro-
totypical—in most cases, they are one-off ventures realized at particular locations.

9.4. The *"Dynaform,"* BMW Pavilion at the IAA '01 Auto Show in Frankfurt, Germany, architects Bernhard Franken and ABB Architekten.

9.5. The *"LightArc,"* BMW Pavilion at the 2002 Auto Show in Geneva, Switzerland, architects Bernhard Franken and ABB Architekten.
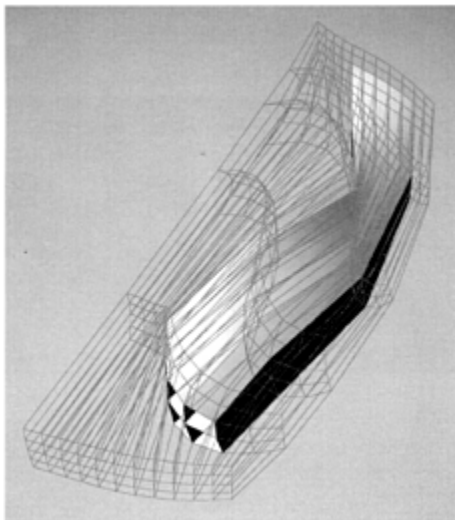
9.6. The *"Dynaform"* was digitally generated using a force-field simulation.
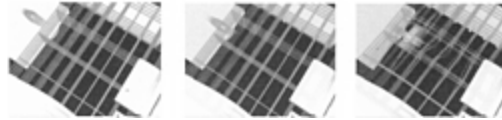
Our projects are, in their entirety, prototypes without any antecedents. As is the case with America's Cup racing yachts, they are highly specialized objects, and built with only one goal. While the speed is the most important goal in designing a racing yacht, the primary objective of our buildings is communication. For a client (BMW) who has chosen innovation as a core marketing value, the buildings had to embody pure innovation, relying on high-technology production processes and the highest quality of finishes. To meet those goals within very short design and production schedules, we have developed a consistent digital production process, which is more similar to Boeing's production methods than to the traditional building process.

THE PRODUCTION CHAIN

We create designs using digital generative processes, which differentiates our architecture from Frank Gehry, for example, who designs his buildings analogously, using physical models that are then transformed digitally. Our production chain consists of five phases: (1) briefing; (2) process; (3) form; (4) digital production; and (5) experience. The starting point for our designs is always the client's brief. We translate the client's wishes and demands into a process that leads to a form generated using a computer-supported force-field simulation. Where possible, the digitally-generated form is translated directly into a building using digital production methods, so that the forces of the creation process are clearly manifested in the building's form (figure 9.6), delivering a sensory experience.

BRIEFING

Our client at BMW is the marketing, rather than the building, department. Consequently, our task is not one of providing a building, but rather a communication service. Up to one million visitors are expected to visit the building in ten days, with an average visiting time of 15 minutes. Thus, our principal task is not to design a spatial program, but rather a scenography that functions like a short film. Furthermore, in the short life of an exhibition, the whole experience must hit the headlines, i.e. reach the press and millions of TV viewers. BMW was particularly interested only in the first and last phases of our production chain, which are the briefing and the experience. Our task is to translate the central message of the brief into a spatial set that enables the user not only to by comprehend the themed content, but also experience it directly in a sensory reaction to the space itself. To that end, we have developed design methods that incorporate special-effects software that are common in the film industry. Changes in form are simulated by applying force fields onto some basic structures, which are essentially subjected to physical laws (figure 9.7). In our digital generative experiments, we define the basic structures, laws governing the
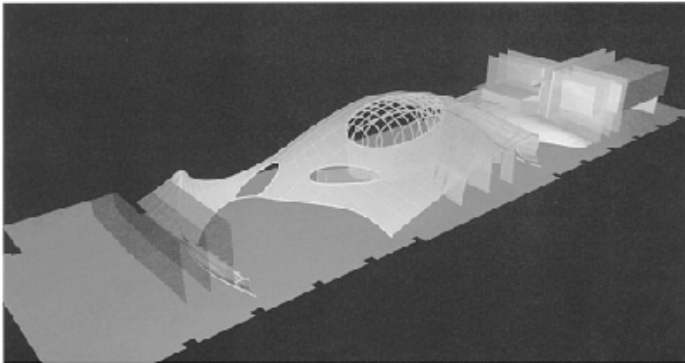
deformation, fixed conditions and forces, in a poetic translation of the given task and the given spatial context.

9.7. Form is generated by subjecting the basic structures to forceb fields extrapolated from the contextof the Project
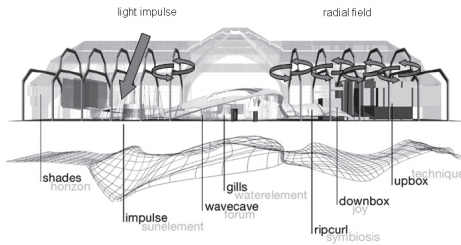
9.8. The forces that generate the *"Wave"* form.

9.9a. The *"Wave"* form generated by force fields.

FORM FOLLOWS FORCE

Admittedly, we cannot grasp forces directly with our senses, but can only infer them through their effects. Our experience, however, made us highly sensitive to deformations that correspond to a natural play of forces. This faculty was an evolutionary advantage, when, for example, a tree bent by the wind could be perceived as indicating a potential danger. Our perception is thus conditioned towards forces, and uses them to interpret shapes. Deformed forms carry the information about the forces of their origin.

The forces we use in the genesis of form originate not only from real influences, but are often extrapolated from contexts that are not strictly physical (figure 9.8). Regardless of

the forces' conceptual origin, the visitor can sense in the completed building the forces that were at work during its creation (figures 9.9 and 10). The design does not reflect an a priori conception of the form by the designer, but rather it develops interactively through a series of experiments based on specific changes of the freely chosen parameters. The information becomes form through a process of interaction between the designer and the computer. The force-field simulation is thus not only a method of generating the design, but is also used for its capacity to produce the spatial coding of information. The forms we generate are never arbitrary; they can be explained and are subject to rationalization.
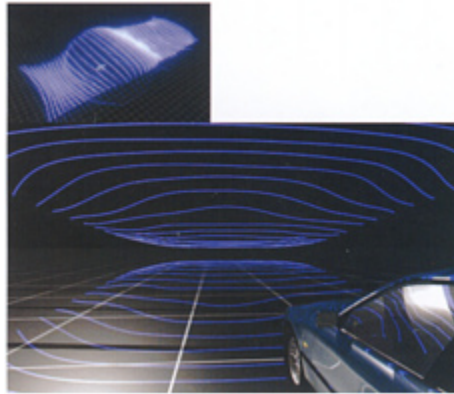

9.9b. The *"Wave"* form generated by force fields.
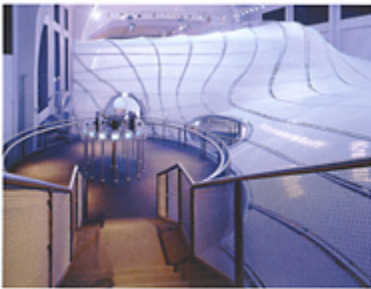
9.10a–b. The *"Wave"* pavilion, as built.

9.11. The plan drawing of the *"Dynaform."*

9.12a–b. The line matrix being deformed by the "force" of the moving car.

PRESENTA\TION

Plans taken as orthogonal sections through an object are typical forms of communication in the building industry (figure 9.11). In dealing with a marketing department, however, we had to take a different approach. To explain the development of a design, we would co-opt design tools as a medium for presentation and generate "films." These films are then integrated into on-screen presentations, which describe the marketing concept and the

sequence of themes (figures 9.12a–b). The scenography is explained as a storyboard, as steps in the series of experiences.

Physical scale models are indispensable in presentations, as complexity of the form is difficult to grasp through the drawings and images only (figure 9.13). A physical model is self-explanatory; it allows any number of perspectives and can express tangible qualities and lighting effects (figure 9.14). Physical models are also necessary in the design development, as we would often notice in the model certain aspects of the design which eluded us on screen. Owing to the complex language of our forms, we require highly specialized fabrication methods in the production of models, such as the use of different rapid prototyping techniques. We had the models constructed using laser sintering or stereo-lithography in BMW's department for prototype construction. For example, to create the wire-frame model of the *"Wave"* project (figure 9.15), we had to unwind every two-dimensionally bent tube, so that industrial model builders, who specialize in refinery models, could produce
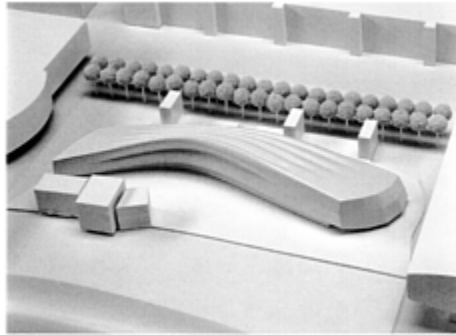
9.13. The massing model of the *"Dynaform."*

9.14. A study model of the *"Dynaform."*
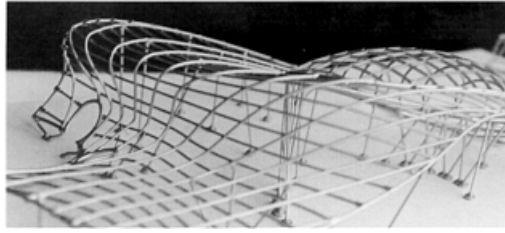
9.15. The wire-frame model of the *"Wave"* project.

the CNC (computer numerically controlled) milled assembly templates. Similar to the construction of buildings, we have to first analyze exactly which production techniques are available, and then deal with the data accordingly. Conversely, the model technicians often provide useful feedback and solutions for the actual realization.

REAL AS DATA

The form arising from the force-field simulation process becomes the master geometry, which may not be changed manually in any way; otherwise, the forces of its creation would no longer be perceptible. The master geometry is a doubly-curved surface without the actual thickness (figure 9.16). We then generate from this surface a number of different "derivatives" to create elements suitable for building; all further manifestations of the project are thus derivatives from the original master geometry, which is considered "sacred," i.e. could not be changed in any way. The derivatives can be rendered images (figures 9.17a–b), the structural engineer's stress calculations using finite-element programs (figures 9.18a–c), or two-dimensional sections as CAD drawings. Other project elements relevant to the construction or the program are also derived from the lines or structures already present in the master geometry. Before the data are manifested as derivatives in concrete space, it goes through several intermediate digital steps. We operate in our projects with derivatives of the first, second, or n^{th} degree. The building in the end is a composition of numerous derivatives and, thus, it can be seen in its totality as merely one possible version of the reality incorporated in the digital master geometry—its nth degree derivative (figure 9.19).
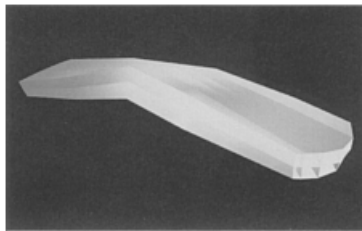
9.16. The master geometry of the *"Dynaform."*
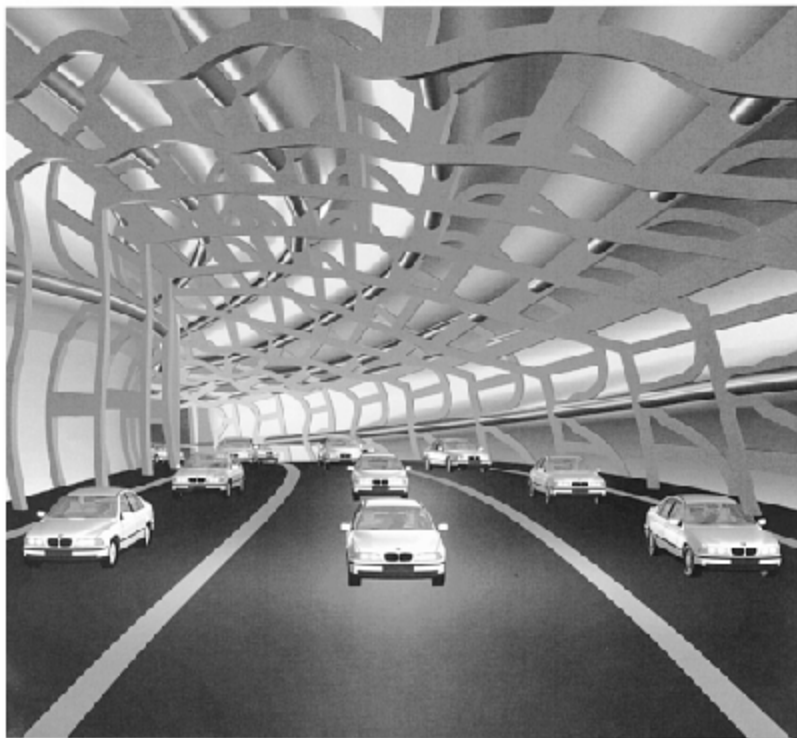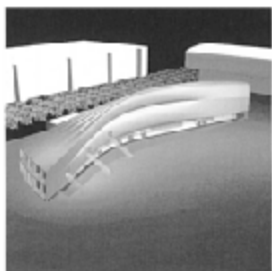
9.17a–b. Rendered images of the *"Dynaform."*
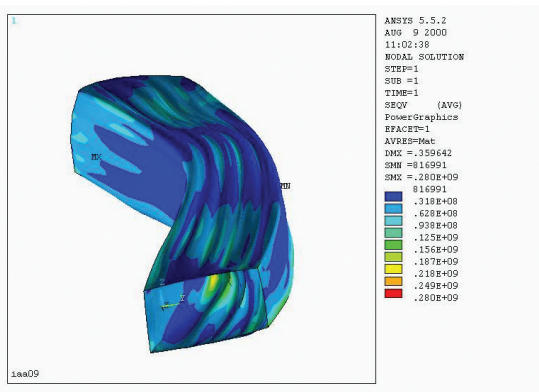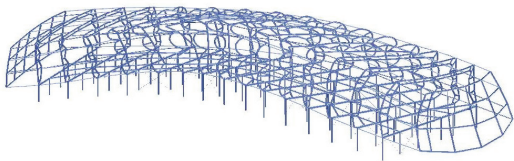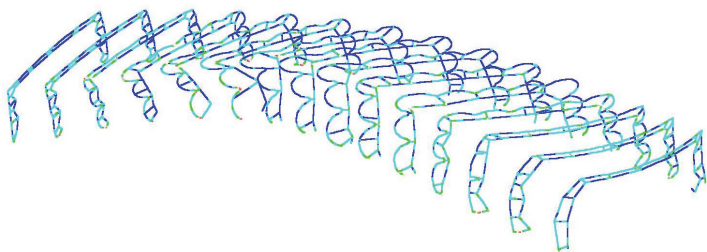
9.18a–c. Finite-element analysis (FEA) stress analyses of the *Dynaform.''*

9.19. The completed *"Dynaform"* as the nth degree derivative of the master geometry.

9.20a–b. The bending moments for the *"Brandscape"* frame structure.

FALSE FORCES

After we define the master geometry, we work very closely with the structural engineers from Bollinger + Grohmann in Frankfurt. Their first step is to use the finite-element analysis programs to explore the effectiveness of the form as a shell structure (figures 9.18a–c). As we have discovered that even though the forces generating the form might not originate

in our physical reality, they often have useful properties for dealing with the forces of the reality, such as gravitation and wind. The doubly-curved geometries are, in principle, very efficient in the removal of loads. On the other hand, the forces from the information world, which have no counterparts in the physical world, often result in shell structures with bending moments (figure 9.20a–b). That, of course, can be dealt with using strong building materials or appropriate construction techniques. Only in that way can the form remain deformed and informed by the forces that are not in fact present. Such an approach demands a high degree of sensitivity in structural engineering and a capacity of displaying intended virtual forces in the flow of forces in the construction, as well as an ability to conceal these real forces. Since the structural system must not change the form, the load-bearing system is continually altered until a suitable system is found for the master geometry.

CHOICE OF PARTNER

As no existing production techniques in the building sector were suitable for our designs, we had to invent new production methods by working closely with fabricators and production specialists. Our experience is that the line that divides design and production is dissolving; as designers, we are closely involved in the entire production process, from the initial decisions about the fundamental issues, to the final choice of materials, processing of data, workshop preparations and assembly planning. The bid offers must meet binding specifications as to material, surfaces and processing standards, while leaving room for innovative solutions. Contractors, which employ entire departments to find the loopholes in specifications that would allow supplementary work claims, are not the right partners for such a process. The three-dimensional geometric data model (figure 9.21) is the basis for the bidding documents, apart from the drawings describing the details. This condition alone reduces the number of possible partners to a select few capable of processing the data. During the bidding process, anything from comprehensive studies up to full scale test models (figure 9.22) are required of the bidding companies as a verification of feasibility. The client only occasionally pays for this preliminary work. If not, the firms must write
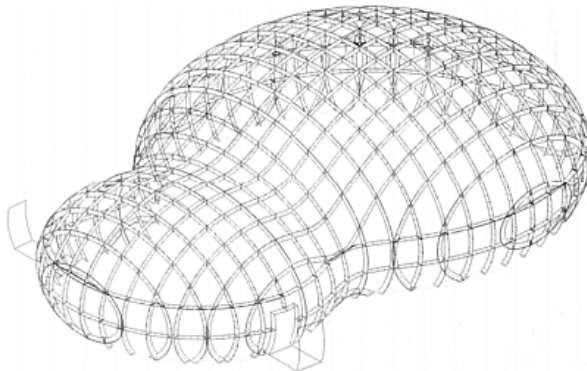
9.21. The complete three-dimensional model for the *"Bubble."*

9.22. The full-scale test model developed for the *"Dynaform"* project.

the costs off as canvassing and a gain in experience. The contracted work is directly related to the three-dimensional data model, making any future exchange of information legally binding. This approach is outside the conventional legal framework, which has as its basis the set of drawings signed by the client's architects. In the case of a legal dispute, the courts would have considerable difficulty checking even the basics of the work process we use. Only extremely brave and innovative firms take on these challenges and become our partners in exploring new processes of design and production.

INTERFACES INSTEAD OF PROGRAMS

A finely-tuned production process is necessary for the team made up of 75 architects, structural engineers, mechanical engineers, communications experts, lighting designers, and audio visual (AV) media specialists to work together within the short, intensive production schedules typical of our projects. As the projects did not have client-appointed project managers, we, as architects, took over that function to a large degree.

No existing software meets all the demands of our projects. We develop the designs in the film animation program Maya, while the structural calculations and tests are carried out in Ansys and R-Stab, which are special finite-element programs. Mechanical Desktop, a mechanical engineering add-on for AutoCAD, and Rhinoceros, a powerful free-form surface program, are used to develop the load-bearing structure. Some structural elements, however, could only be worked out in CATIA, the modeling software used by Frank Gehry. The interior designers, who work on the communications, lighting and construction for the interior, use VectorWorks on Apple Macintosh computers. For the shop drawings, special programs, such as PK Stahl, running on workstations, are used. Separate data post-processing had to be programmed for the CNC machines, which can only understand the machine code.

Because of the variety of programs and operating systems used, we have chosen a process similar to the Internet to facilitate the exchange of data. We decided not to define one mandatory program for everyone, but rather an interface format, i.e. a protocol, with which the special programs can communicate, and a browser, with which everyone can view the data. The interface formats we had chosen were IGES (a standard format in the industry) for all three-dimensional data and DWG for all drawings. In addition, plot files and the PDF format were also used. Rhinoceros was used as a "browser," because it is an inexpensive free-form-capable modeling program. Based on our past experiences, we have compiled a CAD handbook, which was used as a binding data nomenclature, a frame of reference, and the organization of layers for the IAA 2001 *"Dynaform"* project.
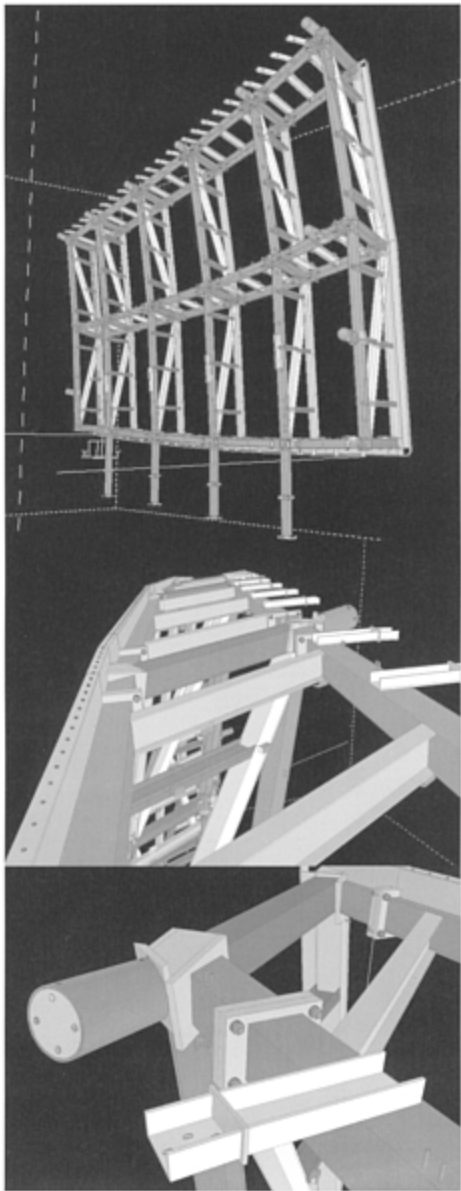
9.23a-c. The steel structure for the *"Dynaform"* project was modeled to the last bolt in three dimensions.

AVOIDANCE OF REDUNDANCY

In our first projects we exchanged data by email over ISDN connections. A large project, such as the *"Dynaform,"* with over 75 designers and engineers and countless collaborating firms, can only function if everybody adheres to the previously mentioned data protocols and uses the same external, professionally supervised and maintained Internet server for data storage. Because of the simultaneity of various project steps, and to avoid redundancy, each project participant has to have access to, and work with, the latest set of data. The server (functioning as a digital design space) places the incoming data automatically into the correct folder according to the nomenclature prescribed by the CAD handbook, saving previous project stages (which are available at all times) and automatically informing the participants by fax or email that the new data are available. By keeping a comprehensive log-book, all activities are transparent and comprehensible.

THREE-DIMENSIONAL DESIGN PROCESS

A complete three-dimensional model for the project is stored on the server. This model is developed by all participants working together, and is maintained by us locally and on the web in parallel. The entire steel structure is completed and modeled (to the last bolt) in three dimensions (figures 9.23a-c). The sanitary, ventilation and lighting systems are fully described in the three-dimensional model to facilitate resolution of potential conflicts and the development of fastening details. As the resulting comprehensive three-dimensional model can be several gigabytes in size, and cannot be completely loaded by a single computer, an exact nomenclature of model "parts" with defined references must be developed to insure full reliability during the development of the project. By working in this fashion, we have come very close to Boeing's design process, in which a single three-dimensional model is referenced by all participants involved in the design development.

FILE TO FACTORY

We use different two- and three-dimensional strategies to realize the freeform surfaces as built structures. Doubly-curved surfaces are, of course, the ideal choice, but also the most difficult and most expensive to build. For example, for the *"Bubble"* pavilion, 305 different acrylic-glass plates were heat-formed onto individually CNC milled foam blocks, and then trimmed at the edges, again with CNC machines (figures 9.24a-d). The computer model and the constructed surface are absolutely identical, which, with a thickness of only 8 mm, approaches the dimensionless data surface (figure 9.25). The effort expended, when one considers the lack of standardization, is, of course, immense—each glass pane is a one-off manufactured object. The supporting structure is based on an orthogonal set of sequential sections made from the aluminum sheets, introducing an additional level of abstraction or derivation from the master geometry. The cutting of aluminum parts was done using CNC-driven water-jet cutters (figure 9.26) in seven different factories. Approximately 3,500

9.24a-d. Foam molds for the heat-formed acrylic-glass panels were CNC milled *("Bubble")*.
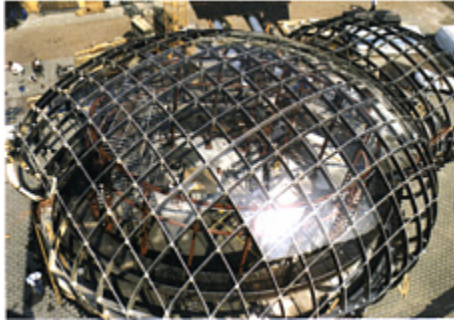
9.25. Assembly of the glass skin for the *"Bubble."*

9.26. The aluminum structural elements were CNC cut using water-jet cutters.


9.27. Assembly of the aluminum structure for the *"Bubble."*

aluminum elements were fabricated in this fashion, including the drilling of the holes and the assembly markings, so that the manual work on-site during assembly could be reduced to a minimum (figure 9.27).

<p style="text-align:center">WIRE FRAMES</p>

For our projects at the Expo 2000 (figure 9.2) and the Salon d'Automobile 2000 in Geneva (figure 9.3) the ambition was to dispense with sections and to directly realize the iso-parametric wire-frame already present in the computer model (figure 9.28). The iso-parametric lines, which were present in the original object as orthogonal lines before the deformation by the force field, directly express the deformations produced by the forces. Working with iso-parametric curves meant that several hundred meters of specially developed aluminum extruded profiles had to be bi-directionally bent with data-driven bending machines (figure 9.29). To control the moments of the assembled grid, the edge supports (figure 9.30) were made from steel-pipe segments (figure 9.31) that were radially bent in two dimensions and welded together to produce the doubly-curved shape. To do this, the manufacturers filled an entire hall with a flexible assembly jig, in which every point within a 25×15×6 m large space could be pinpointed with great accuracy.

In conventional space frames, all joints and rods are often made identical. Using such an approach, however, imposes certain geometric limitations that dictate fairly simple surface geometries. With CNC technology, straight rods can be CNC cut to different lengths and joints with varying connecting angles can be CNC milled from solid materials. This approach allows arbitrary freeform shapes to be produced using some kind of polygonal approximation. In our wire-frames, all of the rods are different and all joints are identical (figure 9.32). The doubly-curved pipes allow the free-form surfaces to be realized almost exactly (figure 9.33). The pipe with a 90 mm diameter is almost as thin, in proportion to the 25×65 m large structure, as the dimensionless computer curves (figure 9.34).
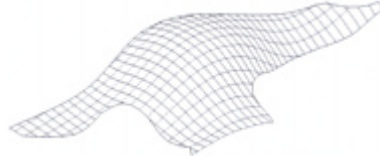
9.28. The iso-parametric wire-frame model of the structure *("Brandscape")*.

9.29. The extruded aluminum profiles were bi-directionally bent using data-driven bending machines *("Brandscape")*.
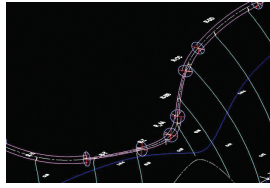
9.30. The edge supports were composed from radially-bent segments *("Brandscape")*.

9.31. Radially-bent tube sections for the edge supports *("Brandscape")*.

9.32. The rods are all different, but the joints are identical *("Wave")*.

9.33. The doubly-curved pipes allow the freeform surfaces *("Brandscape")*.

9.34. The doubly-curved shapes are made from 90 mm extruded aluminum pipes that are CNC bent.

9.35. The *"Dynaform"* pavilion had the world's first one-directionally tensed membrane.

9.36. The test model of the membrane structure *("Dynaform")*.


9.37. The connector detail for attaching the membrane to the support structure *("Dynaform")*.

MEMBRANE

Of course, the wire-frame does not form a covering. This function was assigned in several projects to membranes. In fact, we did some pioneering work in membrane construction in our past projects (figure 9.3), not only in the development of free-form surfaces, but also in digital loading calculations, layout of the cut surfaces, and production. The main drawback in membrane construction is its internal structural laws, which do not actually allow for free-form development. That is why conventional membrane structures all look the same, regardless of which architect produced the design. We are continually looking for ways to shape the membrane into the desired form. In the *"Dynaform"* project for BMW, we produced the world's first one-directionally tensed membrane (figure 9.35). We had great difficulties finding a manufacturer who would do what we wanted. Considerable effort was expended on stress tests and various mock-ups (figure 9.36). We had to develop some new details (figure 9.37) to make the membrane construction realizable as envisioned (figure 9.38).
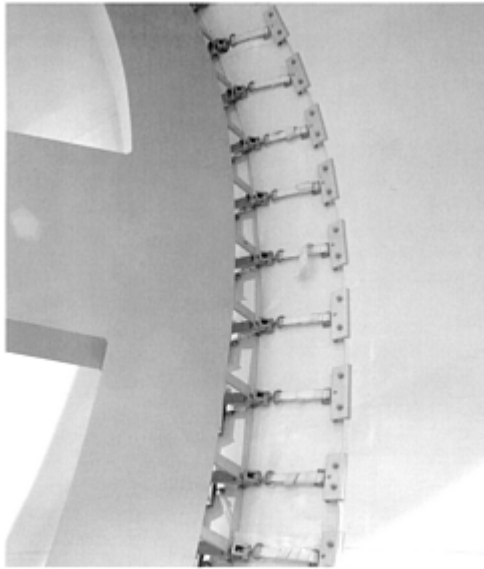
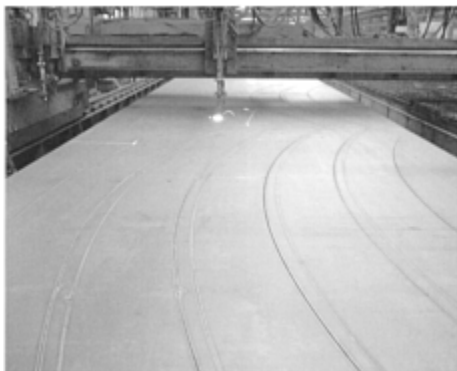9.38. The membrane connections were hidden in the end *("Dynaform")*.
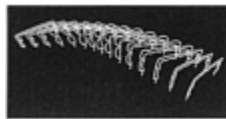
9.39. The structural frames have flat, planar geometry *("Dynaform")*.
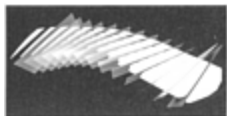
9.40. Iso-parameters defined the location of the sectional planes *("Dynaform")*.

9.41. Fabrication of the hollow box girders *("Dynaform")*.

9.42. CNC plasma cutting of the structural elements *("Dynaform")*.

HIGH-TECH AND HANDWORK

The decision to have a one-directional membrane as a building skin in the *"Dynaform"* pavilion led to the use of flat curves in sectional planes for supports in the master geometry (figure 9.39). These sections could have been positioned randomly; however, to make the forces clearly visible in the supports, we chose iso-parameters from the master geometry as sectional planes (figure 9.40). The consequence was that all of the connection pipes (which were also derived from the skin surface) had to have different joint angles. The hollow box steel girders were manufactured in parallel in Berlin and the Czech Republic (figure 9.41). More than 30,000 individual pieces were cut using computer-driven plasma-cutters (figure 9.42). The curved cutting paths had to be calculated using a special program. The fabricators, however, still needed two-dimensional assembly drawings; more than 800 shop drawings (for the frames only) were produced from the three-dimensional data using programmed routines. Since welding robots that could work with very large dimensions were not available, the CNC cut pieces were welded by hand to very tight tolerances (figure 9.43). In this way,

9.43. Manual welding of the structural elements *("Dynaform")*.

9.44. Assembly of the steel structure *("Dynaform")*.

the high-tech was continually combined with manual procedures; both the manufacturing in the factory and assembly on-site (figure 9.44) were done in that fashion. As there were no orthogonal reference points, a surveyor marked the essential points on site using a laser surveying device driven by three-dimensional data on a laptop computer.

MASS CUSTOMIZATION

Despite all the difficulties and inadequacies, we hope that these prototypical projects from ourselves and others will alter the structure of the industrial building process, so that in the near future we can engage in mass customization—a made-to-order, limited series production. For contractors, the proportion of immaterial work is increasing in total volume. In the offices of manufacturing firms, almost as many engineers are sitting in front of the computers as there are craftsmen on the factory floor. The deciding factor is not the handling of the bulk material, but rather the capacity to support a digital design process, carry out the shop production, and take on the logistics of such a project. A plasma cutter can produce a hundred identical or a hundred different pieces at the same price per kilogram. The difference here is whether one single data record is sufficient for all pieces, or if a new record must be created for each piece—the costs are then transferred to the immaterial work.

That the computer-generated architecture is not, at the end of the day, necessarily more expensive than conventional buildings is shown by our IAA 2001 *"Dynaform"* Pavilion in Frankfurt. The MINI Pavilion, built for the same client as an orthogonal glazed box next to the *"Dynaform"* (figure 9.44), cost a third more per square meter of exhibition space than the *"Dynaform."* As this example shows, the computer-generated architecture does not have to cost more—often, it can cost less. After all, Boeing originally introduced the digital design and production process specifically for its capacity to provide a 20% financial saving compared to previous production methods.

10
TOWARDS A FULLY ASSOCIATIVE ARCHITECTURE

BERNARD CACHE

This chapter presents a critique of a small pavilion (figure 10.1) that we (Objectile) designed as an experiment in our investigation of what we call "fully" associative architecture. Although the pavilion is a small piece of architecture, it was designed as "fully associative," which means that by controlling a few points we could modify the geometry of the pavilion and regenerate approximately 800 machining programs needed to manufacture its parts. The chapter discusses the conclusions we reached after completing the pavilion, which we will use to further push the design of the next pavilion.

The pavilion is fully curved—each of its walls had a curvature that has no regularity. It is subdivided into panels, which are all different. There are four walls plus the roof; with nine panels per wall, that is 45 different panels (including the roof), plus 180 connecting pieces, which are also all different. There is also a supporting structure that consists of 12 different parts. There are other important aspects of the pavilion. There is not a single
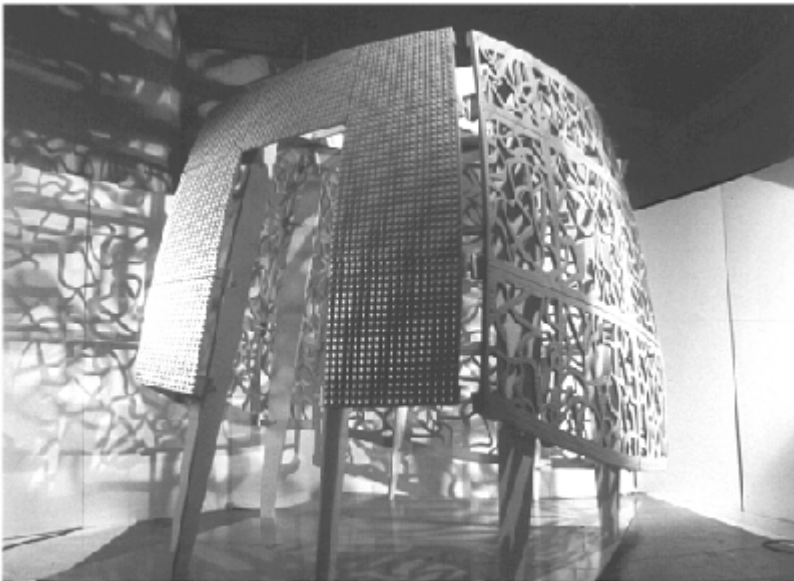
10.1. *Philibert De L'Orme Pavilion* (2001), designers Objectile.

orthogonal angle in the entire pavilion. It was fully machined, i.e. there is not a single piece that was built or manufactured in the traditional way. The pavilion's form is created using projective geometry, producing an illusion of additional perspective because it has vanishing points that disturb the vanishing points we are used to in spaces with orthogonal geometry. We also devoted particular attention to the texture of the panels, which either have an interlacing pattern or are opaque, as is the case at the entrance. The grid of the texture appears to be orthogonal but, in fact, it is not—it follows, i.e. it conforms to, the geometry of the panel. The panels are machined on both sides, which is another important feature, because parts are typically machined on one side only. Everything was manufactured in the woodshop of ESARQ, the school of architecture in Barcelona, Spain, where I had set up a research unit to investigate digital manufacturing techniques for the production of architecture. In the end, the pavilion is a low-tech building; we used very simple dowels to connect the parts. The complexity was actually embedded into the software.

The pavilion was named after Philibert de L'Orme, the French Renaissance architect who was very interested in using projective geometry as a production technique, as opposed to a representational technique. While the initial use of projective geometry in Italy by Brunelleschi is a widely known fact, it is often overlooked that the projective geometry was also used in France very early for stone cutting and for the design of complex pieces of architecture. In addition, Philibert de L'Orme was also very interested in different patterns of interlacing and textile motifs. This is clearly manifested in the church of Saint Etienne du Mont in Paris (which is very close to the Pantheon). His design for the interlacing in stone (figure 10.2) is a very good example of transposing textile patterns into stone cutting. Philibert de L'Orme was actually the forerunner of Desargues.


10.2. Stone interlacing in the Saint Etienne du Mont Church in Paris, designed by Philibert de L'Orme.

The following explains, in some detail, the computational generative framework for designing and building the pavilion. We started with what we call a "projective cube," or what is called in mathematics the Ryes' configuration (figure 10.3). Instead of leaving the edges of the cube parallel, we made them converge into the finite space, creating the equivalent of a vanishing point for each of the three directions. By changing the position of these points, we could modify the geometry of the "projective cube." There are actually four control points that can make the whole skeleton move.

We introduced associativity by essentially establishing geometric relations between elements in the drawing. To establish the curvature of the walls using projective geometry, each of the wall planes had to become a sphere with the center of curvature in infinity. So, in much the same way as we made the edges converge into the finite space, we brought the center of the curvature of the plane within the finite space too. Now, if we cut the sphere, and then deform it with one of the vanishing points, we generate an ellipse, which is inscribed into a parallelogram (figure 10.4) that corresponds to the building's outline.

This geometric construction may prove impossible in certain configurations. But because of the Poncelet's principle of continuity, we know that there is always a solution, in the real space or in the space of imaginary numbers. We were unable to integrate projective geometry within the software available today. The software is still lagging behind the progress of mathematics, to say the least—Desargues' work is still something to be considered by people creating the software of the future. By looking backwards one will invent the software of the future. Computing was not born in some California garage and not in Philadelphia with the ENIAC; the first program ever written is Euclid's Elements, which is probably the only software running bug-free for the past 2300 years! This is an important point because most of the people involved in digital architecture think they operate in a non-Euclidian, virtual and multidimensional space, while there is nothing non-Euclidian and non-Cartesian behind the CAD/CAM software used nowadays. This is very important because there is no fundamental divorce between tradition and reason.

So, having drawn the ellipses to generate the curvature that form the walls of the pavilion, we would establish the first layer of associativity by defining the geometric relationships between the constituent elements. The second layer of associativity is between the files, which have the complex geometrical relationships already built in. Those two layers of associativity define the general skeleton of the pavilion.
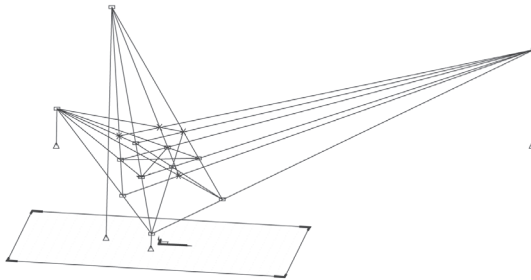

10.3. The "projective cube."

Another aspect of the project is the small connecting parts that are used to assemble the building. Instead of selecting standard elements, such as screws or bolts, or any other part commonly used in industry, we defined our own components. This ability to define components is very important for the future of the architectural practice—we will build our own components and reuse them by adapting them to new situations. In one of our experimental projects, we started with a very simple component—a four-sided board with a certain spatial complexity built in. As boards are inserted into the model, they can be interrelated, so when one board is manipulated, the neighboring boards are adjusted automatically. That provides for another layer of associativity, at the component level.
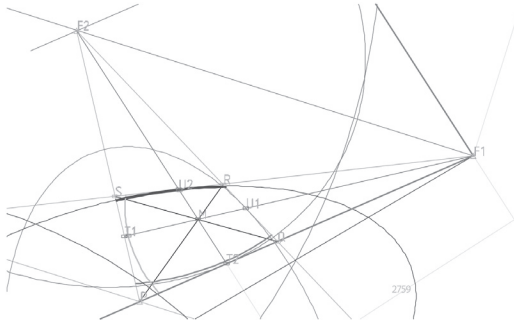

10.4. Constructing the curvature of the wall panels.

Once the boards are in place, the elliptical connecting parts can be inserted. There are several parameters that precisely define the geometry of the ellipses; some are there only for aesthetic reasons, and some for production purposes, such as the diameter of the tool that will machine the part. As it would be a very tiresome task to specify the values of every parameter each time a component is inserted, we could first define only the geometric parameters, and then specify or modify other parameters as the project develops. The parts have fairly complex definitions (figure 10.5) that take into account elements such as the diameter of the machining tool and the fact that we cannot have concave angles with a radius smaller than the tool's diameter.
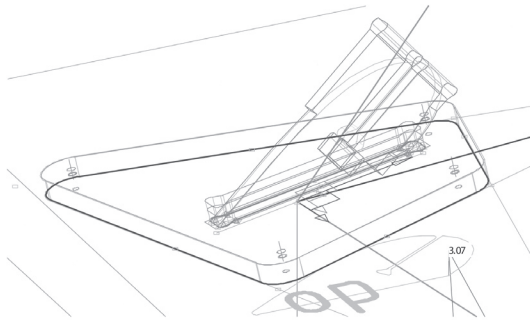

10.5. The connecting parts are parametrically defined.
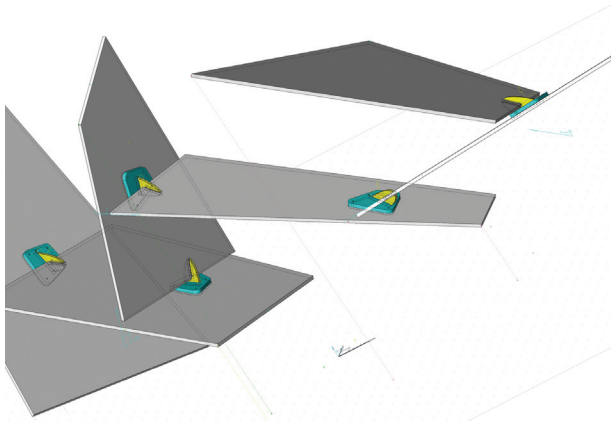
10.6. Assemblies are constructed from mutually associated parts.

As components are added, a number of changes are computed in the model, even though some of those changes are not immediately apparent Everything in the assembly is very closely fitted. But as nothing in the "real" reality is truly exact, and as the software is fully exact, we had to also define small gaps to account for "errors" in the production and assembly, such as adding the paint or the varnish after the machining, which can make the parts sufficiently thicker to introduce inaccuracies into the process. So none of this is absolutely accurate, and everything had to be calculated twice, taking into account all those small variations. There is a considerable degree of complexity built into the connecting parts.

Unfortunately, when we did the pavilion, we did not have this piece of software for connecting parts developed. We had to draw the connecting parts by hand, i.e. using the mouse. It took us three weeks to draw all of the connecting parts and to adapt them to each of the
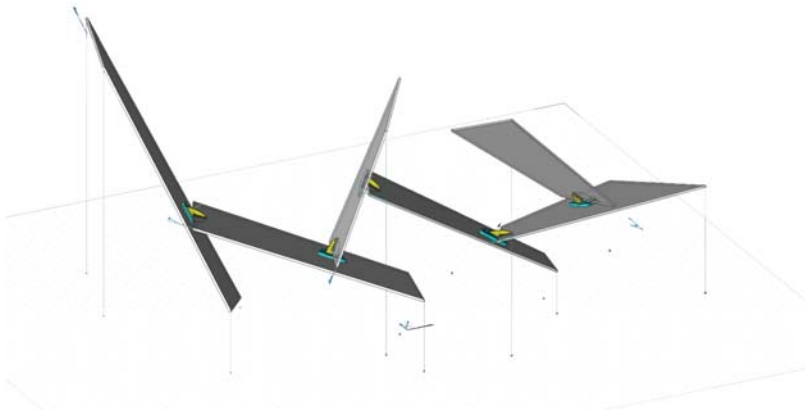

10.7. Control points define the geometry of the assembly.
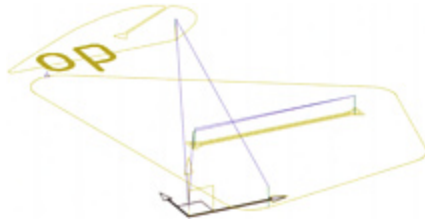
10.8. Trajectories for machining operations are automatically computed and are fully associative.

180 parts of the building. So, even though we had a fully associative model of the pavilion, we still had to engage in a rather tiresome drawing production. That production had to be very accurate, since everything was going directly from our office to the CNC (computer numerically controlled) machine; there was no one in the production facility who could prevent the errors we made in transforming the design into reality. This is another important aspect in digital architecture—we must develop design and production procedures that are close to zero errors. This is really a key issue.

At any point during the design development we could modify any of the elliptical connecting parts (figure 10.6) by simply changing one of the 30 parameters embedded in its associative definition. We could also move any of the control points, and have the changes automatically propagated through the entire assembly (figure 10.7).
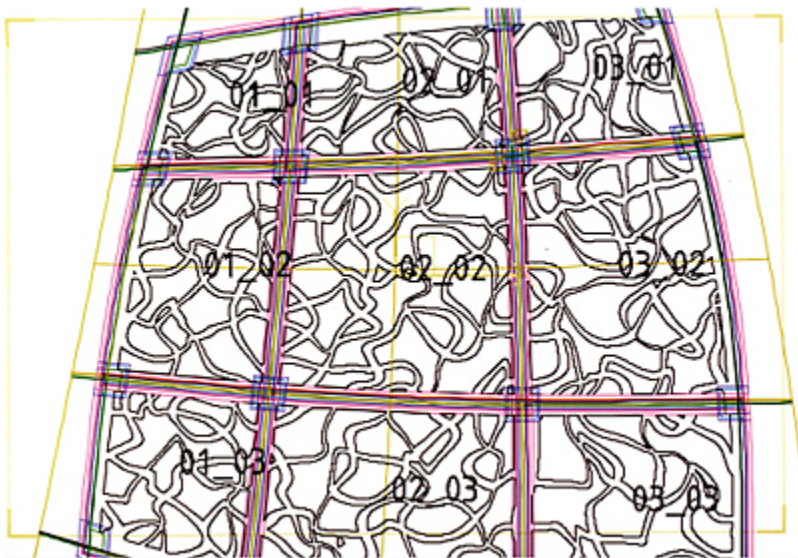
10.9. The wall panels can be defined as a coherent whole.

The next step is the manufacturing of the parts. For each element the required machining operations are computed automatically, for example showing the trajectories of the tool for contouring, pocketing or drilling operations (figure 10.8), thus offering an opportunity to examine the process in detail. When you have 45 panels, a particularly important step is the labeling of the parts. All of this is also fully associative, meaning that if we make a change in the design file, the associated machining operations will be recomputed automatically.

In the project that followed the pavilion, we were able to do without a general hypothesis that there is a "directing plane" to each wall, meaning that everything like the table of the machine, the plane of the boards and the plane of the connecting plates is coherent (figure 10.9). Such an approach allowed much more freedom. We have a different plane for each node of the surface, which enabled us to treat all curvatures in an associative model as a generic case, with an automatic generation of the machining program.

11

BETWEEN INTUITION AND PROCESS: PARAMETRIC DESIGN AND RAPID PROTOTYPING

MARK BURRY

Rapid prototyping provides affordable opportunities to investigate a design within an iterative process: both words "rapid" and "prototyping" in this conjunction imply a physical testing of concept somewhere along a path of design refinement. Curiously, while the architectural design community has been relatively adept in including this spin-off from aero, vehicle and product design industries, working with aspects of its associated design software has been pursued less vigorously, especially the use of *parametric design* software.

Parametric design (sometimes referred to as *associative geometry*) software allows the designer to treat a design as one large database adventure where design process decisions are published as histories embedded in the representation of the design in any given instance of its development. Decisions can be revisited and reworked accordingly, thereby potentially relegating techniques of erasure and remodeling to acts of last resort. Having used parametric design software for architectural design research for the last decade, it is not so much the efficiency gains that interest me—more the opportunities to experiment (increasingly in real time) at both a general or formal design level down to that of detailed design resolution.

There are two main obstacles to the take-up of parametric design beyond the industries that encouraged its development: first, the relatively high cost of the packages, and, second, an implied "design process" that appears to be the enemy of intuition. This chapter draws on ten years of practical experience in pioneering the use of software for iterative design research, including assisting the continuation of Gaudí's *Sagrada Família* church in Barcelona, a project that I have been involved with since 1979. At the risk of catching only a brief moment in the evolution of architectural software use, this chapter will discuss the issue of design becoming a slave to its own process within the use of this particular software while, at the same time, presenting a case for its wider take-up.

PARAMETRIC DESIGN AS AN ASSOCIATIVE GEOMETRY PROCESS

It was interesting to observe in 2002 that, while most architects today have at least a basic understanding of the term parametric design, very few have actually worked with it. Only a few years back, hardly any architect would have been aware of its existence, let alone thought to promote its take-up. There are several possible reasons for this, but we will first deal with a definition of parametric design.

Like many new-age software paradigms, the term "parametric design" is probably a misnomer or, if at least taken at face value, the term is probably redundant given that all design acts on an evaluation of a range of parameters during any given process. The parameters are not just numbers relating to Cartesian geometry—they could be performance-based criteria such as light levels or structural load resistance, or even a set of aesthetic principles. When parametric design is referred to, however, at this stage in its evolution, the reference is to Cartesian geometry only and the ability to modify the geometry by means other than erasure and recomposition. In this sense, parametric design is more accurately referred to as "associative geometry," for in all the cases that I have experienced, i.e. at the front-end use of the software, the only parameters that can be revised *in acto* are those that define the measurements of entities and distances along with their relative angles, and the ability to make formal associations between these elements (figures 11.1a-b and 2a-b).

Figure 11.1a shows the non-associative geometry example of a sphere and a box in space with a line $a_1 \rightarrow a_2$ connecting the center of the sphere to a defined corner of the box. If the sphere is translated (figure 11.1b), the line $a_1 \rightarrow a_2$ remains in place referencing the center of the sphere where it once was, but now remains an elusive and unreferenced distance away. Figure 11.2a shows the parametric design equivalent of the case in figure 11.1a where there is now a formal relationship between the sphere and the box, such that translation of the sphere drags the line with it as it maintains the relationship between the two geometries. If the length of the line changes, the sphere moves with it, as indicated (figure 11.2b).
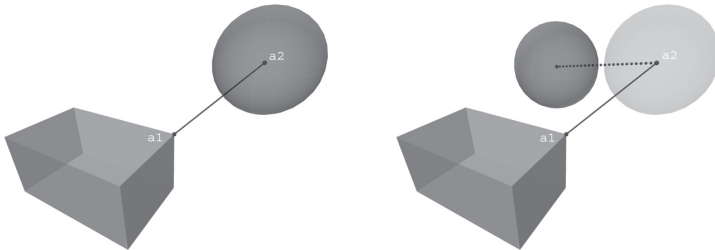
11.1a–b. Explicit geometry modeling.
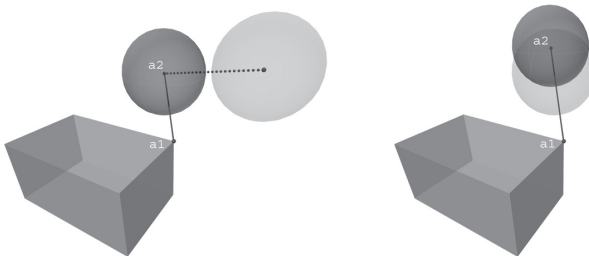
11.2a–b. Parametric modeling.
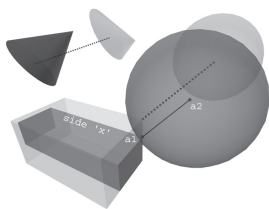
11.3. Associative geometry modeling.

Beyond this apparently trivial expose there rests an important implication: if geometry can be associated, so too can the associations themselves (figure 11.3). In the examples shown, the side of the box "x" is expressed as a ratio of the length of the line $a_1 \rightarrow a_2$ that connects it to the sphere, as is the size of the sphere itself. Increase the size of the box, and with it side "x," and the sphere increases in size while the line $a_1 \rightarrow a_2$ shortens in length. Associations can be made between geometries of figures whose only relationship is sharing Cartesian space. In figure 11.3, the parameters governing the size, shape and position of the cone can also be tied directly to the activities which inform the change in relationship between the sphere and the box.

This ability to form associations between entities has especially useful opportunities for formalizing design, as these relationships can be revisited and revised during the design process itself. Each time a value for any parameter changes, the model simply regenerates to reflect the new values. At once, it proves the value of the concept for some, while fuelling possible claims from other viewpoints that ultimately work against its uptake, especially by architects, for it is relatively easy to introduce a problem to the design process known as *over-constraint* An example of this phenomenon can be given for the box in the figures discussed above. The sphere might be given a ratio where its radius is half the length of the line $a_1 \rightarrow a_2$ connecting it to the box corner. Maximum and minimum dimensions for the radius might also have been declared. Any operation that seeks to extend the line to more than twice the maximum value of the radius cannot obviously be fulfilled.

In general terms, all parametric operations are linked to each other in some explicit or implicitly declared relationship. If the model suffers from over-constraint in relationships declared early in the design process, subsequent design decisions might be invalidated simply through the inability of the regeneration process to comply with conditions set by the designer earlier on. The software itself helps by identifying where the over-constraint might be occurring. It may be easy to adjust the model if the circumstance has been created recently, fresh in the memory of the designer who created the circumstances. More problematic is the unraveling of the geometry possibly set up by the designer beyond their own recent memory. More problematic still is inadvertent over-constraint where two separate and apparently unrelated operations nevertheless conflict: the results of operation "a" conflicting with operation "b" despite there being no "connection" between them. An example would be a staircase within a given volume. Operation "a" calls for the floor to ceiling height to be increased, not because the designer specifically wants to increase the height but because an object within that space, for example, is increased in height, thereby forcing the increase to the height to the ceiling above. Operation "b" sets the stair riser heights to be

equal to 1/16 the floor-to-floor height. The performance regulations might have been built into the parametric model as characteristics of compliance. When the designer first set-up the parametric model, circumstances demanding an increased floor to ceiling height might never have been envisaged, and while the stair geometry might set the height of the risers between certain minimum and maximum dimensions, the designer may not have built in the possibility of increasing the number of stair risers should the need arise.

The problem of over-constraint is at its most acute when it has been set up by a designer other than the individual trying to deal with its consequences. There are, therefore, two interesting observations to be made about parametric design that arise from this issue of constraints controlling interrelated geometries. The first is a situation of "designing the design," so-called *metadesign*. The second begs the question of whether the process is pro shared authorship, or reinforces sole authorship of a design. One view is that it can be shown to be a potent force to counter sole authorship as the precondition of the declaration of parameters, as explicit influencers of the design formalize the design in ways that others can interpret and enact upon. Or does parametric design in fact augment the role of a single designer as sole author controlling the whole design, given that the complex interrelationships between the constituent geometries involved are concomitant with the complexity of the process alluded to above? Both the metadesign issues and the question of shared authorship are inextricably linked with each other. What works for one designer may not suit another.

DESIGNING THE DESIGN

Clearly, parametric design predisposes a strategy in a way that could form part of any non-parametric design process, but with parametric design itself, it is obligatory. In the case of the staircase referred to above, for example, the designer is required to think about the full range of possibilities for all aspects of the design before committing to building a parametric model. Apparently redundant features, such as the number of stair risers, might need to be factored in without any expectation of being required. This represents a potential thinking overload that is incommensurate with the expectations of a designer traditionally trained in the use of computer-aided design (CAD) software where actions yield immediate results. If the staircase no longer fits in the space envisaged due to some other unexpected but consequential change, simply erase the parts that no longer conform and remodel.

A design based on a parametric structure probably cannot be altered in this way, as in most circumstances deleting one or more elements will cut the co-dependencies downstream. There is, therefore, a careful balance required between assessing which design circumstance benefits from being modeled and reworked subsequently via the erasure-redraw route, and which benefits from a fully defined parametric model. This assessment, however, might be based on a conventional set of paradigms and, in my experience, the issue has more subtlety to it than first appears. If parametric design software is used to do little more than "turbocharge" an existing process, the benefits may prove hard to identify. If the process by which a design is produced is rethought to take advantage of the software, defending its use can be self-fulfilling if the results obtained ostensibly justify the means. This can be shown to be the case, and evidence of this is provided from a simple structural

arrangement followed by the more exacting compositional demands of Gaudí's *Sagrada Família* church in Barcelona. There the use of parametric design software has proved to be a powerful ally in both the analysis of Gaudí's original design, which survives as 1:10 and 1:25 gypsum plaster models, and in the synthesis of three-dimensional outcomes based on two-dimensional drawings.

A CHALLENGE TO THE SOLE AUTHOR PARADIGM

There are two polar positions that can be taken with regard to the role of authorship within the context of using parametric design for the building and construction industries. The position changes when comparing design which is more an analytical process, such as detailed resolution of a whole building design, and the design of the whole project which may have an experimental aspect to it as synthesis. There is also the issue of whether design software predicated to a manufacturing process can be usefully transferred to the architecture, engineering and construction (AEC) industries. This is not so much a matter of scale but outcome. Vehicle, aeronautical or product design contexts include total productions composed of many small interrelated but usually discrete components, often headed to relatively large production runs compared with the building industry. In contrast,
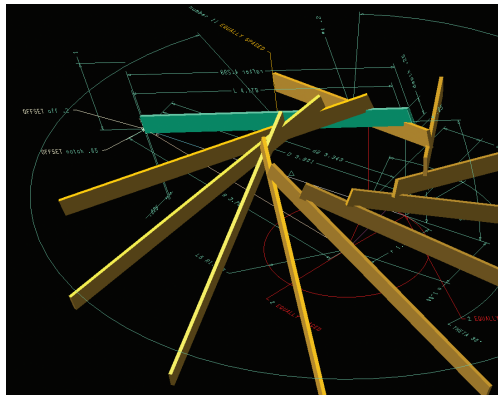

11.4. Reciprocal frame truss: general arrangements.

buildings, almost invariably one-off productions, are further complicated by the difficulty in isolating components from each other. Many of the components are subsets of larger assemblies. There is the added complication of sharing the knowledge about how a parametric design is organized—multi-author designs require that strict protocols be designed that are appropriate for the task in hand. This, of course, is required in any shared CAD model environment but the essential difference for parametric design is that each subassembly can have a dynamic object link to the major assemblies within which they form a part. A change in one context is automatically updated in its parent. Whereas sole authors may defend their unique role in a complicated design as being an inevitable consequence of an adaptation of an intuitive sketching process to one that is parametrically driven, this

argument is self-defeating as soon as the design itself needs to be fractioned into sections for collaborators to develop.

In summary, parametric design suits the following:

- designers committed to working in groups with fluid sharing of material;
- designs that are able to adapt to the advantages parametric design offers in enhancement through the parametric process itself, which allows considerable iterative design development during the design process, albeit within a given set of protocols developed as part of the metadesign process; and
- above all, teams that are prepared to spend sufficient time to develop the design as a construct, that is, prepare the metadesign prior to making more firm commitments during design refinement.

The following case studies present evidence for this particular viewpoint.

11.5. Reciprocal frame truss: detail of reciprocal supports.

RECIPROCAL FRAME TRUSS

Figure 11.4 shows a simple structural arrangement enclosing a single volume known as a reciprocal frame truss. Each rafter is borne by the one ahead of it, while supporting the one behind. Together they form a continuum of mutual dependency. They appear in folkloric buildings around the world. The work of the Catalan architect Josep Maria Jujol also features the truss in at least two works. What is interesting is not so much the formal possibilities of this particular arrangement, for they are, in fact, problematic as soon as consideration is made for lining the surface, but the fact that the simplicity of the concept belies a fantastic level of difficulty in setting up a three-dimensional model of any such assembly. This refers to a system with an angle "a" as well as depth "d" influencing the roof pitch. Taking a half dozen chopsticks and attempting the task of making a "truss to order" quickly reveals the complexity.

There are a relatively high number of parameters for such a straightforward form—effectively a truncated cone—and these have interrelationships that form complex simultaneous equations (figures 11.5–11.7). If the rafters increase in depth, a corresponding increase in

the slope angle results in a way that would not result in the same change in a warren truss, for example. Trying to model the truss in three dimensions is difficult enough without attempting to make changes. Modeling it parametrically is possible, however, but only after a hierarchy of equations are entered into the parametrically manipulable database. Once built, the slope, depth of rafters and the numbers of rafters can be altered sequentially until the best result is obtained (figure 11.8). Further than the formal changes made possible only through the digital computational assistance lies the opportunity to form a half-lapped joint between supporting and supported members. Figure 11.9 shows how the lapping can be controlled to be equal excisions of both members, but also ensuring that the seat of each lap is horizontal. Change the angle of the roof, and the parametric model updates itself as a consequence, maintaining the level seats, providing a result is geometrically possible.
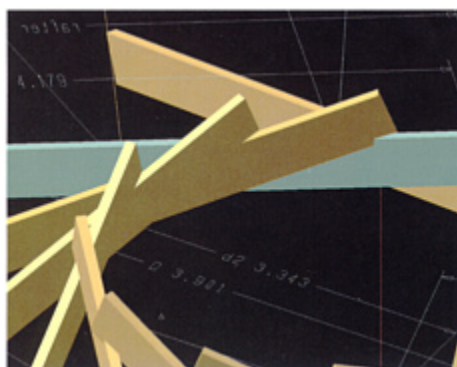
11.6. Reciprocal frame truss: detail of reciprocal supports.
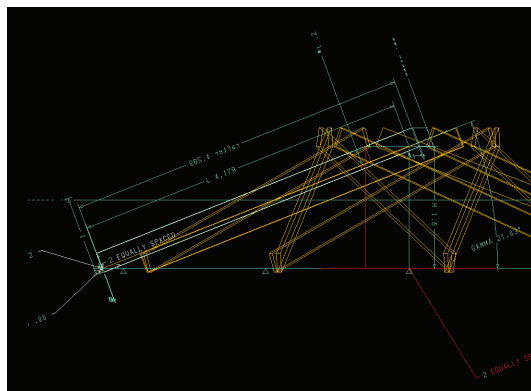
11.7. Reciprocal frame truss: side elevation.
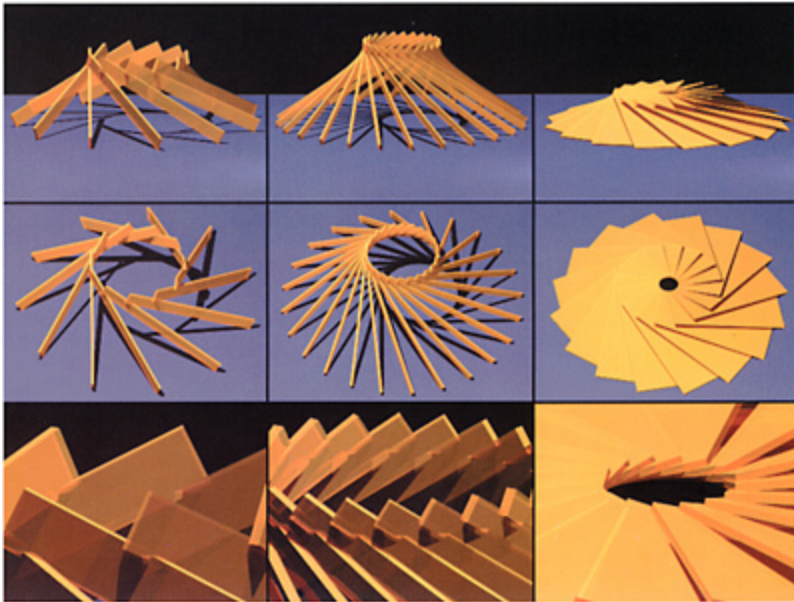
11.8. Reciprocal frame truss: parametric variation.

PARAMETRIC DESIGN AT THE SAGRADA FAMÍLIA

Gaudí died in 1926 having spent 43 years developing and executing the design for the *Sagrada Família* church. The remaining 12 years until his death at the age of 74 were dedicated to this project to the point that he actually lived on site. Probably at the beginning of this period he reflected on the fact that so little of the projected building was complete (less than 10%), and that he himself would not see the building through to its conclusion. Gaudí's work can be characterized by its singularity that would seem to predetermine the actual presence of the architect's hand for all stages of the work. This singularity almost prevents successful integration of another creative mind, and here we have an essential paradox in the oeuvre: on the one hand the work needs Gaudí; on the other, he clearly would not be available for the life of the project even from the most optimistic viewpoint. This is corroborated by the three-quarters of a century since his demise: the building is still only a little over 50% complete, despite virtually uninterrupted building work. Despite significant expenditure of materials and effort, the building is still decades away from completion.

DESIGN OPTIMIZATION: PARAMETRIC DESIGN AS PART OF AN ANALYTICAL PROCESS

The nave roof was modeled at a scale of 1:25 before Gaudí died, and survived the 1936–9 Civil War only as fragments. Any drawings for the roof were destroyed during the war. The model fragments, combined with a commentary from a close collaborator, Rafols,

published two years after his death, reveal that his intention was to make the roof from a series of hyperbolic paraboloids that all met at a virtual point in space above the apex of the roof—the geometric forms were truncated. The task for the latter-day collaborators was to explore the surviving models, capture the data for the geometry, and look for key values for the parameters such as the corners of the hyperbolic paraboloids in space. Only by moving these points in space on the fly, could the geometries be relaxed or tautened sufficiently to make a close match between the restored surviving models, and what would be exact ruled-surface equivalents assured by this process. It is difficult to judge how much longer this research and application would have taken using conventional software. Parametric design certainly ensured a good result and would be factors of ten faster than traditional empirical methods. Figures 11.10a–e show the digitized model, and various samples of the iterations seeking a near-perfect match.
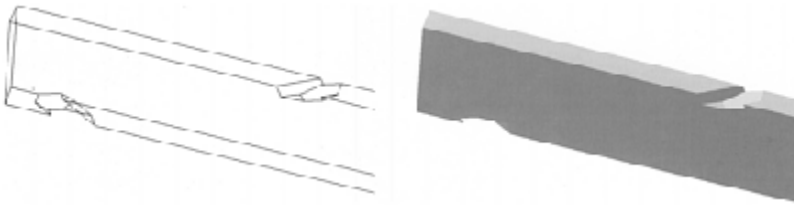
11.9a–b. Reciprocal frame truss: notching that parametrically maintains a level seat in any variant.
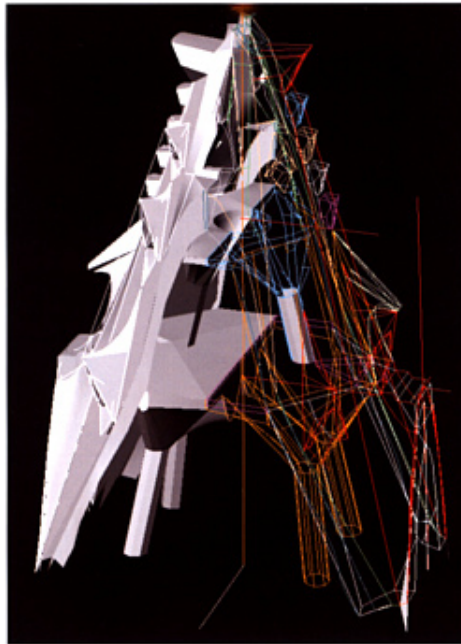
11.10a. Wire-frame and part surface rendering of digital model of Gaudí's original 1:25 plaster model of the *Sagrada Familia* nave roof.
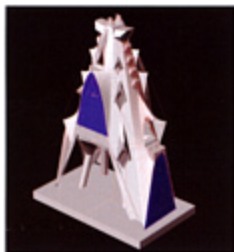
11.10b. Nave roof: rendered digital model of original plaster design model.

11.10c. Nave roof: parametric variant (too short).

11.10d. Nave roof: parametric variant (too tall).

11.10e. Nave roof: parametric variant (close match).

Similar to this exercise, the nine parameters that govern the form of the constituent hyperboloids of revolution that form the nave windows were investigated parametrically. Figure 11.11 shows the clerestory window that only survived as fragments after the Civil War; the photograph here shows the window during Gaudí's time. Figure 11.12 is the interpreted version, and figures 11.13a–f show a series of iterations relaxing or filling the Boolean subtractions of hyperboloids of revolution that form the window.
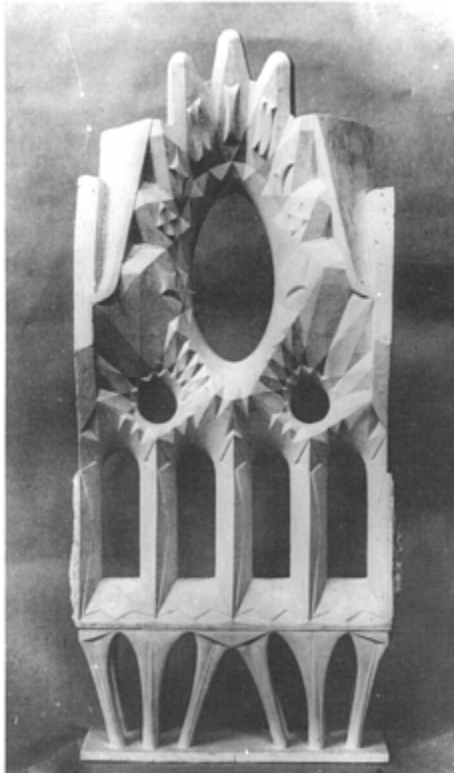
11.11. 1:10 scaled plaster model of clerestory window—photographed before Gaudí's death.
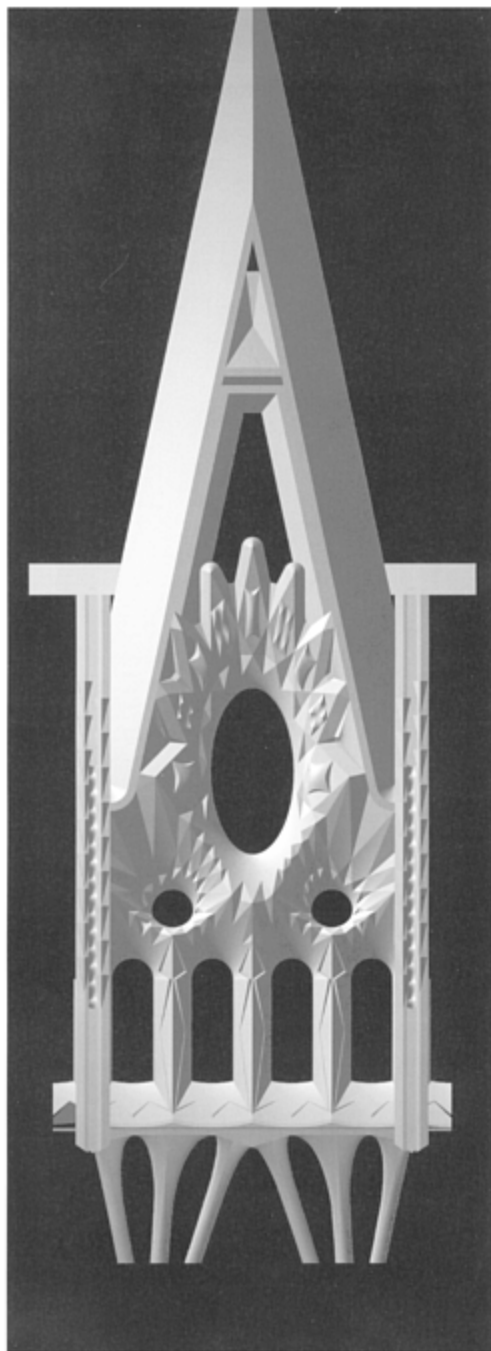
11.12. Digital model of clerestory window
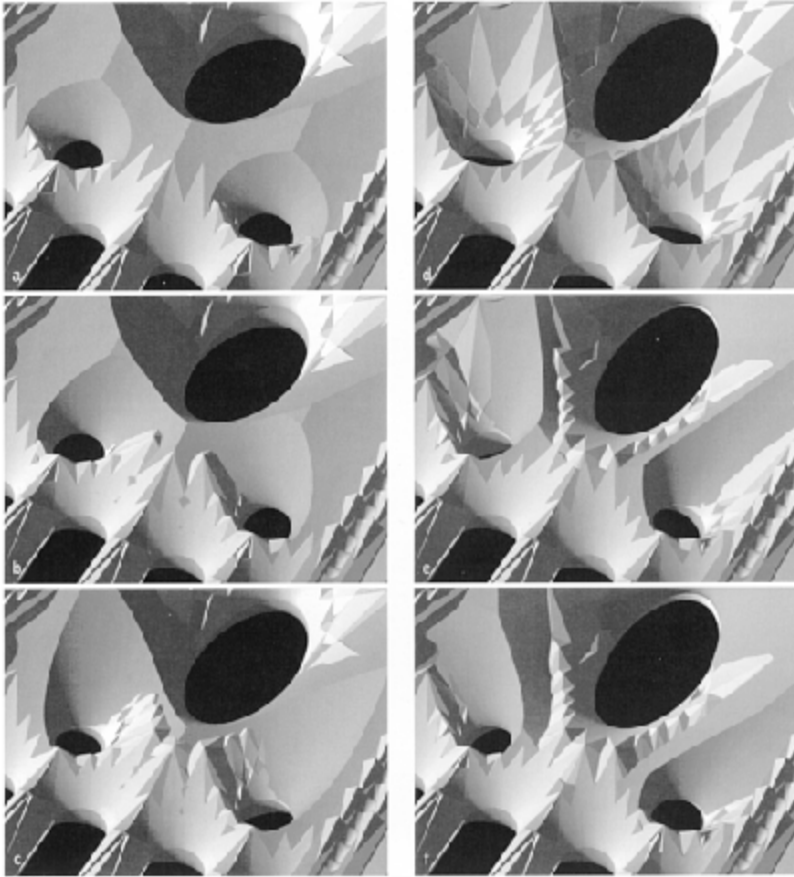
11.13a–f. Six parametric iterations looking for the correct parameters to make a close match to Gaudí's original model (11.11)—figure 11.13d is the closest.

PARAMETRIC DESIGN AS A CONTRIBUTOR TO DESIGN SYNTHESIS

In the years between the conclusion of the Civil War in 1939 through to 1978 almost all available resources were dedicated to building the second transept, the "Passion Façade" on the west side of the building. Essentially, this group of four towers is a version of the corresponding "Nativity Façade" built on the east side of the building and completed shortly after Gaudí's death. A major difference is the plan—Gaudí based the original façade on circular towers, whereas he planned the Passion Façade as elliptical towers with a minor axis equal to the radius of the Nativity Façade towers. This parametric shift is echoed in the height of the Passion Façade, which is higher than the Nativity Façade but lower than the main front towers (Glory Façade), which, in turn, are circular but with a radius equal to the major ellipse axis of the Passion Façade towers.

11.14. Incomplete model of Passion Façade rose window made by Gaudí's successors.

Although the façade was completed 22 years earlier, it was only in 2000 that the Construction Committee for the church was able to proceed with the design and execution of the rose window for the west transept. Coincidentally, my first task in joining the *Sagrada Família* church was to look at this window, but without any computational assistance at that time (1979–1980). The base material was a 1:25 scaled unfinished plaster model built by Gaudí's immediate successors and not by Gaudí himself (figure 11.14). In fact, a combination of the paucity of surviving information from Gaudí, its status in the total and substantially incomplete oeuvre, and the sheer difficulty in developing a modus operandi for its execution led to my deployment on the nave of the church, all of which had been modeled in detail by Gaudí in gypsum plaster at scales of 1:25 and 1:10, and which ended up serving as our apprenticeship model for the next two decades. In analyzing and interpreting the geometry for building from this source, we are now well versed in the subtlety and richness that Gaudí's choice of geometry provides. In returning to the rose window two decades later, we were therefore working on the first substantial element of the building not modeled during Gaudí's lifetime. Having unraveled the mysteries of Gaudí's deployment of ruled surfaces as a rationale for a general description of the church, and one that he had spent his last 12 years devising, this time round, however, the context had changed to one of familiarity. Alas, Gaudí had died before ever having explained his view for their deployment.

The window is 35 m tall and 8 m wide. It sits behind the centerline of the towers towards the interior of the church, and will eventually be partially screened by a colonnade that forms the crest to the porch entrance to the transept. The colonnade is the subject of our current investigations, with construction having commenced in late 2002. The rose window needs to be seen in its entirety from particular vantage points in front of the façade and from the interior—it is a major feature of the natural lighting regime. As it faces west, and in line with the crucifixion theme for the façade bas-relief and sculptural treatment, Gaudí envisaged the façade to be at its most spectacular when struck by the setting sun and, accordingly, his illustration of the façade, made some years before his death, reveals a strong chiaroscuro character. The window is therefore one of several layered elements to enhance this effect and, at the close of day, the crossing will be illuminated by the late afternoon sun predominantly tinted by the stained glass of the central elliptical opening, which measures 6 m by 3 m (figures 11.15 and 11.16).

With a view to celebrating the commencement of the third millennium in 2001 with this window, the challenge was met to take the provisional design model from Gaudí's successors through to the completed and glazed window in a little over a year. This task, lean construction at its leanest, required innovation on all fronts. The general description of the window was made through parametric design-based exploration. We introduced rapid prototyping to the mix coupled with advanced visualization techniques. We reintroduced eighteenth century "traits" as a means of communicating the cutting requirements FOR

11.15. Exterior view of completed Passion Façade window.

individual stone elements to the stonemason, Manuel Mallo, whose yard is located on the far corner of Spain with respect to Barcelona—namely, Galicia, over 1,000 km away in the North West.

Just as we had to think of new ways to communicate complex cutting information to the mason, the mason, in turn, needed to invent innovative means to accelerate the cutting, while the builders too needed to think of new ways to build, all to meet a 13-month deadline.

Using the sketch design model as the essential point of departure, a parametric schema was developed based on the general composition of the layout of the various openings. These were determined by considering two sources of primary material. The first source is the series of developments in the windows for the nave. Starting with the lower, followed

11.16. Interior view of completed Passion Façade window.

by the upper lateral nave windows, and concluding with the central nave clerestory, there is a clear progression in the sophistication of the composition from the earlier definitive work to Gaudí's final models for the clerestory. These models were developed sequentially during his final years and survive as fragments following their destruction during the Civil War, along with photographs that were published at that time. The second source is a proportional system that has been identified by the current coordinating architect, Jordi Bonet.

The schema emerges as a grid of construction lines whose interrelationships are governed parametrically. The schema supports the geometry, much of which is linked *inter alia via* the schema. If two parallel horizontal construction lines that "control" two rows of openings are moved apart, the openings move with them and the effects of the Boolean operations change accordingly, assuming that there is a solution within the constraints. For the rose window, the parametric history contained 3,800 linked events. This is an order of magnitude over the histories anticipated by the software designers for the intended application in product and vehicle design, and leads to the recalculation and regeneration of models taking several minutes rather than the several seconds that is more commonly experienced with this kind of software.

There were three motivations for using parametric modeling for the rose window The first was the need for a reconfigurable model of the whole geometry that allowed more effective team decision-making. "What if" scenarios could be enacted during the brief design phase when all the team members could meet regularly on site in Barcelona (January 2000). The second reason was the desirability of building one half of the model as if it were symmetrical—the towers are slightly out of alignment with the church grid. This, combined with the fact that each group of two towers that form the four tower ensemble for both transepts (Nativity and Passion Façades) have different separations from each other, required a half model to be adjustable parametrically in order to meet the specific variations for each side. Third, and fundamentally for the lean construction approach to this element of the project, the reconfigurable model allowed for last minute changes as site data became available only when scaffolding reached a point where accurate measurement was practical. It also allowed work to proceed at the lower reaches of the window, while the detailed arrangements at the top of the window were still being negotiated (for the intersection of the window with the ceiling and roof, which at that time was still in the incipient stages of its design development). A full design model emerged, which was thereafter in a constant state of flux. All revisited decisions could be parametrically invoked, with revised visualizations being made for assessment (figures 11.17 and 11.18).

The weekly design meetings on-site at the *Sagrada Família* church at this initial design phase included contributions from the master mason. That was the first time we were taking Gaudí's use of second order geometry directly to stone—previous work had been directed towards mold-making for artificial stone (concrete with carefully selected aggregates). As a consequence, we had to devise a new modus operandi in order to provide the stonemasons with competent information. But, as has been the case with all aspects of our work in this project, thinking of the new meant turning back to the past, and the principles of stereotomy led to the resuscitation of "traits" discussed in detail by Robin Evans who devotes a chapter to the topic in *The Projective Cast* (1995, Cambridge: MIT Press), albeit as digitally-produced equivalents.
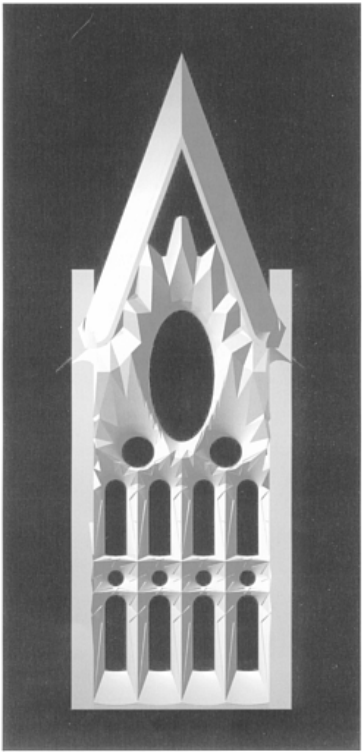
11.17. Computer rendered exterior view of parametrically varied digital model of the Passion Façade rose window.

11.18. Spreadsheet to drive parametric model second order surfaces as part of the associative geometry manipulations for the Passion Façade rose window.
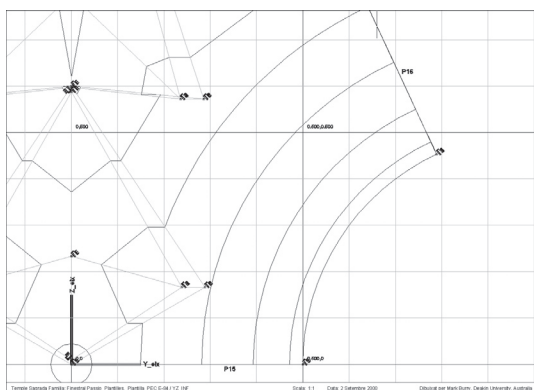
11.19. Passion Façade rose window: the stonemasons' templates, produced in Australia, checked in Barcelona, and worked from in a distant corner of Spain.

The stonemason settled on a system where he would use 1:1 D in AO templates produced in Australia, emailed to site in Barcelona for checking, and then couriered to his quarry and yard in Galicia. Around 780 templates were produced, each with a color-coded reference system (black = cut face, green = line/edge on the surface, blue = 10 cm contour, etc.), a bitmap rendered image, and three-dimensional coordinates to guide the masons (figure 11.19). As the window approaches the large elliptical opening, each piece of masonry becomes more complex and a greater challenge to represent. The master mason eventually had to produce a full-size polystyrene facsimile of each piece, from which a team of masons could semi-automatically produce the actual cut stone using equipment especially adapted by Sr. Mallo to take full advantage of Gaudí's use of ruled surfaces. The templates included contours at 10 cm intervals to assist the rapid cutting of polystyrene sheets of that thickness. As the team worked on each stone element, it was easier for the masons to work collectively from a facsimile using traditional masons' measuring tools than for each person to have to refer to the same set of templates.

In this case, parametric design proved to be an invaluable ally in assisting a large complex masonry element to be built in complex circumstances. The use of associative geometry allowed for rapid and flexible design synthesis and experimentation. It also allowed for continued design development and significant change to occur during construction. Most critically for this piece, it allowed for a single model for half of the asymmetrical composition, which could be parametrically adjusted to manage the differences of the other half, something impossible to achieve using conventional explicit modeling.

CONCLUSIONS

As in *Sagrada Família* "case studies" reported elsewhere, Gaudí's use of ruled surfaces provided an invaluable codex for communication between distanced collaborating parties, in this case relying principally on the Internet for all communication. In this instance, faith in the flexibility of a committed digital approach, where the numbers were fundamental to

the design and design flexibility mid-construction, was taken one step further to embark on a fast-track process. In this situation, neither the geometrical embodiment of the design nor the communication and construction process were resolved at the commencement of construction. Interestingly, where the time honored iterative design approach using modeling in gypsum plaster provided the haptic interaction with the design for both critique and construction, the digital model has provided comparable haptic prototyping opportunities with accelerated production times commensurate with the overall increase in speed of design and construction.

12
SCOTT POINTS: EXPLORING PRINCIPLES OF DIGITAL CREATIVITY

MARK GOULTHORPE|dECOi

INTRODUCTION

The title for this chapter refers to Robert Scott, the polar explorer, who seems a curiously prescient figure when considered from the threshold of the emergent digital age. Scott set out to explore a new territory, a harsh and expansive space of frozen liquidity; yet, equally, he seemed to chart a mental space, the tortured emergence of modernity through the hypertrophy of a regimented system. For Scott's enterprise was vainly crippled, simultaneously impelled and thwarted by the British imperialism that was relentless in its demands for the furtherance of its knowledge and influence, yet hampered in the prescribed manner of its attainment. The expedition was mounted mindless as to the actuality of the deadly new environment, a macabre horse-drawn funerary march.

Haunting Scott's tragic expedition was the phantom of Amundsen, his dog sleds streaming to the pole, who learned from the Inuit and from the environment, allowing a more supple and creative approach to such exploration. Doubtless, Scott is the more romantic figure, who might have finally understood more of the essence of the new environment, its pitiless emptiness and indifference, than his rival. Indeed, even Amundsen's model of adaptation and efficiency seems mere *chimera* to the salient *nothingness* of the entire enterprise: that upon arrival at the pole, as the compass readings petered out in magnetic feebleness, *there was nothing there*—a pre-ordinate mental construct projected onto a lifeless wilderness.

In beginning to negotiate an entirely new digital territory, as we flounder across its limitless horizontality, desperately pricking its surface as if to establish points of principle, or dreaming of smooth new modes of practice, we might reflect that technology is *nothingness*. Some of our most incisive thinkers of technology have defined it as such: as framing (Heidegger), *techne* (Derrida), as no tangible entity—simply the condition of thought, and a basis of mnemotechnics (memory). *Efficiency* does nothing to thicken its glaciality, and perhaps only serves to speed more superficially across its surface.

But technological change certainly marks the break-up, the deep fissuring, of extant modes of *praxis*. the cracked image of an empire of control. *Architecture,* though, lies elsewhere than the pole of a technological imaginary, the accumulation of local inflections within an expansive new territory suggesting a deformation of extant praxis rather than a startling apparition of embodiment. Previous ages have invariably tried to establish a center, a point of legitimacy, to sanction activity; perhaps Scott, in his desperate and illegitimate pursuit of a mythical spot, actually served to burst such belief structures, inaugurating

an aleatory modernity in the revelation of this limitless, fluid, impassive new environment: the pole as nothingness, as white death.

Might one then consider "pioneering" digital work as the establishment of Scott Points across a new territory, compeled yet hampered by a pre-digital imagination, perhaps disillusioned by a pre-digital cartography? Certainly, dECOi's work can be seen to have meandered about the digital landscape, putting down a series of flags (algorithmic, programmatic, parametric), as much Pyrrhic reference points as principles for future navigation, yet which have seemed salient in their revelation of possibility. Oates' famous utterance (and epitaph) on leaving the tent—"I may be some time!"—is perhaps poignant—it may indeed take time to establish the principles of this new terrain, and we might expect that some will lead into oblivion.

Mindful of Scott's dejected arrival at the pole, and the already forlorn flag of Amundsen, we suggest that the digital be thought *as such*. We venture that this will require a profound requalification of habitude, most particularly of creative *praxis* and its typically linear and goal-oriented strategies, before a legitimate architecture may be fashioned within the digital landscape.

POETICS

In trying to think through digital creativity, I was drawn to Gaston Bachelard's *Poetics of Space,* his erudite phenomenological reverie on the sources and effectivity of creative imagination, since his explicit subject is not space as such, but how spatial imagining has acted as a source of creative inspiration in various groundbreaking literary works. Bachelard is, in fact, most interested by the "Image," his term for the radical (and often violent) bursting of literary convention by a singular and startling work, and its dissemination or proliferation through cultural consciousness.

What is most striking in Bachelard's work is his implicit (yet powerful) critique of scientific rationalism, particularly since Bachelard had established his academic reputation as a philosopher of scientific rationalism! In the Poetics and in the equally extraordinary *Psychoanalysis of Fire,* Bachelard broke with his own prior interest in announcing that the most essential and defining moments of cultural renewal seemed unaccountable by scientific rational discourse. The salient "images" of breakthrough were not instigated nor propitiated by familiar patterns of causal, rational discourse, and neither could they be accounted for by it. Hence, Bachelard's exploration of ways in which spatial images have offered potential to such writers—how they have used spatial constructs to release new modes of thought and practice—and his development of a wide-ranging freely-associative phenomenological style to try to account more effectively for the *discharge*.

The Poetics is a rare book in its singular focus on the attainment of cultural renewal, and its attempt to talk about the *condition of possibility* for such attainment as of the effectivity of transmission of cultural ideas. It was written in the 1950s in a period of frenetic post-war technical territorialization, almost as if to counter in advance the effects of such rampant scientification of culture. Bachelard insists that scientific rationalism offers an inadequate discourse for cultural renewal, and he denigrates the simple pursuit of technology as an end in itself. Most essential is Bachelard's insight that the realignment of cultural

norms is attained by erudite venturing into a new *conceptual process,* and he offers count-
less examples of writers who have allowed a spatial image or metaphor to instigate such
breakthrough.

The Poetics explores a range of spatial conditions, from familiar inhabited space (the
cellar, the attic, the corner, etc.) before investigating uninhabited spaces and the projected
imagination required for their "habitation" (the shell, the nest, miniature). He concludes
with a "phenomenology of roundness" which opens to an entirely imaginary spatiality.
Here, then, is a speculative 1950s imagination groping towards new patterns of cognition
released in a series of prospective spatial conditions. As a treatise on the fatality of techno-
rationalism, and an exploration of the liberating potentials of imaginary spatial "stretch-
ing," the *Poetics* offers a provocation to our current attempts at the projection of a new
digital imaginary.

The categories of shell and nest certainly merit reexamination from a digital perspec-
tive, since these as-then uninhabited spaces may well prove to be the epitome of digital
spatiality. Certainly, the most marked characteristics of digital architecture are its propen-
sity for complex-curved form and for environmental "gathering," corresponding to the
shell and the nest respectively. But Bachelard would demand a much more felicitous spatial
description, dissatisfied by the simple appearance of a thing, asking after the essential par-
ticularities of nest and shell, both of which exert a traumatic magnetism over Bachelard in
their being *trace of an absent presence*.

The reverie on shells highlights Bachelard's interest "to experience the *image of the
function of inhabiting"* which he contrasts with the simple *"will to shell-form,"* which he
derides. For Bachelard, the mesmeric geometries of shells, their outer appearance, actually
defeat the imagination: "the created object itself is highly intelligible; it is the *formation,*
not the form, that remains mysterious." The essential force of the shell, being that it is
exuded from within, is the secretion of an organism; it is not fabricated *from without* as an
idealized form. The shell is left in the air *blindly* as the trace of a convulsive absence, the
smooth and lustrous internal carapace then exfoliating in its depth of exposure to the air, a
temporal crustation.

Such inversion of ideological tendency, an expansive mental *shell-emptiness,* Bachelard
captures deliciously: "the mollusc's motto would be: one must live to build one's house,
and not build one's house to live in!" Such inversion would seem to be a recipe for an auto-
generative, even *genetic architecture,* on condition that its secretions are unselfconscious
and "felicitous." For Bachelard the *process of formation* is left as a mental material residue
that then bends imagination to its logic, which would be the fully cultural wager, the poetic,
of such improbable forms.

Yet such implosion of determinism seems to carry an uncanny presentiment that, as the
shell-form becomes technically feasible, such forms will not be generated by an impelled
imagination, but simply as an abridged evolution, never attaining the *force of image*. If we
are to crystallize a new "function of inhabiting," our creative imagining needs to attain a
felicity that separates it from an aborted genetic process, and the means of deploying its
algorithmic and parametric (digital) propensity to material *effect*.

Bachelard's chapter on *Nests* seems to similarly articulate forms that were pre-digitally
imaginary but which now merit consideration in their actuality by architects. He muses on
the nest as an intricate imprint of the inhabiting body, adjusted continually as a soft cocoon

that outlines the aura of movement of the bird's rounded breast. This raises the specter of an environment adapting to our bodies and continually recalibrated to suit the vulnerability of our relation to the environment. Such forms of "dry modeling," merging camouflage and comfort in a density of ambient "stuff," seem suggestive of an *alloplastic* relation between self and environment, moderated by an endlessly redefined digital matrix. The empty nest, like the shell, carries an unknowing impulsion, a *trauma,* as if an interminable and complex three-dimensional weaving had been interrupted. Such *forms of absence,* as *images of the function of habitation,* offer a *cultural* correlative to the technical positivism that surfaces in the present.

12.1. *In the Shadow of Ledoux* (1993), CNAC Le Magasin, Grenoble, France, architect dECOi.

In presenting our projects, then, this chapter will endeavor to draw out the principles, or points, of the new digital territory that we are traversing, emphasizing the cognitive shifts that such transition entails (the creative deformation). The chapter will try to account for the spatial felicity of the nests and shells that we have imagined, attentive to the nuanced phenomenology of Bachelard. We do not want to propose a return to phenomenological discourse, which is certainly a form of mysticism, but simply to use Bachelard's sensitivity and intellect to interrogate the possible value of such architectures after some ten years of

digital speculation (simply that). Ultimately, though, it is texts like the *Poetics,* which are daringly speculative yet erudite, that offer not only a means of critically assessing such works, but of hinting at the necessity for reimagining not simply form but cognition itself. This is where technological change will impact most palpably on architectural production, and not through its literal appropriation as a tool—it opens new creative circuits.

IN THE SHADOW OF LEDOUX

In 1993 we were invited to produce an object at the scale of 1:1 on the theme of public/private space by Le Magasin in Grenoble. We looked back to the *oeuvre* of Claude Nicholas Ledoux, and considered, in particular, the spherical *House for the Agricultural Guards of Maupertius,* which offered a (then) radical vision of communal private space, and the *Bains at Chaux,* a redeployment of the ancient bath-house as communal public space for fraternal gathering. These spaces we collaged, a classic post-modernist operation, but we then worked with the shadows, the graphic margin, of Ledoux's media. In modeling the negative form, we used a condom filled with plaster as a generative medium, taking it to be the salient public/private interface of the present. Such process, which articulates a transition from *collage to morphing,* generated a curious curvilinear surface which we then interrogated as a model of contemporary public/private space.

It is a smooth, limitless surface—part public, part private—but where the boundary between them has dissolved into a series of undemarcated zones, it is as if one is free to circulate the world, alternately transgressing thresholds of publicity and privacy, or else circulated by media that involutes such demarcations.

In realizing the piece at full scale we then fabricated it as 365 sheets of plywood (figure 12.1), sanded smooth to create a continuous tensile surface, embedding the names of the sponsors into the grain of each ring. This created a very real social surface where each individual, free to circulate, is nonetheless trapped within his or her own circuit, measuring the distance from Ledoux's idealized fraternity.

Here a process of critical reflection, as to the origins of public/private space, developed into an open-ended generative process from which emerged a form that was resonant, yet in an entirely non-representative sense. It is a form that has not been generated from without as a prescriptive geometry, but has been "secreted," as it were, by a genetic evolution. In fact, the process of squeezing condoms gave birth to a series of self-similar objects, sharing a base property conferred by the tensile membrane, which was "blindly" squeezed.

The reception of the piece gave us insight into the potential *latency* of architectural form, freed from the burdens of representative literalism, and also into new possibilities of aleatory creative *praxis:* it was as if the residue of process could be sensed but never assimilated—Ledoux both present yet absent. This, like Bachelard's descriptions of the absent body of the mollusc, is suggestive of forms of traumatic reception, trauma occurring as a lack of assimilation, an absented reference.

As a non-standard geometric form, the object seems to have anticipated an emergent tendency, but the very difficulty we had in creating its complex curved form led us to develop precise rather than arbitrary methods of form generation in later projects.

ETHER/I

Invited to produce a sculptural piece for 50th anniversary of the United Nations in Geneva, we dwelt on the nature of the organization as being one that is essentially *inexpressive* in its coming into being only at a moment of failure, a breakdown of human relations. We devised a generative process that began as an interrogation of the most basic coming-together of two people—a couple in a duet—whose movement we registered through video capture. We worked with a sequence of William Forsythe's "Quintet," where five bodies endlessly couple and uncouple as a mesmeric portrait of inconsummate tension, a dance which itself has been called "an architecture of disappearance."

We mapped three sequences of movement, capturing complex trace-forms of movement-in-time, as a form of post-Muybridgean plasticity, the frozen video images merging spatially in the matrix of the computer. But we further evacuated the representative sense of the process in extracting the difference between attempts at a repeated sequence, eliminating the "positive" trace of the "negative" dance (figure 12.3). This was a mapping of the inability of the body to repeat a precise choreography, the essential element in a live performance now rendered visible at a new threshold of technical precision.

The final object was back-focused as a double skin of tessellated aluminum (figure 12.4), a luminous and ephemeral surface. It marked the moment at which a process of critical reflection gave birth to an open-ended creative process, which we then allowed to develop, sampling its evolutive potential. Here, since the process derives from an environmental "gathering"—a literal thickening of materiality around a body in motion—we would liken it more to Bachelard's category of the nest, which also suits its febrile luminosity. If the shell-form is a heavy and bodily secretion, built up from the earth, the nest is a material densification in space, plucked from the air.

The resultant form has been referred to as a *hyper-surface,* yet the prefix *hypo-* is more apposite in capturing its inexpressive or evacuated sense, which nonetheless carries an imbued interpretative latency. The resultant form, one of a sort of *smectic* immateriality (an interstitial liquid-crystal state), is one of *precise indeterminacy,* a trace of an absent presence.

Again, we remark the suspension of what one might call the "autoplastic" determinism of traditional design strategies in preference for the "alloplastic" indeterminism of such open-ended process, which we capture in the appellation, *Ether/I:* the dissolution of the creative self.

12.2. *Ether/I* (1995), United Nations 50th Anniversary Exhibition, Geneva, Switzerland, architect dECOi.
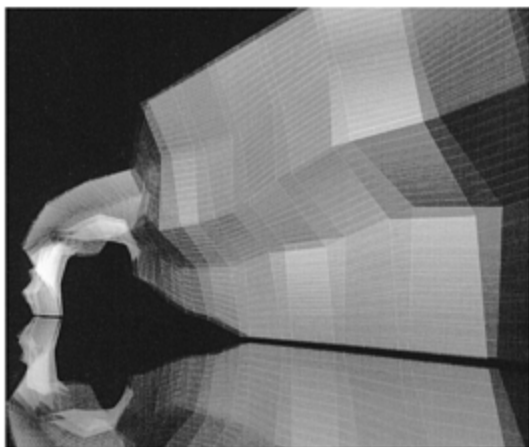
12.3. Ether/I, mapping the sequences of choreographed movement.
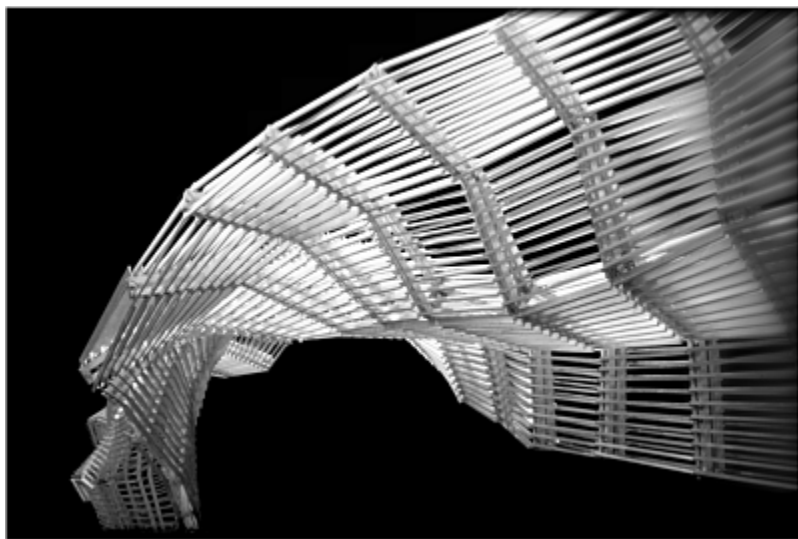
12.4. Ether/I, the double skin of tessellated aluminum.

HYSTERA PROTERA (STUDIES IN THE DECORA(C)TING OF STRUCTURE)

This process-based project developed as a reflection on new generative possibilities offered by computer-aided design (CAD), using three-dimensional mapping and morphing techniques to project lines on animated amorphous forms, giving sequential traces of displacement or movement. This created fluid cyclical series of three-dimensional *glyphics* (not graphics because their content seems indeterminate), as decora(c)tive trace-forms or

spatial patterning (figure 12.6). These we termed *trappings* for the double sense of decoration and movement-capture that is implicit within their form. Morphing the original gave rise to series and series of distorting analphabets which hang in space as layers of three-dimensional motifs, related through their mutual, yet absent, progenitor.

Such endlessly genera(c)tive potential offers hitherto unimaginable formal complexity, and the potential of architecture moving into fully three-dimensional space (spatial structure/surface assemblies). In this sense the project surpasses the time/movement trace/form of *Ether/I,* which, while effortlessly capturing an unfolding movement through space,


12.5. *Hystera Protera* (1996), graphics commission for the Public Art Commisions Agency, London, UK, architect dECOi.

required a flattening back into the two-dimensional plan/section to allow construction. Here, since all trace-forms derive from a standard origin or formwork, they may, in principle, be quite simply constructed as fully three-dimensional figures in space.

This passage from two- to three-dimensional potential seems to demand that a certain ideology of control be let slip, since the process is necessarily one that releases forms that are, as yet, unpredictable in their formal complexity. The project suggests, therefore, a *hysteron proteron* (a suspension of natural or logical order) within the open-ended creative process, which we here refer to as *Hystera Protera,* as a temporally-generated cave-form/writing, involuting or invaginating continually. The forms are as much process as product, marking the transition from form to norm (to the potentiality of form held in an informational matrix) and the release of *hyster(a)ic* formal strategies…

One senses a "felicitous" deployment of digital genesis here that offers a delicious correlative to the spatial propensity of the nest- and shell-forms of Bachelard's projected imagination. It is as if there were a bizarre genetic code at work, or a convulsive and amorphous body secreting spatially, inhabiting the digital machine…
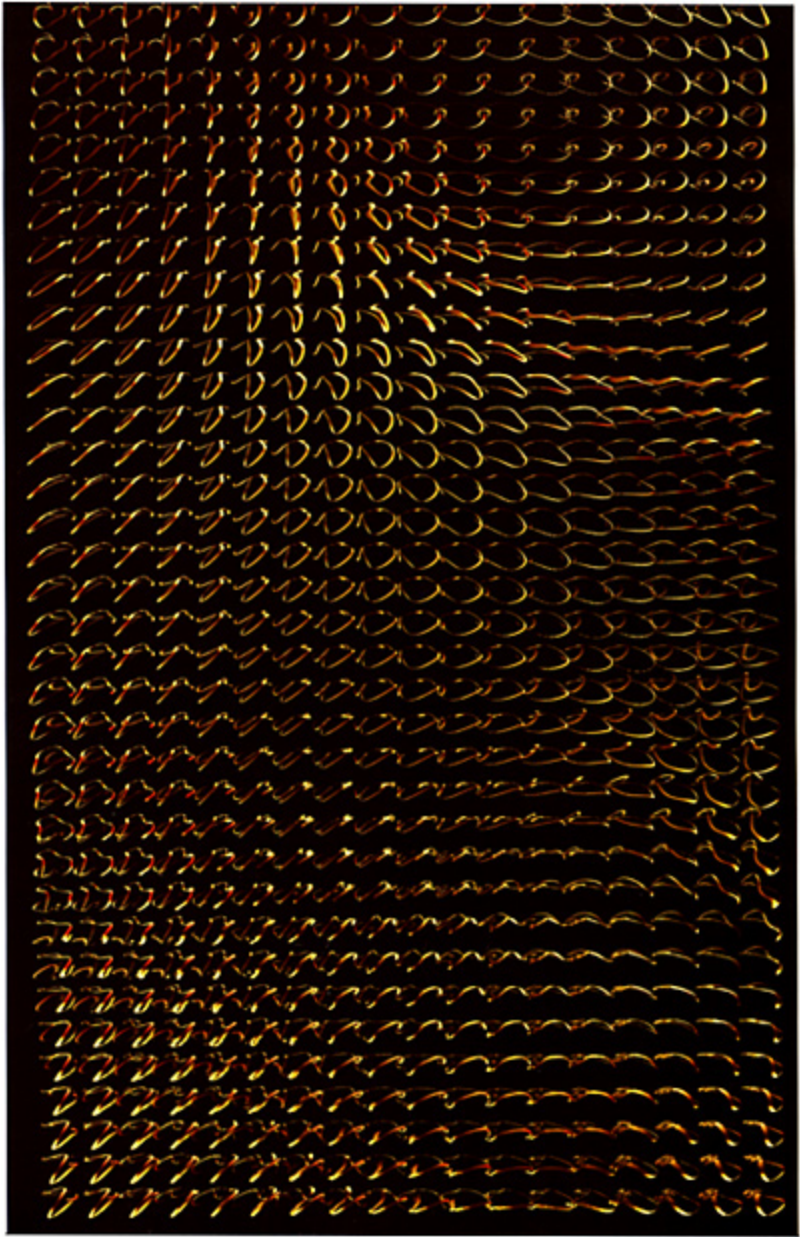
12.6. *Hystera Protera:* cyclical series of three-dimensional *glyphics*.

12.7. *Pallas House* (1997), Bukit Tunku, Malaysia, architect dECOi.
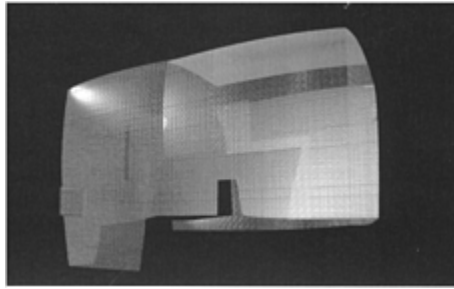
12.8. *Pallas House,* the panels of the complexcurved perforated screen were to be CNC machined and cast in a metallic or resinous material.

PALLAS HOUSE

The *Pallas House* was designed as a family house for the director of a development group in Malaysia eager to explore new possibilities of construction enabled by information technologies. Its site was on a densely wooded hillside on the edge of Kuala Lumpur, the client being a young couple who asked for an otherwise quite traditional family house.

Formally, we have followed the local precedent of providing a shroud as a filter to the harsh tropical climate, wrapped around a raised internal dwelling-space, but liberating the tradition of "pitched roof and hanging blinds" in suggesting a complex-curved perforated screen. In so doing, we have limited the elements of experimental construction to a series of sweeping earthworks (which would require sophisticated modeling to allow formwork to be built), and an external decorative screen, which we intended to be fabricated by a numerically controlled machine (in either case decorative rather than highly functional elements). The remainder of the house, wrapped around a central atrium, and entirely naturally ventilated, proposed rectilinear glass/ masonry assemblies familiar to the local builders.

Both the landscape and the external skin were generated using *Objectile* software, which has been developed to directly link a mathematically-driven three-dimensional modeling

software with numerically controlled machines, allowing direct production of complex and non-standard building components. The proposition was to take the experimental work of *Objectile,* who had derived numerous experimental test-pieces as complex machined plywood panels, into full architectural production. The surface was therefore devised as a series of complex-curved shells, which implicitly meant that no two panels were alike, and demanded the non-standard manufacturing potential of post-industrial processes. The complex-curved forms were nonetheless generated formulaically such that should such process prove too expensive, the façade might be realized with flat rectilinear panels, with the surface defined as one in which any rectangle placed on it would have planar coincidence through its four corners. We then generated a series of decorative motifs (several series) by the *trapping* of lines on rotating solids, which were to serve as perforations to allow for the penetration of light and air, and to give an animate heave or flutter to the surface. The panels were to be routed in wood and then cast in a metallic or resinous material (figure 12.8). This process was eminently feasible, if as yet expensive in its experimental character.

The house is suggestive of the potential offered by computer generation and computer numerically controlled (CNC) manufacture for new possibilities of decorative and non-standard form, hinting at forms of (now numeric) craft. The formal expression seems to be straining away from the highly abstract register implicit in forms of industrial manufacturing process towards a much richer and more exotic animate potential. We worked hard to derive motifs that were acceptable to the (Chinese) client, adopting a form of "uni-décor" typical of the excessive, richly-carved dragon surfaces of ancient Chinese ceremonial bronzes, but pressing our new technological capacity into a directional and non-standard possibility. The motifs added a breathing quality to the skin, opening to the east to allow penetration of morning light, and closing to the west to protect against the harsh afternoon sun, implying a sort of frozen climate-responsiveness. What seems most interesting in such open-ended digital sampling is the curiously *inexpressive* and *plastic* quality of the resultant form, which in this context we thought of as an *Asiatic*—other, that is, than that offered by a *determinate* creative process.

The *Pallas House* is evidently a shell-form in its algorithmic fomentation, its curious organicism a byproduct of a precisely-indeterminate process. The heavily-fluid surface, cast in molten metal, seems an appropriately sedimentary and mineral process of formation. Yet it also seems to have affinities with the category and character of nest-forms, since it is a protective wrapping that "gathers" its character from the environment around it, as a luminous and perforated filter.

In commenting on the essential characteristic of shell-forms as being their *derivation from within,* hence not reducible to a simple external geometric description, Bachelard's invocation of the mollusc's motto—that *it is necessary to live to build one's house and not to build one's house to live in*—seems apposite. The striking inversion of determinacy that he posits—that designing shells from without as an "intentional" strategy is flawed in its failure to capture the essential shell quality—supports the curiously internalized complexity of generative processes from which emerged the design of the Pallas House carapace. Climate, culture, animation and mathematics are all implicit within the thickness of the surface, a hanging shroud of absented progenitors…
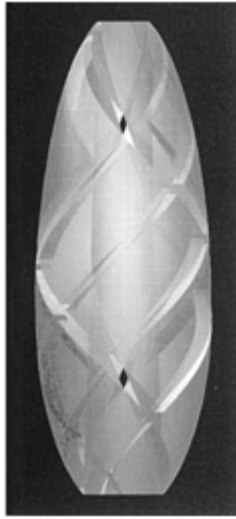
12.9. *Swiss Re* (1998), parametric study for Foster and Partners, London, UK, architect dECOi (with Mark Burry).

FOSTER/FORM I: SWISS RE

Invited by Norman Foster to suggest new possibilities of computer modeling to assist in their development of various formally-complex projects, we were given an opportunity to investigate mathematical and parametric modeling. In association with Professor Mark Burry of Deakin University (responsible for the "parametric" modeling of Gaudí's *Sagrada Familia*), Peter Wood of the University of Wellington (programming), and Professor Keith Ball of University College London (a mathematician specializing in complex geometries), we developed an "elastic" modeling program for creating variable forms of "egginess" (the form of the Swiss Re building, figure 12.9). The specific challenge of the project seemed to be to understand the particularities of such a complex-curved surface in order that as large a proportion as possible might be tiled with quadrilaterals (Fosters' preference) with entirely coincidental edges in order to standardize the details. Our goal, however, was to go further than an analysis of the complex relational geometries, required by such formal constraint, to develop a flexible modeling tool that would allow rapid reiterations of the surface according to the various forces (political as well as structural) acting to modify the form throughout the design process.

This led to an elegant mathematical description that articulated the necessary relationship of intersecting spiral helicoids with the form of the egg itself, the parameters of which then fed into a scripting program which would run as an add-on to standard architecture modeling software. This allowed the form to be easily finessed and the implications on the façade geometries to be rapidly comprehended.

While remaining a purely formal study, the project was rich in its suggestive potential for forms of relational modeling that offer precise yet flexible descriptions of complex

surface geometries. These have been pursued as fully creative possibilities in such later projects as our studies of the *Gateshead Regional Music Centre* (Foster) or our design of the *Paramorph, Gateway to the South Bank*.

FOSTER/FORM II: GATESHEAD REGIONAL MUSIC CENTRE

This study carried forward from the work done on *Swiss Re,* attempting to turn what was an essentially analytical model into a fully creative tool. The form of the *Gateshead* project was essentially defined as a complex-curved carapace, whose surface swelled differentially over each of the three theatres below (figure 12.10). The implicit challenge was to find ways to allow such apparent formal complexity within a highly restrictive budget. Our approach was to develop a mathematically-driven parametric tool that would not only allow for a clear understanding of the surface geometries (whether it could be tiled with flat rectangular sheets, for instance), but to permit rapid reconfigurability of the form such that it could be simplified or shrunk to suit the (perhaps variable) dictates of the budget.

The sensual, flowing forms that we derived resulted from a series of form-finding experiments where we did not so much "design" the form as to create methods by which the form could find itself—as a series of forces acting on elastic surfaces. This has again inspired and then has been informed by a series of "parametric" descriptions of the project, where we have not designed an object as such but have devised a field of parameters which describe the *possibility of (a) form*. Such process was aided by a clear understanding of the parameters of the project, which were already established, but it has enabled a series of elegant, fluidly indeterminate forms to be derived, which are nonetheless highly precise, since we worked with mathematicians and used highly accurate three-dimensional engineering software (Cadds 5).

Again, this project marks a shift away from auto-determinism as a creative strategy, allowing that such a phantom birth might nonetheless give hyper-precise construction information and considerable potential for effortless variability of a complex form.
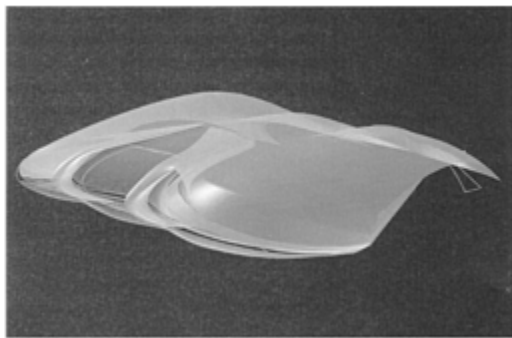
12.10. *Gateshead Music Centre* (1998), sketch design for Foster and Partners, architect dECOi.

12.11. *Aegis Hyposurface©* (patent pending) (1999), Birmingham Hippodrome Foyer Art-Work Competition, UK, First Prize; commissioned, architect dECOi.

12.12 and 12.13. *Aegis Hyposurface:* a dynamically reconfigurable surface capable of real-time responsiveness to events in the surrounding environment.
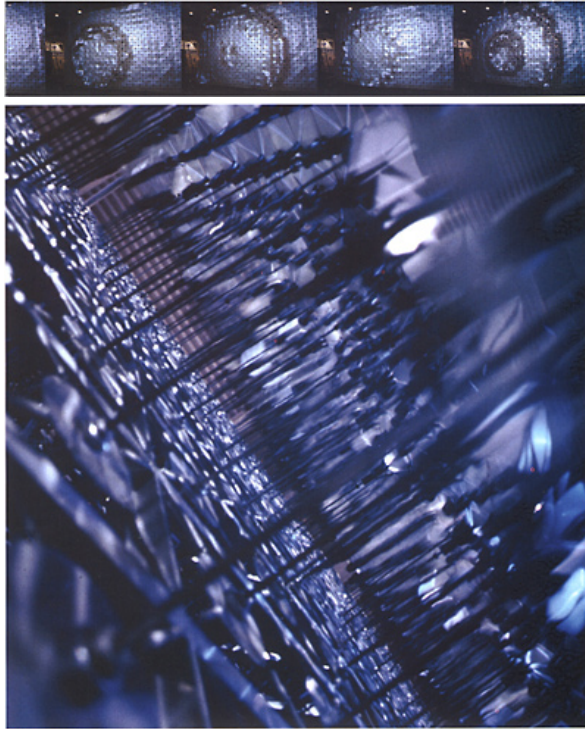
AEGIS HYPOSURFACE©

The *Aegis* project was devised in response to a competition for an interactive art piece for the cantilevered "prow" of the *Birmingham Hippodrome* theatre. *Aegis* was proposed as a dynamically reconfigurable surface capable of real-time responsiveness to events in the theatre (figure 12.11), such that movement or sound can create actual deformation of the architectural surface (figures 12.12 and 13). Effectively, *Aegis* is a dynamically reconfigurable screen where the calculating speed of the computer is deployed to a matrix of actuators which drive a "deep" elastic surface. The implicit suggestion is one of a physically-responsive architecture where the building develops an electronic central nervous system, the surfaces responding instinctively to any digital input (sound, movement, Internet, etc.).

The development of the project has been interesting in that it has demanded the collaboration of different areas of technical expertise, from mechatronics to mathematics, challenged to devise an operating system capable of deploying information at the necessary speed to create dramatic animate potential across 1/000 actuators. Yet our fascination (as architects) has been to begin to qualify the *cultural* affect of such a device, in its capacity to offer an extended potential to the field of kinetic art. What it highlights most evidently, perhaps, is that in considering new possibilities of a now dynamic decora(c)tive potential (where all previous forms of pattern or ornamentation can be deployed temporally, morphing from one to another, for instance) the effective use of such a device will demand an understanding of the "psychologies of perception" enabled in the performative capacity of electronic systems. This is to suggest that the literally animate character of a dynamic architecture is as nothing compared to the implicit animatism that might be activated, animation reliant on a figurative ambiguity whose limits can be negotiated temporally to gauge their affect. At what moment, for instance, does a pattern become distinguished as a writing, or an abstract figure become significant?

The project is called *Aegis* for its capacity to absorb events from the surrounding environment, allowing that its expressive register be colored differentially according to the patterns of activity which surround it. One thinks, of course, of the aegis of Athena, which alternated between defensive and aggressive character, sometime cloaking shield or warning device. Athena would weave into the aegis trophies of her conquests (the skin of Pallas, the head of Medusa) as well as everyday objects such as feathers or scales. This gave the supple surface not only a variable character, but one that drew from the surrounding environment. This has led us to consider the object, which is nothing other than a matrix of possibility (of form) conditioned by external response, as an "alloplastic" device or an architecture of reciprocity, reconfiguring in response to the activities that impinge upon it.

The current specification of the device is one of 8 m × 8 m, comprising 1/000 actuators refreshed every 0.01 seconds (figure 12.14), allowing propagation of effects at some 60 km/h, with a displacement of 50 cm at 3Hz. This highlights the potential of current technologies where already many thousands of devices may be controlled accurately to allow a physical responsiveness to objects. As such, *Aegis* is a step towards nanotechnology, suggestive of an entirely other formal universe to come—one of dynamic potentiality of form.

12.14. *Aegis Hyposurface:* 1/000 actuators are refreshed every 0.01 seconds.
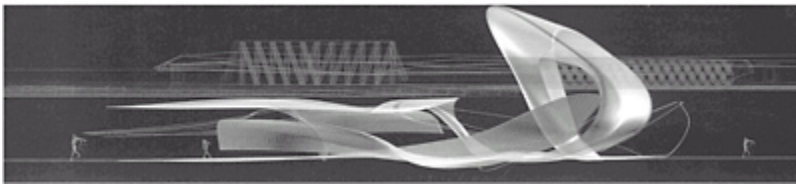
12.15. *Paramorph* (1999), *Gateway to the South Bank* Competition, London, UK, architect dECOi.

PARAMORPH

The *Paramorph* was developed in response to a competition to devise a *Gateway to the South Bank,* the site being the forlorn Waterloo station entrance of the pedestrian route connecting the major cultural institutions of the South Bank. The site itself comprised a small plaza (Sutton Place) and a pedestrian tunnel underneath a Victorian railway viaduct (Sutton Passage).
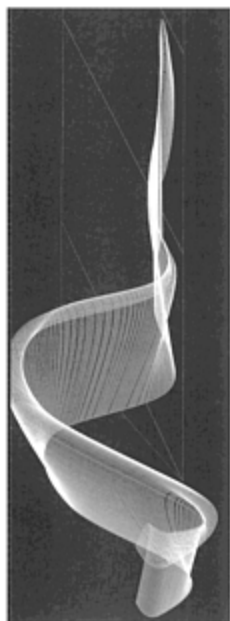
12.16. *Paramorph:* one of the contextual mapping strategies.

Our gateway derives from a series of contextual mapping strategies, where sound and movement models have been taken as environmental "samplings" to generate form (figure 12.16). In this we concentrated on non-visual aspects of the site, producing mappings which revealed its dynamic rather than static character, time becoming actualized in the exploratory process. The physical context was uninspiring, and it was the movement and sound within the tunnel that gave it its particularity. This derived a constantly-evolving formal solution for a gateway-in-depth, genera(c)ting series upon series of sheaths, sheets, shell-forms, etc. as a quite open process of discovery from which a "final" form emerged as a distillation of such processes. The mappings were revelatory and dynamic, a series of strategies which were aimless but cogent in deriving a series of formal solutions, each of which propagated the next The "final" form folds down from the scale of the public plaza to the quite constrained passageway beneath the viaduct as a languid spatial vortex, a condensation of the dynamics of the site itself.

The *Paramorph* is conceived as a series of tessellated aluminum surfaces that act as host to sound sculpture, imagined as morphings of site-sound, and released in response to the movement of people through the space (figure 12.17). These are deployed by temporal relay such that the generative process continues into the actual architectural effect- one of an endlessly distorted redeployment of the dynamics of the site itself. Such transformation of the ambient environment feeds back into that same environment as a temporal condensation—a distillation of sensory effect.

The *Paramorph* and the *Aegis Hyposurface* mark the furthest points of our exploration of possibilities of architectural *reciprocity* released by interactive electronic processes: the cultural gateway becomes a registration device of patterns of daily activity.

   The developmental process of the *Paramorph* was accompanied by the creation of customized parametric models that offer possibilities of "elastic" geometric constraints (Mark Burry at Deakin University). This effectively embeds a geometric property into a descriptive model as a sort of inviolable genetic code, which then informs the various reiterations of the form that we apply. Such a "smart sculpting" device allows us to facet, rule or "NURBS" (Non-Uniform Rational B-Splines) the surface such that, at any moment, we can precisely control the geometries of the form, allowing it to be built with straight-line sections, for instance, or flat facets; the form seems fluid but is, in fact, highly constrained. Hence, we are able to offer transformative reiterations of the form, each self-similar but different, and this allowed us at the time of the competition to confirm the feasibility of construction and have a contractor who had accepted the (low) budget!

   A *Paramorph* is an object or organism that, while keeping the same basic characteristics, adopts different form(s). The entire project, both in a productive and receptive sense, is again suggestive of the transition from autoplastic to alloplastic space offered in the transition to a now electronic creative/receptive environment.
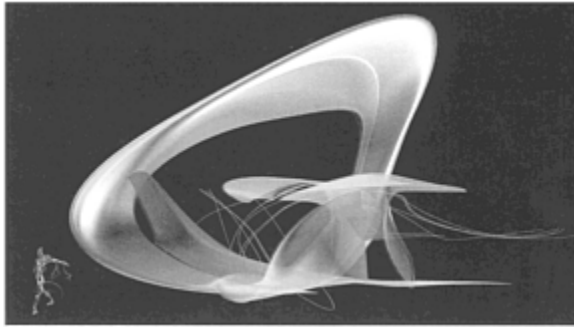
12.17. *Paramorph:* view from Waterloo station.
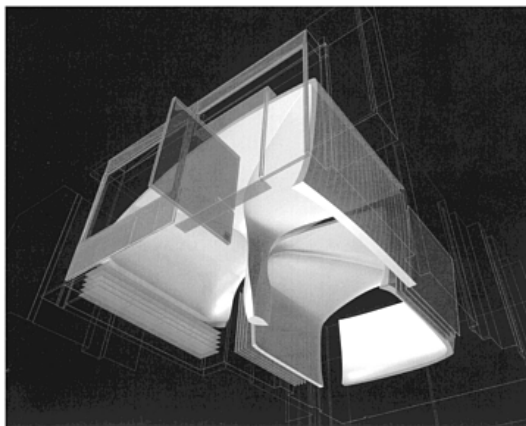
12.18. *Blue Gallery* (1999), London, UK, architect dECOi.

12.19. *Blue Gallery.* the basic framework was cut from sheet aluminum.

12.20. *Blue Gallery.* the aluminum framework was sheathed in aircraft ply.

BLUE GALLERY

The design of the *Blue Gallery* subjects the ubiquitous white box to a plastic deformation, distorting (quite literally) the norms of artistic presentation. The surfaces of the gallery remain relatively neutral, but they carry a latency which causes them to gather as lines of force, as if the entire space were one of *spatial stretching*. The gallery surfaces are articulated as two morphing shells which mutually distort as they merge (figure 12.18). The point of fusion occurs as a "dropping point" where the ceiling surfaces gather and fall to earth, as if the very perspective of the gallery itself were being liquefied, the surfaces pulled to earth. The mutual distortion caused by the two shells imparts an *animism* to the space as if the surfaces were still in the process of formation.

The effects of such morphing are quite subtle, to be sensed as a background energy, but creating a range of opportunities for the exhibition of both sculptures and paintings.

Certainly, the architecture exerts an influence on the artists, but as a gentle challenge to convention rather than a radical disjunction.

The fluid form has been modeled with a NURBS software so that precise full-size cutting patterns could be given to the fabricators. The basic framework (figure 12.19) was cut from sheet aluminum, sheathed in aircraft ply (figure 12.20), and the entire surface then coated in a seamless glass-reinforced plastic. This gave surfaces that were highly resistant and flexible, allowing for heavy loadings on the cantilevered planes of the walls.

The project represents, in its modeling as in its materiality, new forms of architectural *formation*. It is *minimal yet decora(c)tive,* suggestive of new genres of curvilinear possibility. Yet it is not its non-standard geometric form, nor its innovative technical investiture, in which lies the essential force of the project, but its implicit disturbance (one might say *deformation*) of the cultural norms imbued in the hermitic space of contemporary "art" space. Our hope was that it would animate what had become an ossified type-form and its conspiracy of neutrality! This it did in that the artists refused to engage with it to the point of demanding its destruction, which occurred only three days after its opening! Perhaps in its unassimilability by the artists, it most palpably captures the inherent trauma that Bachelard locates in the shell-form, the luxuriant *horror-vacui* of an emergent form as spatial trace of bodily adaptation…
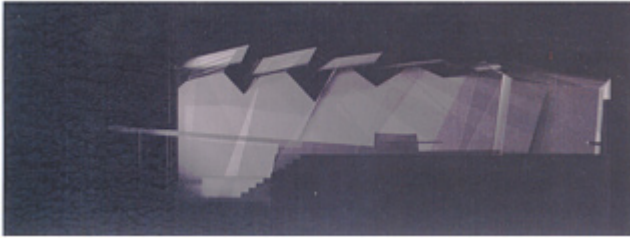
12.21. *Dietrich House* (2000), London, UK, architect dECOi: section through main space.

DIETRICH HOUSE

The *Dietrich House* is an extension to an existing London townhouse (figure 12.21), where we have proposed to infill the dark and narrow walled garden with a top-lit living/dining space. The client, an architectural publisher, encouraged us to advance our research into the new formal possibilities offered by digital modeling techniques.

The project marks an attempt to attain a compelling spatial geometry but as a highly constrained and rational "diagram" conforming to the severe budgetary limitations of the client. Beginning from a pure rectangular space, defined parametrically, we have deformed the building envelope to allow for drainage, ducted air and storage space, producing a series of warped trapezoidal frames in the margins of which such functions are

accommodated. Such "elastic" process, sampled successively, has given birth to a crystal-line form of facetted white surfaces (plastic and plasterboard), as if the elegant (and fluid) modeling of constraint were giving birth to excess! The serial deformation shifts the interior volume differentially, creating an animate interior volume of folding planar surfaces, bathed in natural light. The project, which follows on from the parametric studies of the *Paramorph,* demonstrates the opportunity for an enriched formal vocabulary released by open-ended digital processes, while within a highly constrained budget.

Ideally, all surfaces would not only be cut by a CNC machine and the templates derived automatically from the generative software, they would be also lightly incised with a secondary graphic that would catch the light obliquely, floating the surfaces as a suspension of delicate motifs. Such spatial suspension, coupled with the slight shifts in the angle of the surfaces, intends to offer a proprioceptive heave that further opens the luminous space.

12.22. Excideuil Folie (2001–2), Excideuil, Perigord, France, architect dECOi.

EXCIDEUIL FOLIE

The *Excideuil Folie* has been commissioned without any "brief" as such, and in an essentially unremarkable rural context. Indeed, the only "context" that seemed of cogent interest to the client body (farmers) were the limestone caves beneath the site, a phantomatic (unvisited) spatiality.

We have therefore attempted a *digital cave,* looking to create an inflection of the landscape to pocket space as a minimal but spatially incisive gesture. We have worked with five splines, "primitives" of digital systems, twisting them serially to create notional shelter, and orienting it according to the parameters of exposure, view, traffic, etc. This created a restless *paramorph,* its defining exoskeleton a three-dimensionally articulate model that could be globally varied in deference to any of the design forces impinging upon it.

Ultimately, we have facetted the mollusc form to generate a structure-surface that is a coherent three-dimensional shell (figure 12.22). The plates of the shell separate as a sectional thickness to give structural depth, the parametric malleability enabling us to vary the thickness according to structural needs, deploying the material efficiently.

Such a *context-machine,* able to inflect according to the influence of a variety of local conditions, also carries the latent capacity to be a *structure-machine,* offering the possibility for highly articulate three-dimensional assemblies that are structurally efficient. The cutting patterns of the fiberglass triangles are genetically linked to the transmutable paramorph, offering a seamless connection between the open conceptual design and the precise fabrication process.

12.23. *Handlesman Apartment* (2002), London, UK, architect dECOi.

12.24. *Handlesman Apartment:* one of the digital study models.

HANDLESMAN APARTMENT

Following on directly from the research and development work of the *Excideuil Folie* is a tower-top apartment extension in London (figure 12.23), which has been developed as a continuation of the parametric propensity hinted at in the previous projects. Here, a dramatically animate space has resulted from a consideration of a range of "contextual" factors: thermal laws governing the amount of glazing, planning restrictions as to the volume of any extension, and structural and constructional factors demanding a rapid and lightweight intervention. These specific constraints are brought into play with the more general "contextual" concern as to the "look" of such an extension in so prominent a location.

Again, such constrained elastic modeling offers the possibility to alter the form actively in response to a variety of practical, legal, political and aesthetic factors. The complex form (figure 12.24), deploying three-dimensional structure/surfaces, announces the possibility of efficiency within a greatly expanded formal register: the structural engineers can alter the form, and fabrication information automatically updates by virtue of a globally-constrained modeling. The project will be fabricated from fiberglass triangles, glass panes and fabric blinds, the entire surface responding actively to the changing environment as a "breathing" skin, digitally alive.

We see it as a knot of gathered contextual forces, which may be loosened or tightened according to choice, no longer "designed" as such, but a variable model to be sampled and edited as a temporal transformative genesis. In this environmental "gathering," wrapping a density of structure/surface around a bodily impulse, as a light yet rigid assembly, the apartment seems to offer uncanny correspondence with the spatial descriptions of nests offered by Bachelard. Here, perched atop a tower, and responding to the swirl of contextual forces impinging upon it, a compellingly animate spatiality emerges from within the digital mix. Perhaps it is here, in the cohabitation of efficiency and excess, and in the release into three-dimensional assembly, that a legitimate glimpse of a new digital propensity-in-form is revealed.

Bachelard asks after the motivation of birds in their instinct to build nests, poised precariously between danger and comfort. He concludes that the impulsion constitutes a form of optimism, a vital dexterity brought to bear in negotiating with an imperfect materiality, fragile and compromised yet ambitious. For Bachelard, the nest carries a life-giving impulsion in its balance of insecurity and security, and the felicity with which it cocoons the vulnerable bodies within. As a spatial category, it carries a vital force of innovation and renewal.

CONCLUSION

Frequently over the past ten years I have been exhilarated by what seems the promise of a new possibility for architecture or for architectural production allowed by the advent of digital systems. Yet, equally frequently, I have felt our efforts to be utterly futile in trying to establish legitimate architectural principles aligned with such technological change. I have no doubt that the transition from mechanical to electronic systems is a technological change of enormous significance, and that one might therefore expect new possibilities for both architectural form and *praxis*. Yet my invocation of Robert Scott's prescribed failure,

born of his inability to rethink the basic principles of operation within a new territory, highlights the danger of constraining digital technologies to current expectations of architectural form and to extant modes of *praxis*. Amundsen seems to exist only as a phantomatic possibility as yet, since I see no such streamlined or In(t)uit-ive *praxis* emerging; indeed, Amundsen's goals were essentially the same as Scott's.

Whenever we (dECOi) have allowed our production to be constrained by the norms of quotidian software, we seem to fall into a macabre hypnotism, producing ponderous and uninspiring blobs simply as a grotesque distortion of standardized norms. Effectively, one has in no way surpassed the technological mandate of the pencil—that of forms of determinate inscription, and the "design" strategies attendant on that. Pronouncements of architects as being "digital," and the apparent optimism of such a pronouncement, requires that the new territory be *thought as such,* which suggests learning from those who already inhabit it effectively (programmers, mathematicians, etc.); these have long since recognized the algorithmic, programmatic and parametric nature of such technology. Yet these offer no qualitative notion, *no image (or pole) of technology.* even its promise of efficiency is mythic if considered on a cultural plane, for it merely opens new planes for the intellect to traverse. It is *the desire for technology in architecture* that seems our only really legitimate focus, which drives our intellect; the attainment of digital proficiency is an important but entirely secondary affair.

My invocation of Bachelard should serve as another warning to digital hypertrophy in his realization that scientific rationalism provides no legitimate potential for cultural renewal, but curtails expansive imagining. It strikes me that the architectural scene has bifurcated between the techno-rationalists (who preach a determinate machinist erotic) and the techno-lunatics (who tempt an indeterminate formal speculation). The latter, flirting with new modes of *praxis,* seem the ones more genuinely liable to produce "images" of cultural renewal, but Bachelard's demanded for "felicity" requires a prescient imagination (not a recklessness) that is attuned to the spatial and social potentials released by such systems. Certainly, I share Bachelard's sense that the attainment of any cultural "image" requires a realignment of creative imagination that frequently requires a requalification of the creative process. His speculative account of the use of spatial thinking by poets, I use not simply to qualify the particular spatial qualities of our architecture, but to insist that it is in the yearning for hitherto "uninhabited" cognitive space that a genuinely transgressive digital architecture might be born, imbued with formal, spatial or material *quality.*

Oates' famous utterance (and epitaph) on leaving the tent- "I may be some time"—is then perhaps the salient expression of such attempts to requalify architecture in light of digital technologies. Indeed, I believe we have not yet seen a sufficiently "felicitous" architecture to pronounce itself as such, the figure of Amundsen seemingly the mere phantomatic "other" that haunts our flounderings. I venture that it will indeed take *trauma* to establish legitimate principle in the desiccated and immaterial digital territory that engulfs us, and an intellect capable of a ranging "phenomenological" richness…

ACKNOWLEDGMENTS

13
MAKING IDEAS

BRENDAN MACFARLANE

INTRODUCTION

The tools we use today are digital—their impact on our times is undeniable. It is always the case with whatever we create—the tools are somehow an undeniable part of the product. These new tools give us new ways of seeing, new eyes—possibly a new future—almost to the point where one can think digitally. The screen becomes the body; only the gesture now becomes a translated thing—a thing outside of itself. And with this digitalization of everything around us, we have found a common way of linking such benign relations as between, for example, a gust of wind and the spiraling trace of a leaf, a richer way, we believe, of describing things outside of their usual definitions where architecture becomes part of the whole—beyond just its own egoistic interests but now describable in a very technical way, a very objective way, no longer just a propositional notion, but also in a very real and exact materialized way.

Now, if one starts to stop and think as an architect—our office being one that lives in the strange interworld between creation and fabrication—of the implications and applications of this way of communicating, then it seems we are moving into a very exciting period of creativity where everything will be much more interlinked and part of a rich and interwoven puzzle.

Making ideas—can ideas be made? Can one have ideas and can one make at the same time?

So, what is the relation between the idea and its fabrication in the age of the digital? Our research in making some of the following projects has also led us backwards into questioning the very idea. This is not new, only that it is an interesting thing to wonder in what ways the digital has influenced the very way we invent and think through a project and our ideas that come are also to be influenced, reformed, reworked, etc. I believe in the same parallel interest or a parallel question that Bill Mitchell describes in Chapter 6, when he discusses design worlds and fabrication machines. It is true that there is now an undeniable interest in the questions of fabrication techniques. Building before digital now seems somehow simpler and open to any number of controlled approximations. As digital projects have provoked complex form problems, the technical responses needed to build them have become a lot more sophisticated. This has brought about a greater interest in how a thing is realized. Ultimately, how the idea is somehow tested and developed becomes, with each project, an important factor. These interests in digital techniques for the architect, of course, have had parallels in other industries, such as the automotive and aerospace, where there has already been an interest for a long time before the building industry.

The architect, of course, also has other worries, notably those of specificity, language, culture, etc. But we cannot just discuss technique. Surely, digital architecture will be completely useful when it works for cultural, social, economic and ecological concerns. Ironically, we are presenting and discussing the digital, and at the same time a major ecological disaster is unfolding in Antarctica; economic, social and security issues are becoming worse for many at the ease of a few. How can a digital architecture start to engage some of these issues? This is not just a necessity, but where we also feel a truly important body of work lies. With the digital revolution has come the direct link between our office and other people fabricating the project, and ultimately the client and user—this is an experience shared by more and more architects. We are now in the situation of being in contact with different industries ahead of the project development, just to see how a particular project may be built or even developed in its very language.

The other interesting aspect to us is the question of emerging digital languages. We believe what should happen with the digital is that language should become more specific. With the arrival of the first generation products, there was and there still is a strong influence of a language that is biased towards "soft" forms; this cannot remain the primary interest. As digital techniques become more and more sophisticated, and are not just realized, in more and more projects there will be new tendencies away from the abstraction and neutrality of earlier models towards a real-world rendering and the manipulation of the actual and the existing, producing more unique works.

OFFICE

Our office is situated in Paris. We have built very little, but we take a certain pride in being small. We bring to our work not just the usual baggage of architectural culture and education, but a belief that today's architect has to be aware and connected with a huge array of sources outside of the profession. It is these sources that drive and help to inspire our work, coupled with the exacting issues of specificity. For quite some time our interests have been towards a light architecture, a porous architecture, a moving architecture, one that lets winds pass through a building, a building that wobbles, that moves, that speaks, that produces smiles. But what if a smile could produce the architecture? The event as
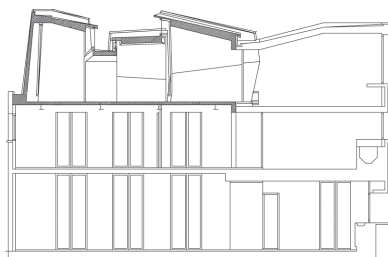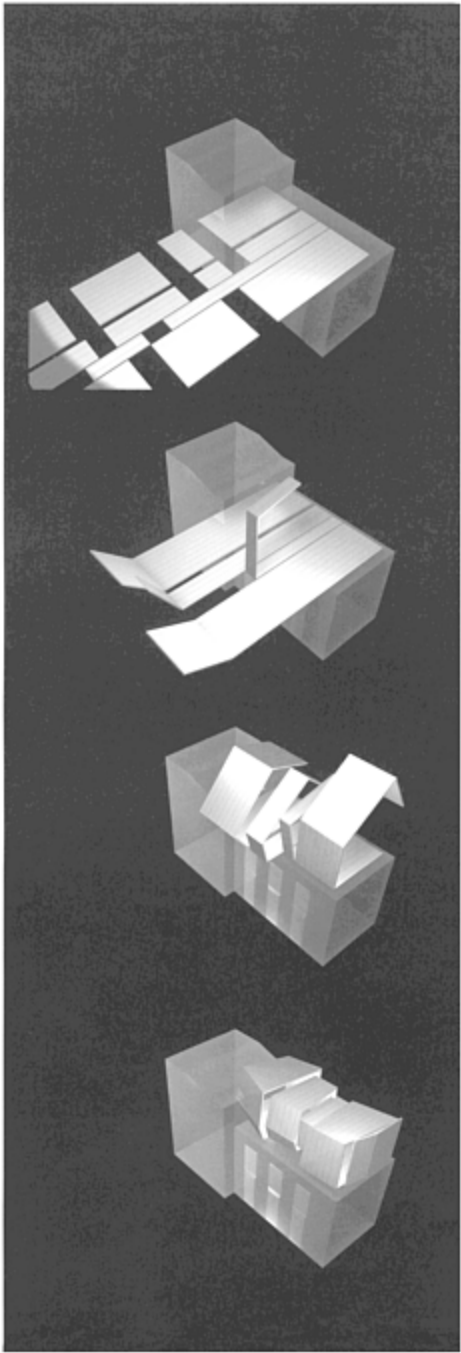
13.1–13.3 *Maison T* (1998), house addition, Paris, France, architect Jakob + MacFarlane.
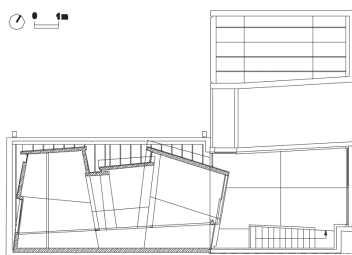
13.4. *Maison T:* floor plan.

13.5. *Maison T:* longitudinal section.

13.6a–d. *Maison T:* the generative process.

generator and the architecture as either a temporary thing or as more permanent, depending on the circumstance, not unlike the dreams of the happening and the performance, but now a resultant thing; architecture as something between the materiality of the house and the transience of a piece of clothing. Surely, as the digital world has given us new means of communication, we now have much greater precision to not only generate these kinds of responses, but also to generate the events.

MAISON T

The *Maison T* project is a small house addition (figures 13.1–13.3) that we did about five years ago in the suburbs of Paris. It was the last project we produced before going completely digital. For us, it was a pre-digital project with plenty of aspects that we could not have taken further unless we had had more advanced technology. We created and built this project using traditional building representations (figures 13.4 and 13.5), but had many problems of information transfer, and structural and skin definition due to these basic methods. The project demanded an intense on-site presence, with plenty of unknown problems. After this project, we were looking for a better way of creating and representing a complex form.

The idea here was to create new bedrooms for two boys on top of an existing house. The volumes came to express the emergence of the boys as they grew up, and were looking for an independent identity while still remaining within the family. We assumed the program for those two boys as the formal generator, each with their own specificities for view, light and privacy; the form was, therefore, being dictated by two things—from inside by the event and from outside by the skin of the existing roof, with its urban and functional constraints as an outer layer (figures 13.6a–d). So what we tried to do with the project was to build essentially from the components that we found under the roof, inside the roof, and the external layer of metal. What we did was to blow those up essentially, creating the volumes; the idea being that we did not want to import but we wanted to produce from what we had. That is part of our ongoing interests in some of the following projects.

13.7. *Restaurant Georges* (2000), *Centre Pompidou,* Paris, France, architect Jakob MacFarlane.
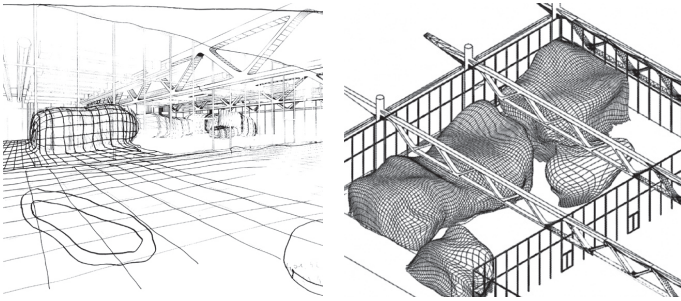
RESTAURANT GEORGES

What we learned on the *Maison T* project was important in our next project, *Restaurant Georges* (figure 13.7), which is a response to what we found to be the most provocative existing conditions at the Pompidou Centre. As we started this project, we moved, in parallel, the whole office into the digital. *Georges,* therefore, from day one was modeled and conceptualized using virtual representation. We found ourselves completely liberated and conceptually freer to explore this project. There was a kind of new momentum even behind the way we worked on this project, partially generated by these new means we had at our disposal. All of a sudden, three or four people could be working on the concept simultaneously, while being able to communicate using a common model or language (figures 13.8a–b), which is something we had never had before. The very way in which the office functioned changed overnight.

All we had as the site for intervention was the actual floor surface, which led us to conclude that by manipulating that surface we could almost blow the floor upwards, thus creating a series of "pockets" for individual functions (figures 13.9a–d). Our intention was to make an architecture of intervention, clearly inside an existing system, and to take that system and then, by reforming or deforming it, come up with the means of a dialogue between us and it. That was the overall guiding idea, but in order to follow and elaborate that idea we needed the digital means—without them the project would not have developed its soft form and would not have been realizable technically. In modeling and developing the project in its virtual state, we developed its vocabulary, its nature as a skin, its unique oddities, its presence, its built virtual nature, etc.

The restaurant is located at the top floor of *Centre Pompidou* (figure 13.10); part of the unique vocabulary of *Centre Pompidou* is essentially the huge air conditioning units, the water system, the electrical system—all of those codified in the color scheme of the period when the project was built, which was, of course, blue for air, green for water, and yellow for electricity. Particularly important for us was the fact that we could not intervene on any of the other surfaces but the floor, so we conceptualized the project by eventually appropriating the existing systems. It was an appropriation of the ceiling system and an intervention or deformation of the floor system.

In the early studies, we worked fluidly with conventional and digital media, going backwards and forwards. We would often pick up a pen and play around with a project (figure 13.11). That is only natural—we are so much freer by moving backwards and forwards with new means (figure 13.12). I am suspicious of when other people just show how "clean" they are in terms of the virtual world. Such "purity" simply is not true or necessary, whether we like it or not.
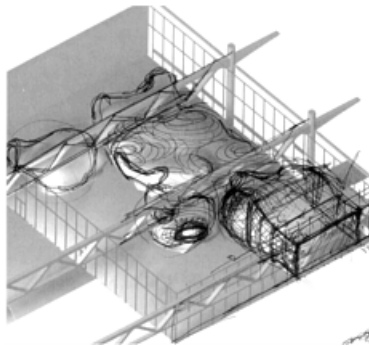
13.8a–b. *Restaurant Georges:* early conceptual sketches and models.
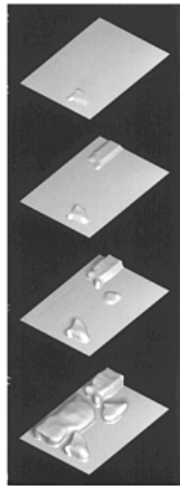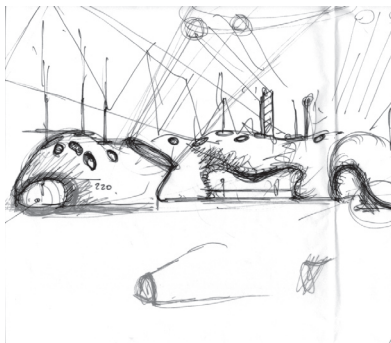

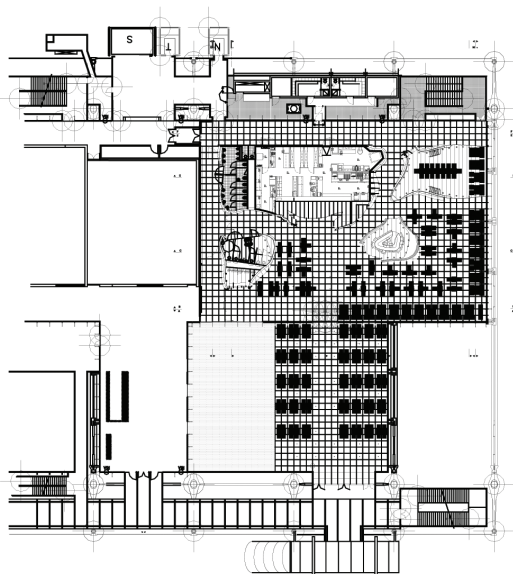13.9a–d. *Restaurant Georges:* the generative process.
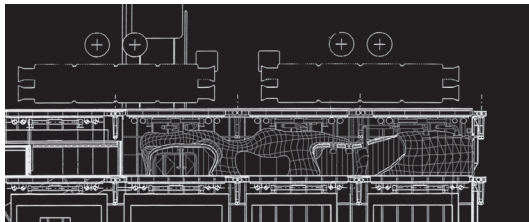
13.10. *Restaurant Georges:* cross-section through *Centre Pompidou.*

13.11. *Restaurant Georges:* one of the "hybrid" media sketches.

13.12. *Restaurant Georges:* one of the sketches done using conventional media.

13.13. *Restaurant Georges:* plan from the competition phase.

With regard to the history behind the project, we started with a program that was proposed by the *Centre Pompidou,* on which we won the competition. The proposition was for a restaurant that would give a new place to the city of Paris, and provide a new identity inside the *Pompidou*. We were actually involved as part of a much vaster operation aimed at a "renaissance" of the *Centre Pompidou.* The project, therefore, had a double service.

The interior space has the area of 900 m², and the exterior terrace 500 m², so the total is a space of 1,400 m² (figure 13.13). We broke the program into four volumes (figures 13.14 and 13.15). The first volume, closest to the entrance, is the coat check/bathroom volume. The second, the biggest volume in the back, is the kitchen volume. The third volume is a video bar. The fourth volume has a double function: one where the group of administrators at *Pompidou* can eat or entertain while the rest of the restaurant is open to the public, and the second one, when it is completely open on the sides and part of the public space of


PLAN DES VOLUMES ech:1/100 eme
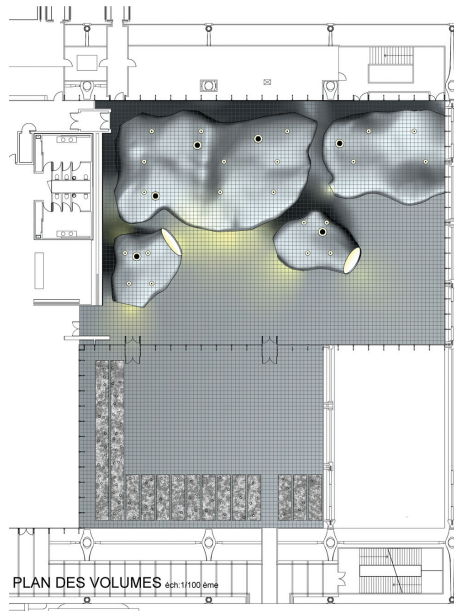
13.14. *Restaurant Georges:* the four main volumes.

the restaurant. The bar operates in a similar kind of way, as a gallery for video artists as well as being a bar. There were aspects to the whole project that had a double programmatic nature, which made the project part of the museum; our intention, in part, was to somehow break down the border where our project began and where the museum left off (figure 13.16).

After "skinning" the project, we were asking ourselves how we would then do it. As usually is the case, the solution was to have a monocoque structure, where the skin and the structure are active in their relationship to each other structurally (figure 13.17). The easiest way to do it was to come up with a very simple XY orthogonal Cartesian grid (figure

13.18). In this case the grid was 80 cm wide, which was the exact Cartesian grid of the *Centre Pompidou* as conceptualized by Renzo Piano and Richard Rogers. That was not accidental, because we wanted our project to be a deformation of that grid of the existing site. The next question we faced was how to deform that 80 cm floor grid.
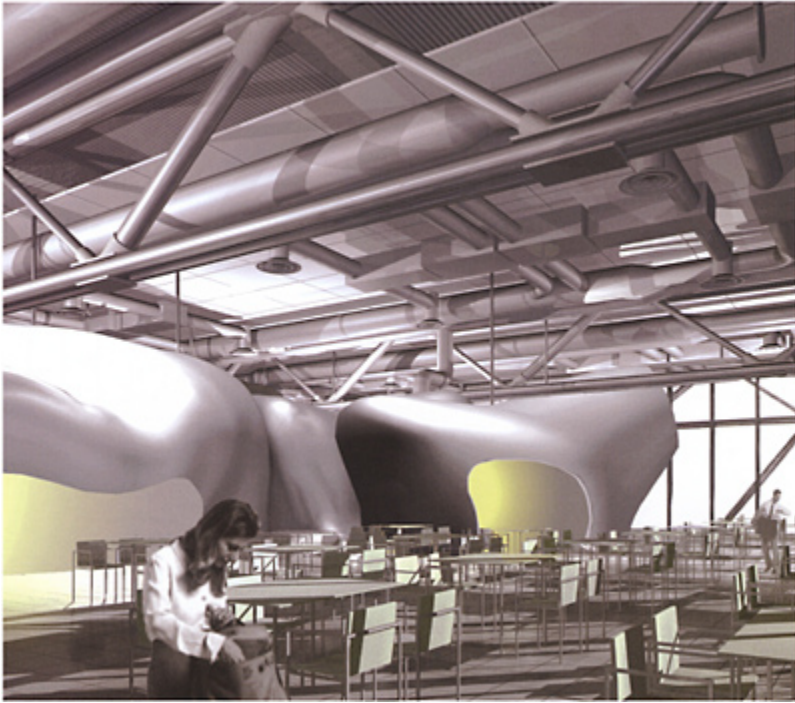
13.15. *Restaurant Georges:* interior perspective from the competition phase.


13.16. *Restaurant Georges:* exterior perspective from the competition phase.
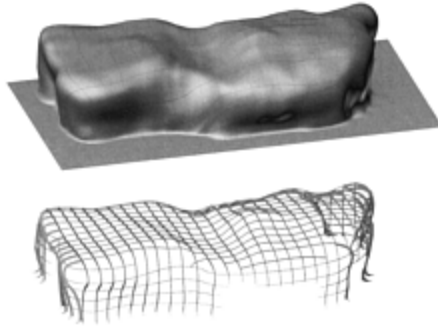
13.17. *Restaurant Georges:* the "skins" were conceived as monocoque structures.

We went through an enormously prolonged process, which would not be the case today; three years ago we were trying very hard to find a way in which we could volcanically develop the form, deform the grid and let the gridlines essentially become deformable by the volume itself. We, of course, finally found the software to do it.

The project was developed with, and built by, a boat-building company near Bordeaux in France that has built a number of racing yachts for the America's Cup; as a very big company, they were able to take on the size of this project and absorb its complexity. We went through a fantastic process, as though they were building four large boats instead of four volumes. The models we developed (figures 19a– d) were very important, as they articulated the tectonic relationships between the skin, the primary structure, secondary lateral structures and also the structure that would eventually hold the volumes down to the floor, which in this case was never fixed to the floor—it was glued to it because we could
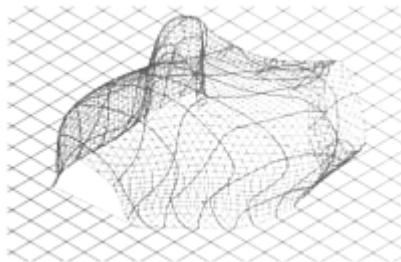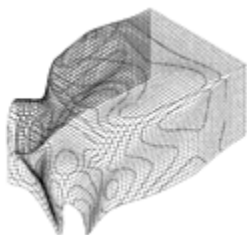

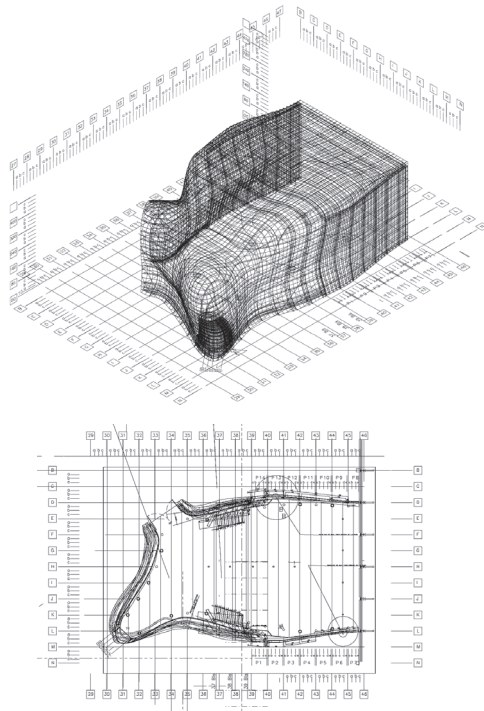13.18. *Restaurant Georges:* the deformation of the existing 80 cm floor grid.
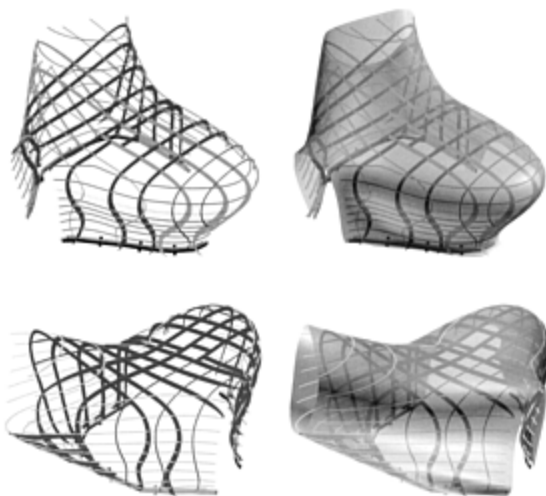
13.19a–d. *Restaurant Georges:* model of the monocoque shell for the "bar" volume.
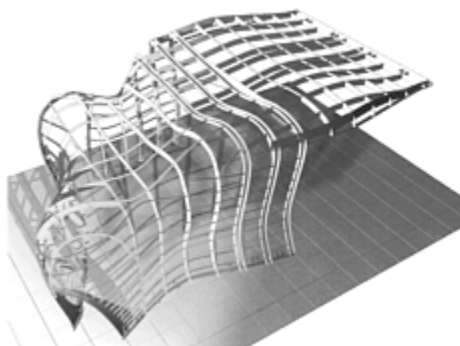
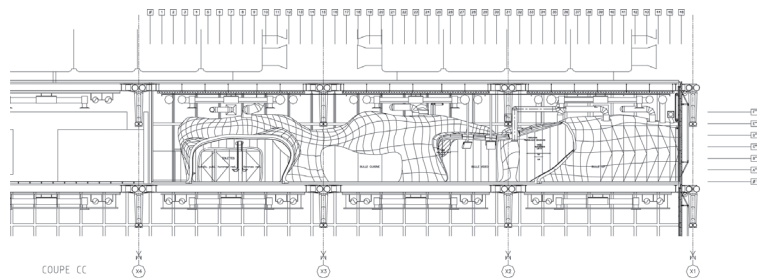13.20. *Restaurant Georges:* the structural model of the "reception" volume.

13.21. *Restaurant Georges:* the contour model of the skin for the "reception" volume.

13.22a–b. *Restaurant Georges:* shop drawings produced by the boat-building company.

not screw into the floor of the *Centre Pompidou* as it has what is, essentially, a tension cable structure. In modeling and developing the project in its virtual state, we developed its vocabulary. We were able to virtually model the project from the beginning through to fabrication. We never built the "real" physical models until after the design project was finished. We essentially felt highly comfortable with this new way of modeling. There was a clear cycle of images from early conceptualization to the finished piece, which, like any representation, do not show all the immense transfer of information back and forth.

The "reception" volume (figure 13.20) presented the most complex structural problem because the end of it had to be held up—it was a floating volume that had to be suspended right to the very façade of the southern face; essentially we wanted it to be chopped. We did not want to make the door or the window into any of the volumes in any way special. We made openings in the volumes in two ways: one was a chop across the volume and another was a cut, as if one took a knife into the volume at right angles and cut around. These two methods were the minimal means by which we made all the openings in the project—minimal because, in many ways, we wanted the volumes to be almost pure, as if they were impenetrable.

13.23. *Restaurant Georges:* cross-section through one of the volumes, showing the relationships to existing systems.

13.24a–b. *Restaurant Georges:* lateral modeling for the "reception" volume (images by RFR Consulting Engineers).

13.25a–b. *Restaurant Georges:* gravity modeling (images by RFR Consulting Engineers).

13.26. *Restaurant Georges:* a detailed three-dimensional model of a structure segment.

13.27a–c. *Restaurant Georges:* assembly of the monocoque structures.

13.28a–b. *Restaurant Georges:* on-site assembly and finishing.

The boat-building company produced their own models and shop drawings (figures 13.21 and 13.22a–b). Working with them was an interesting experience since they had all the required technology (as mentioned earlier, the technology was there years before we came along). We had a number of skin questions to deal with. Essentially, there were two important problems to resolve: one was, of course, the overall structure as it came down onto the periphery and the other was to make the "mouth" around the doorways as thin as possible (figure 13.23). We did lateral forces modeling (figures 13.24a–b), gravity modeling (figures 13.25a–b), etc., to make the volumes as thin as possible.

We had a highly detailed three-dimensional model of the structure right down to the bolt holes (figure 13.26). The structure was digitally cut out of 10 mm thick aluminum, and that part of the project is the "pure" part. Each of the volumes was put together and bolted inside the boat-building factory (figures 13.27a–c). There was an artisanal aspect to the manufacturing of the volumes; we used traditional boat-building methods to bend the 4 mm thick sheets of aluminum. To create some of the more complicated double curves, we used a machine that was quite interesting, which looks like a sunflower with thousands of little points that can either expand, and therefore create a convex curve, or contract and create a concave curve. The volumes were then disassembled and transported on trucks to Paris. The maximum size of the individual segments was determined based on the size of the two side elevators at *Pompidou*. The segments required a considerable amount of finishing on-site (figures 13.28a–b), so the boat-building contractor relocated its crew to Paris.

13.29. *Restaurant Georges:* the floor is deformed into the walls.

13.30. *Restaurant Georges:* the space in-between the volumes.

13.31. *Restaurant Georges:* view from the terrace.

13.32. *Restaurant Georges:* the brushed aluminum sheets both absorb and reflect the light.

13.33. *Restaurant Georges:* the insides are covered with a thin skin of rubber.

13.34. *Restaurant Georges:* the inside of each volume is colored differently.

The floor was also made from aluminum, from the same 4 mm thick skin, and deformed onto the walls (figure 13.29). As we modeled the volumes, at some point they took on a certain kind of flaccid and turgid nature (figure 13.30); we were very intrigued by that. We obviously wanted to create the circulation spaces between the volumes that were, in many ways, dictated by the movement of people for accomplishing different things. There is a certain theatrical quality to the project in terms of the way in which the people bringing the food to the table are seen and not seen; there is a certain play. The volumes become a kind of backdrop to quite a strong event (figure 13.31). The volumes have a reading at being caught in time. We became very interested in that, because at some point we actually became uninterested in where to end the project. For us, it was an absurd question; we just wanted to say go —stop. Otherwise, we would have never finished. So that is, in part, why that sense persists and stays there, and we enjoyed the ambiguity of it.

The aluminum is brushed because we wanted the material to both absorb and reflect the light (figure 13.32). The movement of light in the building is quite extraordinary during the day; we knew we had a fundamental problem in having too much light coming from the windows and having almost nothing in a diagonal opposite. We wanted to create a balance in the space by bouncing the light around, which was possible by brushing the aluminum.

The insides of the volumes are completely covered with a thin skin of rubber. This second skin is the softer skin; it is the skin closer to the body, a rubber skin that is deformed again, which runs across the floor, up the walls, over the ceiling and down the other side (figure 13.33). Each volume takes on its own color (figure 13.34). There is an allusion to


13.35. *Restaurant Georges:* the "reception" volume was color-coded red, because of its use by the administration.

the color-coding of the 1960s, which is not quite definite; there is a sort of philosophical play around what we did with it. The red, for example, was a codification used in the *Pompidou* as an "administration" color, which is why we used it on the inside of the "reception" volume (figure 13.35). In a sense, we provided a memory of a certain period of time in the *Pompidou's* history. The furniture was designed by us, but that is a secondary theme—we

wanted to keep it absolutely a datum which would be in perfect dialogue with the volumes or the pockets as they emerged out of the floor.

We appropriated the plumbing in the *Pompidou* by never touching it and feeding it towards or directly into the volumes where it was functionally necessary (figure 13.36). Ironically, as the *Pompidou* has gone through the period of "renaissance," they decided to paint the pipes and, in doing so, they got rid of the color-coding, which for us was a conceptual error. In a strange way, our restaurant defends the last part of Pompidou that was not painted-out white.
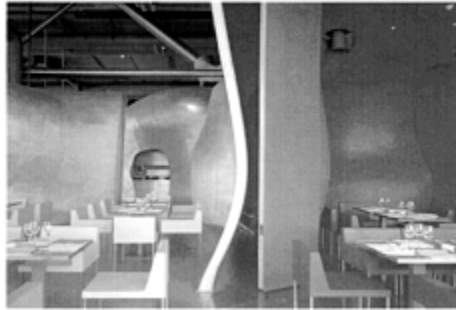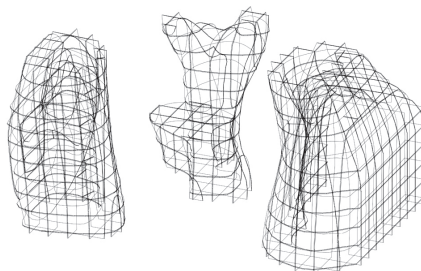

13.36. *Restaurant Georges:* the plumbing was appropriated from existing systems by feeding it directly into volumes.

13.37a–b. *Florence Loewy Bookshop, Books by Artists* (2000), Paris, France.
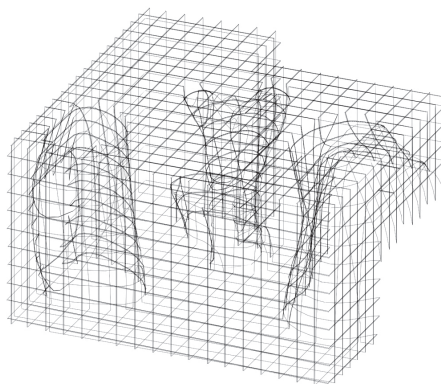
13.38. *Florence Loewy Bookshop:* three-dimensional grid based on the average sized book.

13.39. *Florence Loewy Bookshop:* three islands of books.

FLORENCE LOEWY BOOKSHOP, BOOKS BY ARTISTS

Here was a client who sells books conceptualized and fabricated by artists. It is an incredible collection and unique in France. Our problem was to create a shelving system as well as stock system in the same space, a very tiny 35 m² (figures 13.37a–b). So we decided to take the average-sized book as an increment that became its own space maker. The book determined a simple three-dimensional grid or crate that was then left to fill the entire space (figure 13.38). We then modeled an imaginary circulation route that was then overlaid over this matrix, which would eventually hollow out a good 70% of the crate. The result is three islands or stacks of books (figure 13.39). Books are presented on the outside of these stacks to the public, while storage for the books is found on the inside (figure 13.40). The event generates its final form (figure 13.41), but the form is no longer a skin. It is a phantom; what is left is almost a non-existent thing and that interests us a lot.
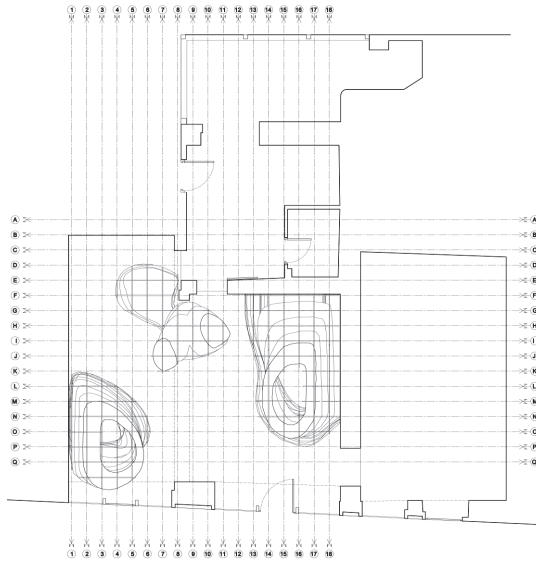
13.40. *Florence Loewy Bookshop:* plan; the inside of the three "islands" is used for storage.

13.41. *Florence Loewy Bookshop:* the elevation view of the book stacks.

The wood was the material of choice, as it is ideal for being digitally cut using a three-axis milling system; we wanted to use a five-axis machine, but that was too expensive. Each stack is composed of a series of flat rings containing the vertical dividing grid, constructed in a factory like the structure of the volumes of the *Pompidou,* only to be disassembled and reassembled in the final space (figure 13.42). As we carve away from

13.42. *Florence Loewy Bookshop:* the structure of the book stacks.

the inside and the outside (figure 13.43), the result has an aspect which gives a transparence between the two volumes in specific places (figure 13.42). For us, in some ways, the process of the bookshop becomes an even purer translation from virtual modeling to final built form, unlike the *Pompidou,* which entailed a certain artisanal finishing to the skins of each volume.

13.43. *Florence Loewy Bookshop:* inside one of the book stacks.

13.44. *Maison H* (2001), Corsica, France, architect Jakob + MacFarlane: site plan, an early study.
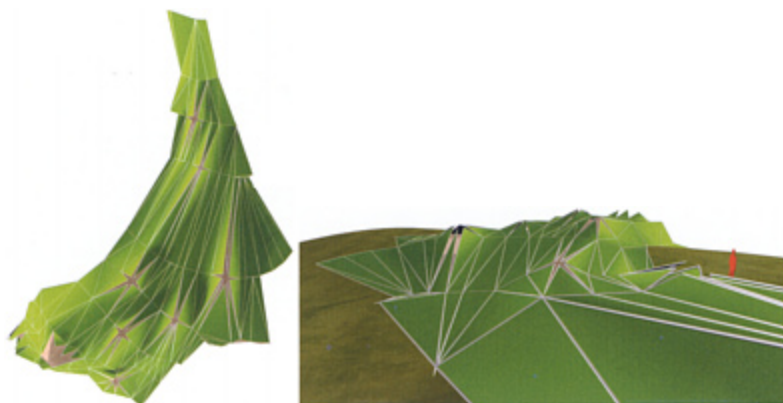
MAISON H

At present we have just started to develop this private house for a client on the island of Corsica. The site is in the south of the island, just opposite the town of Propriano, on a piece of property that goes down to the beach. The site is covered in olive trees, and is remarkable because it looks onto a small beach at the bottom of a cliff.

The client wants us to create a way of living *across* the site and *in* the site. He wants to be able to live in different parts of the site in terms of the seasons and in terms of his interests. We conceived a number of small houses that could become the guest house, a house for lunchtime, a winter house and a summerhouse. We decided to take the existing topographic lines across the complete site, and then work with the resulting mesh (figure 13.44). There is a climatic aspect to the site which we also want to incorporate. During the day the winds come from the sea and at night they operate in the opposite direction; the wind across the site is controlling where people want to be throughout the day in the heat of the summer. So we are very much aware of that, and the client has very specific ideas about where the family wants to be throughout the day.

13.45. *Maison H:* the hollowed out matrix, an early study.

Programmatically, there is a lunch house, a space where the client could entertain a group of people, a house for invited guests, a principal house that overlooks the sea, a house for meditation and a space for tennis. We created a series of "pockets" (the concept we developed in the *Pompidou* project) or inhabitable spaces; it is somewhat like what we were exploring at *Georges* but also combining with it the preoccupations we developed in the bookshop project, with the matrix now becoming the hollowed-out event (figure 13.45). The site here becomes the appropriated skin and is appropriated by itself (figure 13.46a–b).
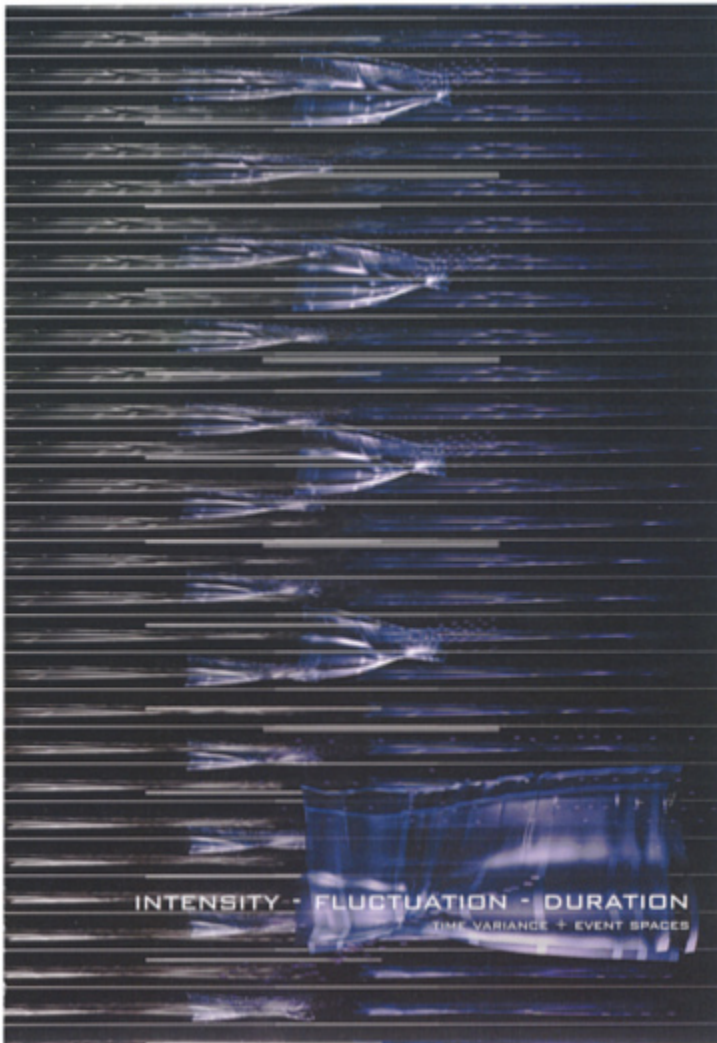
13.46a–b. *Maison H:* the site as an appropriated skin, early studies.

14
DESIGNING AND MANUFACTURING PERFORMATIVE ARCHITECTURE

ALI RAHIM

14.1. Unfolding of animation processes through time.

At *Contemporary Architecture Practice* we explore the relationship between contemporary techniques, culture and architecture. We use techniques of design that are animated, process-driven methods that provide new transformative effects in cultural, social and political production. Such a technique acts on, or influences, an object, which, in turn, modifies human behaviors and technical performance. Techniques have always contributed to the production of human and cultural artifacts, but their refinement and acceleration after the industrial revolution has emerged as the single most important element in the evolution of cultural endeavors.[1] Our work seeks to harness the potentials of cultural proliferation, by using animation techniques to simulate the production of new architectural and cultural effects.

At each stage in its development, a technological device expresses a range of meanings not from 'technical rationality' but from the past practices of users. In this way, a feedback loop is established between technology and cultural production that leads to a restless proliferation of new effects. Technology is not merely technical; it is an active and transformative entity resulting in new and different cultural effects.[2] Technology, in this sense, is not an efficiency-oriented practice measured by quantities, but a qualitative set of relations that interact with cultural stimuli. This interaction produces a pattern of behaviors that can result in new levels of performance and in newly affective behaviors or actions. In fact, contemporary techniques themselves are new effects of previous techniques that result in further cultural transformation through a complex system of feedback and evolution. The path of evolution produced by a cultural entity—an object, a building, a company, or a career immersed in its context- produces a distinct lineage[3] as the result of propagation. Each lineage, economic, political, social, commercial, scientific, technological, etc., exists indefinitely through time, either in the same or an altered state. Contemporary techniques enable us to access these potentials and separate these lineages. This act of separation is similar to the propagation that produces a performative effect.

Once lineages have produced effects, memes provide for the dissemination of ideas which cross these lineages. Memes are copied behaviors and are transmitted either through people by *heredity,* in which the form and details of behaviors are copied, through *variation,* in which the behaviors are copied with errors, or through *selection,* in which only some behaviors are successfully copied. They react to external stimuli and produce or transform a situation through influence and effect—they are performative. To quote Stephen J. Gould, "transmission across lineages is, perhaps, the major source of cultural change."[4]

This process of cultural evolution serves as a generative model to develop techniques in which the environment influences the outcome of the developmental process, while simultaneously producing a rate of change in the environment. This relational system of feedback allows us to design in an adaptive field while testing our results of cultural stimulation iteratively. Animation software that uses evolutionary simulations, which are sufficiently open-ended to make it impossible for the designer to consider all possible configurations in advance, does this. These are generative and are reliant on the simulation of multiple simple systems that produce larger effects than the sum of their parts; hence, effects are no longer proportional to their causes, but are emergent. These differ from prior investigations according to the continually changing landscape of epistemological thought.[5] The past and present are simultaneous and the future is not preconceived. This allows us to release our ideas from the pragmatic determinism attributed to concrete and material processes,

suspending the reflection of concept/ image-object/image relationships. This foregrounds process and delays the urge to generate form.

Material processes, used by most critical designers, are not generative as they are linear, shaped directly by the forces acting on them, which is inadequate in contemporary cultural settings because of their inability to participate in the process of cultural proliferation. This alerts experimental designers to processes which are static and deterministic. As Henri Bergson said:

> But the whole Critique of Pure Reason (Immanuel Kant) rests also upon the postulate that our thought is incapable of anything but Platonizing, that is, of pouring the whole of possible experience into pre-existing molds [author's inflexion].[6]

The relationship between the mold, the raw material placed in it and the object it produces is static and predictable. This represents a mode of conceptual understanding, and defines characteristics of objects as their constancy with respect to certain cognitive actions. The isomorphic relationship between concept and object is deterministic and cannot be projective as it continually draws upon existing material that is readily usable, having a limited number of possibilities and hence limited outcomes. For example, collage is reliant upon available collageable material, and hence the potential latent within the collage is limited. Roger Caillois has argued that: "When several representations have already over-determined its content; the content is able for this reason to best fill the ideogramatic role of systemization that pre-existed it and to which, in the last analysis, it owes its appearance."[7] For example, the aggregation of heterogeneous figures creates a series of negative spaces reliant on the inverse proportion of the initial figures or some other variations, such as casting of material into a mold. Hence, material processes are reliant on a predetermined cause and effect relationship.[8]

Material processes, however abstract, depend on a linear correspondence between concept, form and representation. In another sense, continuing the tradition of architecture's relationship to signification and language and form, binds architecture to exhausted rules and potential. The determinate nature of these approaches carried architectural processes as far as they could, only to create forms that strain under the burden of their representation and produce predetermined effects that are isolated from the process of cultural proliferation. Generative processes abandon this model and begin operating autonomously from it.

To avoid this overburdened predisposition towards architectural form and to avoid this negation of contemporary culture, experimental architects use animation processes that unfold through time. These processes within the matrices of the software are comprised of vectors, fields, pressures and constraints in combination with inverse kinematics, particles, metaclay and surfaces (figure 14.1). These elements continually adapt and change through time where strong mutual interactions exist between each constituent. Each combination of virtual elements grows in an opportunistic manner and becomes constructive,[9] which allows it to increase in complexity while its traits became historically bound to previous states, simultaneously developing new ones. This participates in the content to material arrangements of architecture by exploring relationships between organization, building program, space, material form and the subject (figure 14.2). It equips the experimental architect to evolve from what was previously intuited with limited understanding and fixed practices to a dynamic method capable of simulating the actual performance and interaction of behaviors. Separating these emergent lineages and testing their behavioral effects

by simulating scenarios, once our interventions have been immersed in their cultural contexts, achieves this. This process is performative and stimulates cultural transformation by altering behaviors and changing habits due to our interventions.

These animated models' generative ability is reliant on dynamic time. Henri Bergson, among others, has emphasized the difference between time as a number or static being
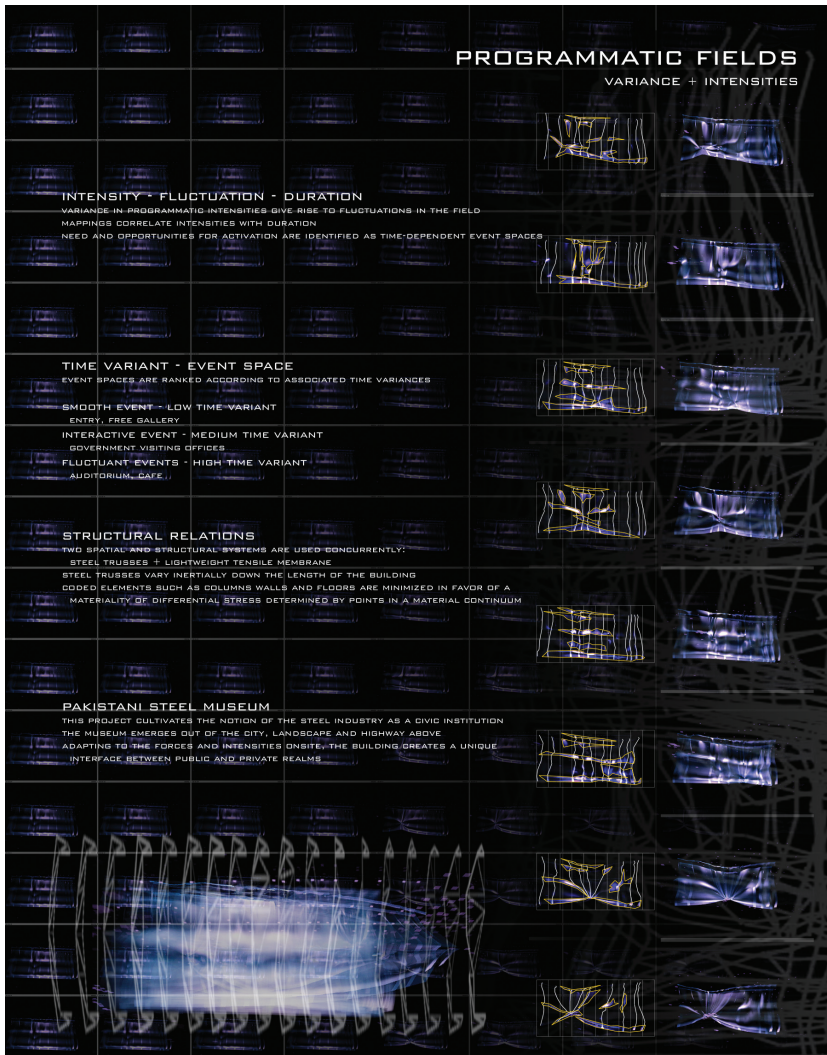
14.2. Programmatic fields, driven by variance in intensities.

and time intermingled with organic bodies. Here time has no reality independent of the subject and is dynamic. This dynamic view of time, referred to as temporality, recognizes that the future is undetermined, that the chance plays a large part in determining the future, and reality evolves as time passes. Past, present and future never occur at the same time,

as temporality consists of accumulated moments and is irreversible[10] because our memory prevents us from reliving any moment. Here time is directional and consists of duration.

Static time, on the other hand, is reliant on the determinism of Newtonian science which presents an axiomatic vision of the universe deducing empirical laws of planetary motion from the inverse square principle, denouncing gravity as being an essential quality of bodies; Newton accepted mechanically-inexplicable forces due to his religious tendencies. In essence, every event in nature is predictable, and predetermined by initial conditions. Like a clock that exists objectively, independent of any beings, nature is described as a simple reduced system that is causal and can go backwards and forwards without altering its effects. Historical records, for instance, can read from left to right and vice versa, and any given moment, assumes to be exactly like any other moment. We are transported backwards and forwards by our memory. These dates are specific in time, but are records—and our memory can recollect any moment in history that we know. Time here is static, as the past, present and future are subjective and experientially-based, rather than one reflecting an ontological divide. It is a simplified standardized notational system separate from beings, a number, a reductive quantity with no duration and an object at every moment we perceive it. Chance plays no part and time is reversible.

Using animation techniques allows us to inhabit the duration of dynamic time. This is only achieved when a system behaves in a sufficiently spontaneous way and where there is a difference between past and future, and time is directional and irreversible. This randomness and spontaneity must outweigh causality and predictability to increase temporal duration. Here time is a varying principle at each stage of division. During the animation, durational time is quantifiable at precise moments of past and present, a quantitative multiplicity, and it is between these two moments that the potentials are at their maximum. For example, in the act of choosing, the potentials are at their maximum as we choose from a number of possibilities. Once we have chosen, we cannot undo this act. There is an asymmetry between the past that is fixed in time, and the future that is yet to exist. At the precise moment of selection, there is a change where the potentials have moved from being at their maximum to an actualized probability. This probability describes only the potential property and not the actual physical property of objects.[11] The objective substance of materialism here has disintegrated into relative probabilities instead of material realities. Thus, in duration, there is a perpetual creation of possibility and not only of material reality.[12]

Experimental architects are able to take advantage of this shift from material reality to potential probabilities. Emergent animations are reliant on the computational logic of high-end software to achieve this unpredictability by moving away from deterministic, material quantities to relative qualitative potentialities. These animations further Henri Poincaré's findings of complex behavior emerging out of three isolated bodies interacting with a gravitational field.[13] These animations utilize time in its irreversible, destabilizing manner, and use duration to maximize creative potential. This duration is temporal and perpetuates a field of possibilities with the potential of generating new effects in content, organizations, programs, spaces, structure and material arrangements for architecture.

These potentials contained within duration are infinitely machined in time. These machine-like processes of lineages in the natural world are non-linearly determined

through time, so that they spontaneously self-assemble. It is literally a machine with every piece machined to an infinite degree. This machineness exceeds the inadequately machined mechanical process and is reliant on a double articulation[14] of concepts translated to content and expression, which is its specific corollary or technique within the animation. Concepts come prior to the application of any software package, while contents comprise of concepts translated into the framework of the animation and vectorial intensities that are destabilizing. Techniques are the embodiment of precise combinations influenced and shaped within the animation that serves as abstract locations of more than one coordinate system. Concepts inform content, and content destabilizes technique which transforms and adapts the arrangements. To be able to develop techniques that correspond to concepts, we need to define limits[15] as the probabilities of potentials. Here, techniques do not restrain or limit potentials, but rather the probabilities of potentials limit and guide how specific techniques are organized. These procedures and combinations are adaptive and reliant on each other's arrangements explored through an iterative process. The concept informs the technique, and vice-versa.[16] These are scale-less operations within the animation and they recreate traits or potential. The relationships between concept and technique, although distinct, are simultaneous and are influenced by each other—they behave singularly as a system of flow.

For example, in our project, titled the *Confluence of Commerce* (figure 14.3), a shopping mall with a mixed-use program, the project was conceptualized as being informed by immersing itself within the context of the city, and invigorating a cultural transformation. This was
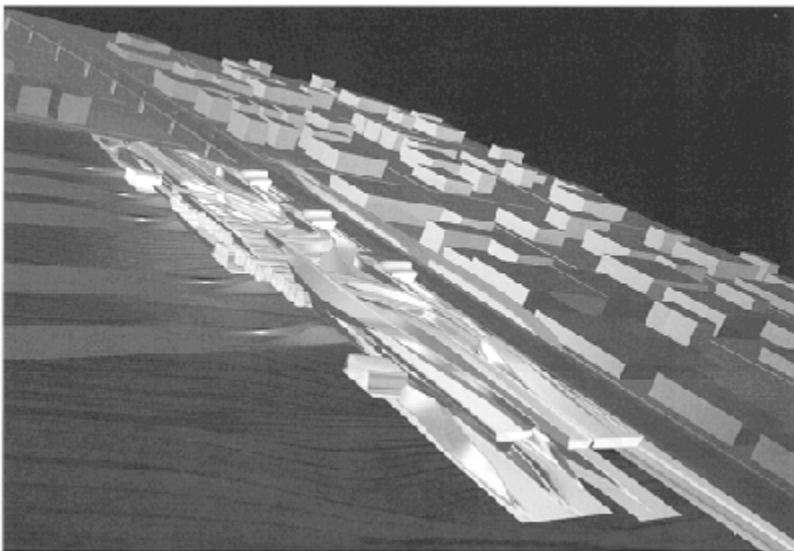
14.3. The *Confluence of Commerce* (2000) project, Karachi, Pakistan, architect Contemporary Architecture Practice. 204
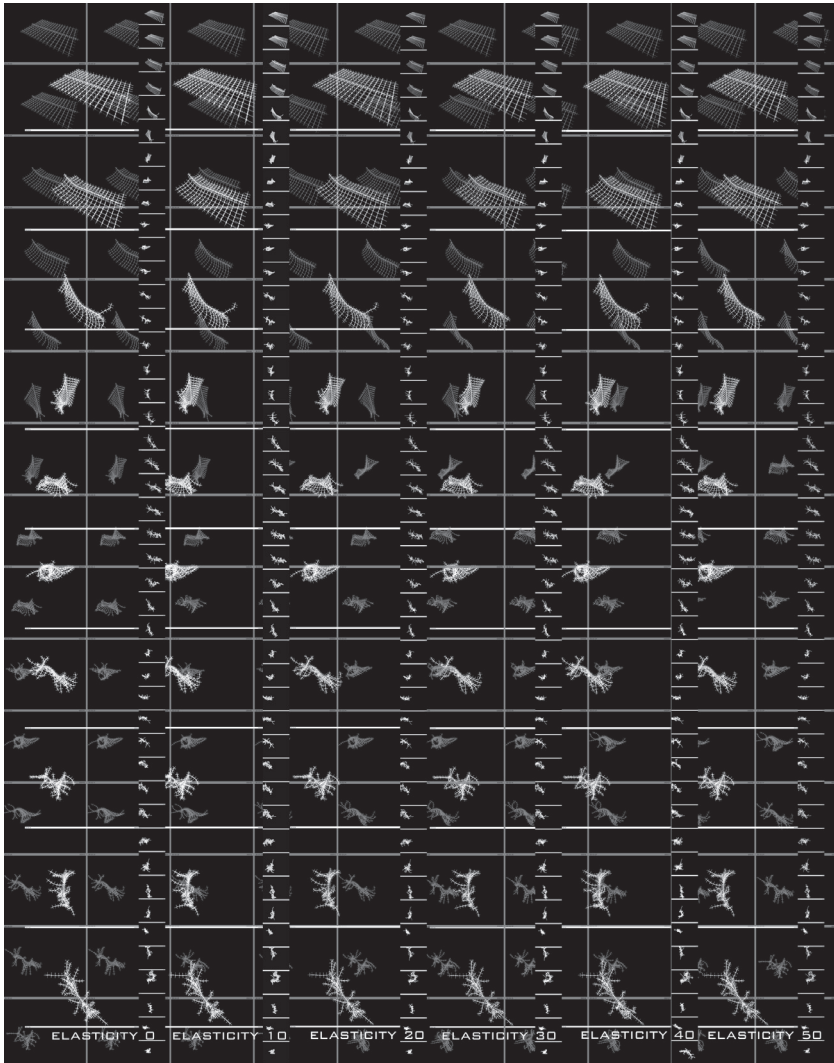
14.4. *Confluence of Commerce:* spinal hierarchy research using inverse kinematics chains.

achieved by releasing the typological association of the shopping mall driven by the economic hierarchy of anchor stores that usually determines locational hierarchy and spatial arrangements into one that operates as an even field of potential with economic gradients. These gradients adapt to the changing needs and demand in culture and effect and influence cultural proliferation simultaneously.

In order for this project to evolve indeterminately outside the influence of specific images of hierarchical economic structures, materiality and form, we used generative machines as content and technique engines simultaneously. This allowed us to deterritorialize our ideas

of economic control of the *Confluence of Commerce,* test relational influences in the city through several scenarios and develop specific material forms simultaneously.

We tested several temporal techniques that were consistent with our concepts, and selected a combination of abstract elements that linked our concepts to specific techniques. We used Inverse Kinematics (IK) chains (figure 14.4), where the relationship between the hierarchies of the technique and the initial concepts had very specific associations. We tested several different scenarios with our concepts using different configurations, including hierarchical structures and non-hierarchical structures, until the formations responded to the content of our concepts.

The selected technique that formed the machinic engine was comprised of vectors, fields, pressures and constraints, in combination with inverse kinematics and surfaces. We used these force fields to replace sites, programs and events, and coded the hierarchical economic structure with IK chains, creating a dynamic landscape based on elements that had to interact, realign and produce new and unforeseen relationships, while suspending any correspondence between meaning and form (figure 14.5). This projected modes of deterritorialization as a process, and relieved specific objects of their representational burden.

Each process of deterritorialization was comprised of two axes of double articulation, both horizontal and vertical. The first axis was comprised of both the organizational and material formulation. Each formulation was organized along the horizontal axis according to a gradient from form to its non-formal corollary. Organization was now inherent to the property of the IK chains, and material had moved to dynamic properties of surface. The second axis was comprised of degrees of turbulence, which opened the horizontal axis to new relational associations. For example, for the horizontal axis, the organizational component moved from site, program and economic hierarchy to effects on site, intensity of event-based spaces and economic similarity. For the material component, properties of surface moved to IK chains constrained to surfaces. These relationships were effected using duration, magnitude and direction of the vectors.

Two vectors were applied to the vertical and horizontal axes. The first vector applied to the horizontal axis investigated the site and economic viability through the projected number of people who would use the facility, the economic intensity of each program, and the operational hours of each program. The vertical vector served the specific function of deterritorialization. The turbulence in the system was quantified by using the magnitude and duration of each vector pointed towards the IK for each specific program and its capacity to generate money. The programmatic requirements initially called for cinema theaters, cafés, shops and public spaces that were all investigated as either resisting or enhancing the generation of money, and were coded into the model with different resistances in the joints of each IK. These relationships were simulated, generating relational potential. This allowed the possibility for new relationships to occur in the positional and territorial relationships of the first axis. For the organizational component, the formulation of specific orders of arrangements occurred, and for the material component, strict self-definition and material structures began to form affiliations with economic potential.

This process was iterative until this singular flow of concept and technique emerged into spontaneous organizations or machines at differing points within the animation. They were further fine-tuned to provide for the increasing duration and potential within the system,

by providing for maximized emergent behavior. This is comprised of qualitative flows of duration that spontaneously emerge into an organization. They have no scale or objectified time. Within this self-organized machine, the potentials are at their greatest and are not project-ed, and their possibilities within the technique are limitless. It surpasses any objectified mechanism and is reliant on time having direction. This single flow animation, if played in reverse, looks incorrect, similar to if we were to play a video showing the turbulence of clouds before a thunderstorm in reverse. Here, we would see downdrafts when we expect updrafts, turbulence growing coarser rather than finer in texture, lightning preceding
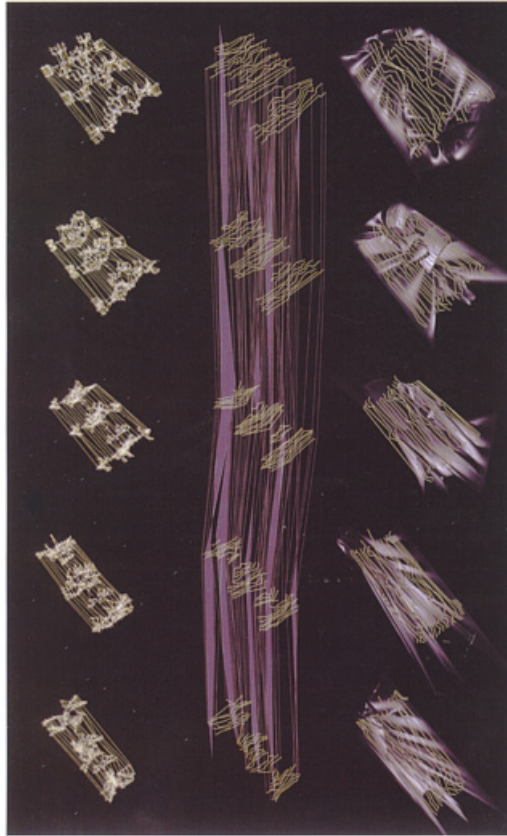
14.5. *Confluence of Commerce:* the abstract machine—quantitative and qualitative time.

instead of following the changes of cloud, and so on.[17] This abstract machine does not emerge if the animation is reversible. For example, if we captured planets moving through a time-lapse video and played it backwards, it would look the same due to the progres-sion of movements being the same, with the only difference being the planets moving in

reverse. This system still operates within the Newtonian universe and is not unlike key-framed animations in which the effects of changes are reversible, and, thus, predictable.

The emergence is due to qualitative duration flowing together, where the qualities are the animation's interactions between its parts. It maximizes generative potential. What emerges from the machine is a single articulation of both content and expression, and marks specific points or instants[18] that demarcate the duration when qualitative multiplicity occurs. These qualitative multiplicities are indivisible quantitatively without a change in nature, because of their unequal differences distributed in subjective time.

Contemporary animation techniques are destabilized by temporally-located potentials that make possible the development of new organizations. These processes amplify the difference between the possible and the real, and contain a set of possibilities, which acquire physical reality as material form. The static object which produces predetermined effects defines the real, whereas actualization,[19] on the other hand, is emergent and breaks with resemblant materiality, bringing to the fore a new sensibility, which ensures that the difference between the real and actual is always a creative process.[20] This sensibility, which subverts fixed identity, is a flexible spatio-temporal organization producing performative effects. One possibility out of many is actualized and its effectiveness is measured by the capacity to produce new effects, which modify behaviors and performance.

For example, in the *Confluence of Commerce,* in which we used the organizational and material nature of non-hierarchic economic structures and surface, the economic structures began determining the extent to which the economy affiliated itself with material possibilities, while simultaneously providing for the most economic generation in the site. This allowed us to organize a strategy of behaviors driven by economic variation through time. When we realized that the economic potential of each program affiliated itself with different levels of inhabitation, we actualized different spatial scales with different economic qualities.
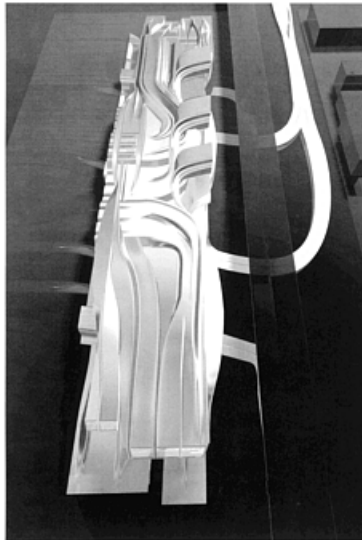
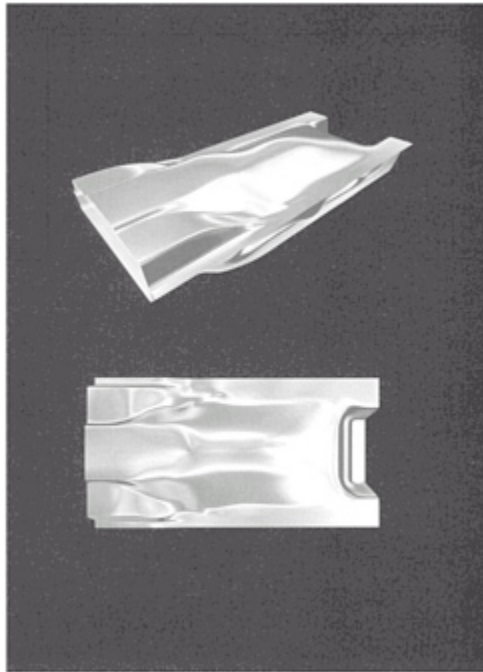14.6. *Confluence of Commerce:* roof plan.
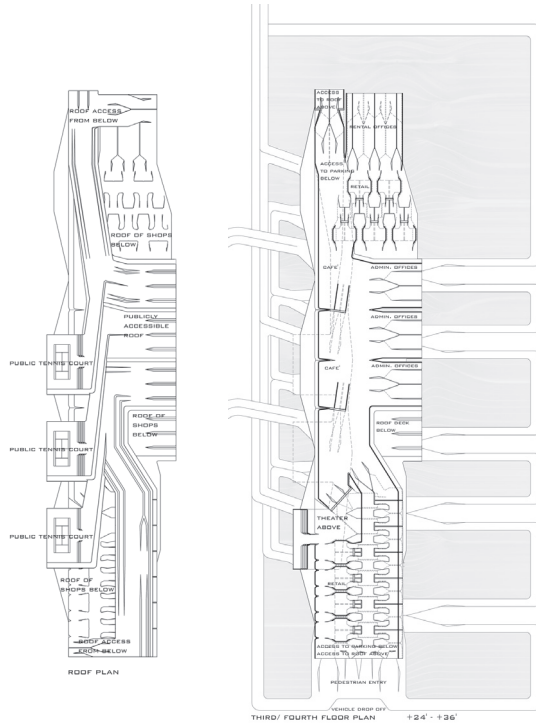
14.7. *Confluence of Commerce:* floor plan showing the cinema theater spaces.

The lowest economic generator allowed for areas that distributed people into a homogenous field, with different intensities emerging depending on economic performance. Each one of these spaces can perform in a multiple of different ways, dependent on their emergent generational capacity of economic gain at particular times of need during the day, week and month. As the generational capacity becomes inflated, the spaces become more specific. For example, the roof structure is made public and allows for a series of simultaneous activities, ranging from tennis and basketball to running, blurring the terrain of the public from ground to roof (figure 14.6). A sole-ownership shop continues to blur its threshold by spilling into more and more different shop spaces when necessary, or is able to expand on their own roof structures. Here the spaces can be used for several activities, but not in as many variations as is the case with the public spaces (figure 14.7). The second instance on this gradient is the offices; these are not as homogenous and as multifunctional as the shops, but are more specific to their program and less homogenous than the cinema theater. Here the office is able to function and adapt between working and meeting spaces. The cinema theaters are the most specific at the scale of threshold that delineates a theater from its surrounding spaces, as well as the specificity that develops within the surface. This allows for the singular event of watching a movie (figure 14.8).

This new dynamic organization was a confluence of different lineages that emerged into the program and structure simultaneously, which adapted and transformed, maximizing the performance and intentions of each element of the design based on economic potential

(figure 14.9). Once these lineages were separated, the effects produced through the actualization process were at the various local sequences of the program, with local specificity in a continuously varied form (figure 14.10). This highly differentiated structure allows for the directions and paths of inhabitation to interrupt each other with the intention to align and realign each individual's destination through social interaction.

Here, our perception of this duration is a projection of subjective actuality, and hence this represents a potential for something actual, as opposed to something literal. This projection is singular now and, when projected in material arrangement, points in one direction instead of multiple directions dependent on when we are conscious of it.[21] In other words, when the potentials have emerged into a machine, they are dynamically actualized through the differentiation of potential. It is the flow from one state to another that produces a performative entity. This process is creative as the qualitative multiplicity of duration must meet the actualized or projected world of singularity and quantitative time where it is experienced subjectively. When the form is actualized from a qualitative state of potentials

14.8a–b. *Confluence of Commerce:* the cinema theater.
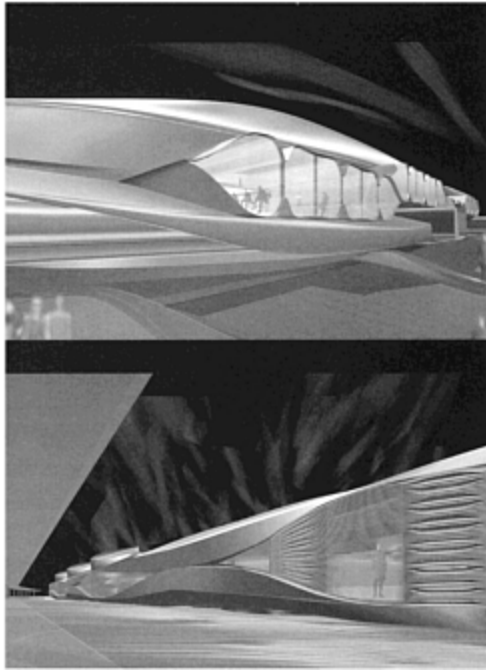
14.9a–b. (far right) *Confluence of Commerce:* exterior perspectives, north and south façades, respectively.
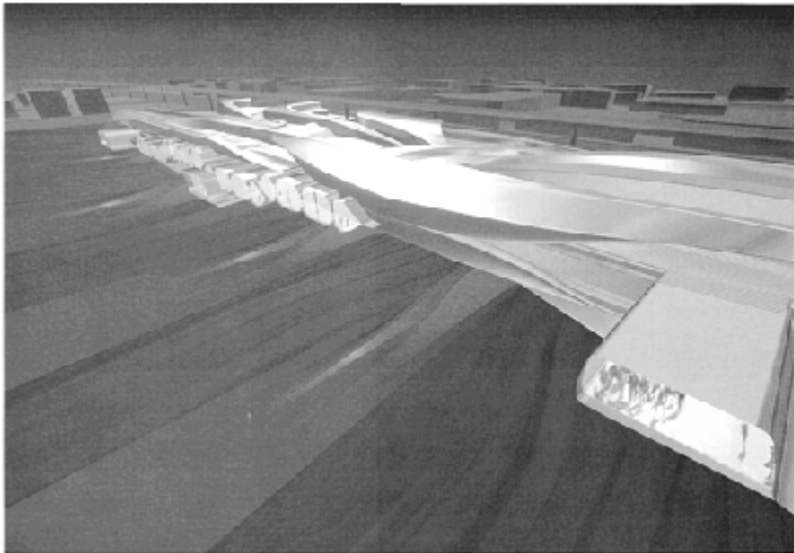
14.10. *Confluence of Commerce:* exterior perspective of the café and offices.

to a singular machinic assemblage,[22] the *Confluence of Commerce,* it still maintains dura-tional time as an irreversible flow, and can only be considered static if viewed through the lens of reversible, objective time taken out of its context

For example, in the evolution of the computer, it is clear that each lineage encom-passes the contributions of scholars, philosophers, visionaries, inventors, engineers, math-ematicians, physicists and technicians. Each lineage was stimulated over time by vision, need, experience, competence and competition. As these lineages developed simultane-ously through time, philosophically and intellectually they organized effects already in existence—the use of machines and automation. Theoretically, they organized advances made in symbolic logic and science mathematics, which only then became feasible. These factors were impacted by differing intensities of economic, commercial, scientific, political and military pressures, crossing the technical threshold, spontaneously emerging into the technological object of the computer—a separation of the lineages, an emergent effect.
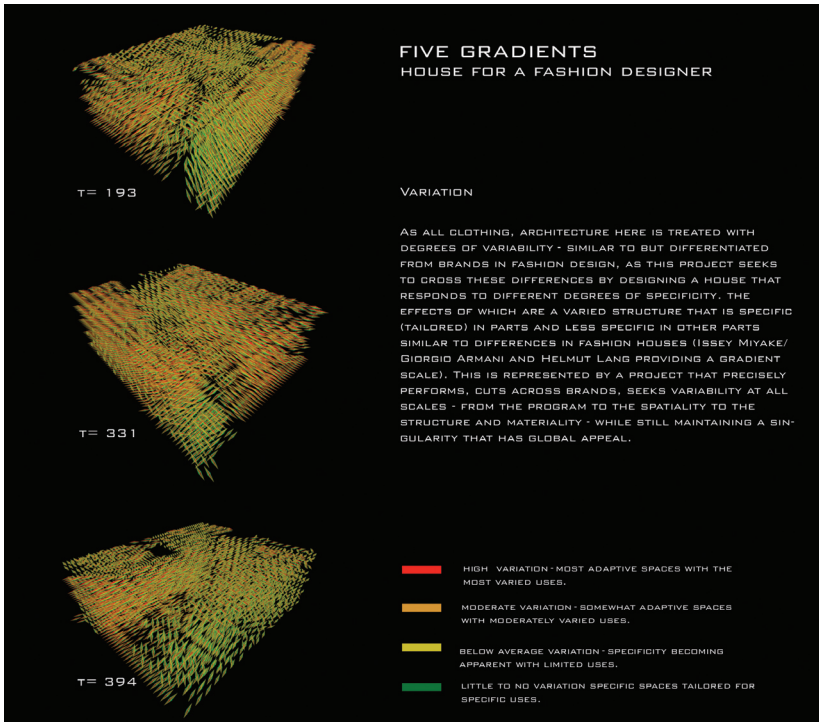
The computer is a temporally-organized technological object. If we were to view these non-linear organizational processes as fixed in space and time, the resulting objects would be severely limited, and strain to represent meaning through formal expression. This object type would be passive and defined only by its material attributes, which are linear and causal. Such an object is static.

To avoid this stasis, we must view the object in its context and understand it as part of a continuous temporal organizational process of cultural proliferation. For example, the Internet was created initially for the purpose of exchanging information between nuclear facilities operated by the military. It has emerged, however, as the largest storage bank of information in the world, with far greater and more complex performative potential then could ever have been predicted. The effects, no longer proportional to their causes, are emergent. Once recontextualized, the computer is instrumental in spreading memes, which change behaviors, and continues to influence contemporary culture.

This is exemplified in our *Variations* project for a residence for a fashion designer (fig-ure 14.11), where we conceptualized an approach that locally affiliated site, organization, program, space and material challenges. The form of the project emerged from spatial con-siderations that influenced all scales of development. This was developed through the study of the site in addition to the intensive event schedule necessary to be contained within the landscape and inhabitation of the project; these ranged from being a primary residence in addition to launching specific lines of clothing privately and publicly. We used animation techniques to study the relationship of the scale and intensity of event and their correspon-dences with the temporal cycles of the site. Specifically, we used inverse kinematics, which coded events as a field condition, with equal capacity to react to particular site cycles mea-sured by their intensity, duration and frequency (figure 14.12). These relationships were deterritorialized through the use of vectorial and gradient force-fields responding to dif-ferent degrees of environmental specificity. For example, an existing well on the site was coded with a continuous point-force which acted on the field condition and subsequently reacted to the continuous vector of force exerted on it. This provided unlimited potential in the system that grew in complexity, evolved and formed mutual associations between site stimuli and event. These pointed towards future possibilities, and were guided and shaped to form tendencies through an iterative process.
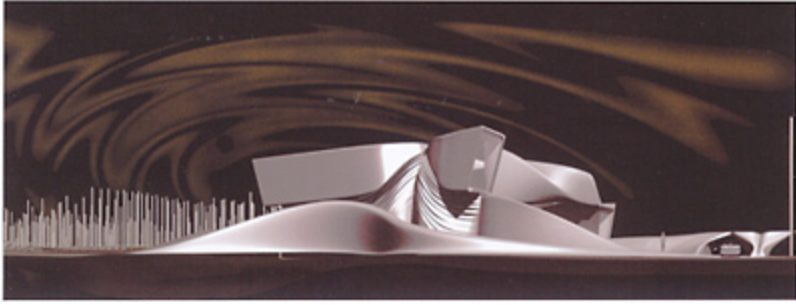
14.11. *Variations* (2001), residence for a fashion designer, Surrey, UK, architect Contemporary Architecture Practice.

FIVE GRADIENTS
HOUSE FOR A FASHION DESIGNER

T= 193

VARIATION

AS ALL CLOTHING, ARCHITECTURE HERE IS TREATED WITH DEGREES OF VARIABILITY - SIMILAR TO BUT DIFFERENTIATED FROM BRANDS IN FASHION DESIGN, AS THIS PROJECT SEEKS TO CROSS THESE DIFFERENCES BY DESIGNING A HOUSE THAT RESPONDS TO DIFFERENT DEGREES OF SPECIFICITY. THE EFFECTS OF WHICH ARE A VARIED STRUCTURE THAT IS SPECIFIC (TAILORED) IN PARTS AND LESS SPECIFIC IN OTHER PARTS SIMILAR TO DIFFERENCES IN FASHION HOUSES (ISSEY MIYAKE/ GIORGIO ARMANI AND HELMUT LANG PROVIDING A GRADIENT SCALE). THIS IS REPRESENTED BY A PROJECT THAT PRECISELY PERFORMS, CUTS ACROSS BRANDS, SEEKS VARIABILITY AT ALL SCALES - FROM THE PROGRAM TO THE SPATIALITY TO THE STRUCTURE AND MATERIALITY - WHILE STILL MAINTAINING A SIN-GULARITY THAT HAS GLOBAL APPEAL.

T= 331

HIGH VARIATION - MOST ADAPTIVE SPACES WITH THE MOST VARIED USES.

MODERATE VARIATION - SOMEWHAT ADAPTIVE SPACES WITH MODERATELY VARIED USES.

BELOW AVERAGE VARIATION - SPECIFICITY BECOMING APPARENT WITH LIMITED USES.

LITTLE TO NO VARIATION SPECIFIC SPACES TAILORED FOR SPECIFIC USES.

T= 394

14.12. *Variations:* programmatic variation.

The actualization process involved applying these tendencies to multiplicities in event intensity and duration, producing a variety of performative effects. A system of differentiated channels modulating water flow was actualized to provide for drainage and irrigation during different seasons; that is, a system of troughs and channels are used to irrigate or drain the land in different seasons providing a contingency of effects according to

ecological specificity. Ecologically, the effects are controlled to develop through time. For example, localized effects are produced by regulating the direction, amount, drainage and flow of water within the system at any given time. This controls not only the scale and type of vegetation, but also the activities surrounding these systems. Water is collected or released according to differing levels of saturation. A pool for swimming in the summer becomes a retention pond in the winter (figure 14.13); this provides for a matrix of possibilities contained in a flexible, yet specific, organization of water channels. These channels combine to form an emergent organization of water flow that produces programmatic, material and ecological effects that influence behaviors.
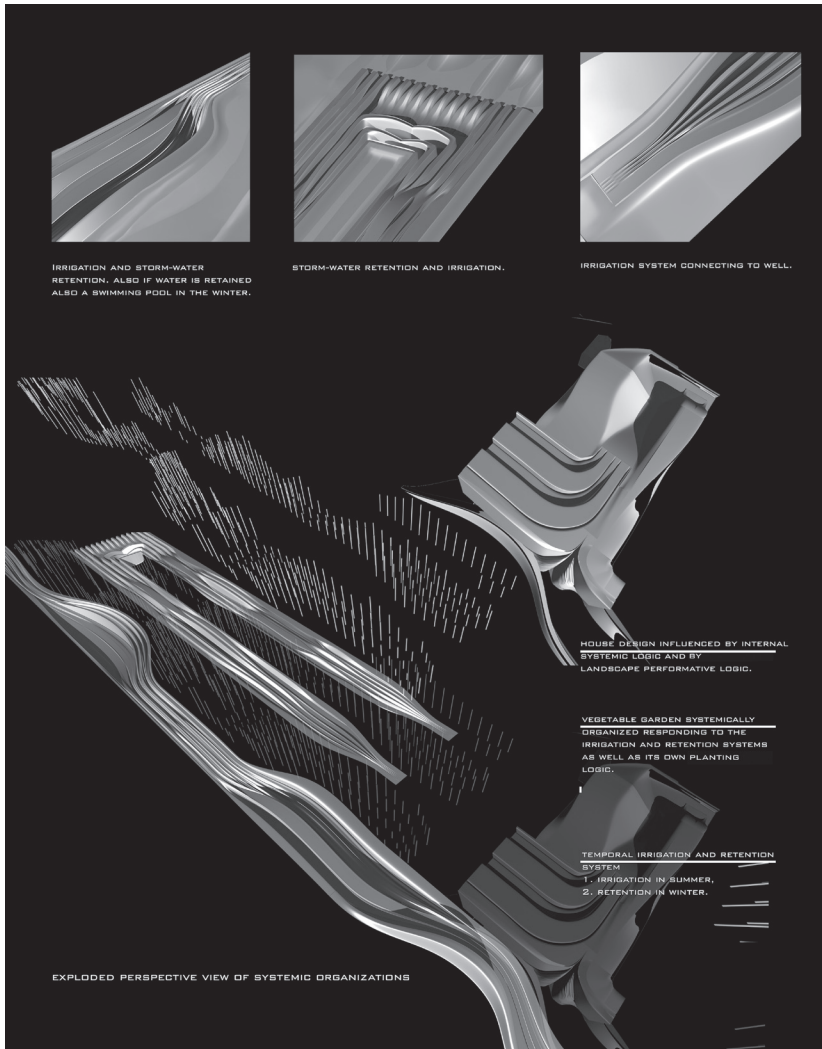
14.13. *Variations:* irrigation and storm-water retention.

At the scale of habitation we see a continuity with the landscape where the actualized organizational process has no bounded limits—figure or ground, building or landscape, inside or outside, public or private—but provides a continuous interchange or gradient between the two extremes (figure 14.14). This allows for the maximum variety of affective scenarios to occur which merge programmatic events. The provision of different alternative scales of circulation routes through the organization are used and are activated at different times during the day, week and year, producing markedly different effects. For example, the main circulation route provides for multiple event intensities to occur, while the short cuts of secondary and tertiary scale provide for connections collapsing two simultaneous events (figure 14.15). This continuous differentiation of porosity determines various performative effects at different times during the project. For example, if two events of the same intensity occur simultaneously, i.e. entertaining outside and on the second level, they are joined by the secondary or tertiary scales of circulation, merging with each other. If they are two separate events with different intensities, for example sleeping and entertaining, they spawn additional unforeseen events (figure 14.16).
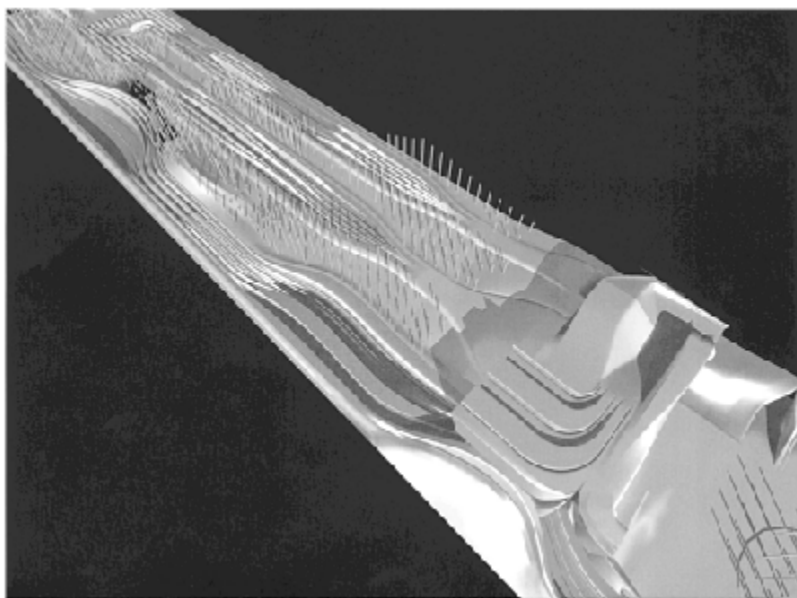
14.14. *Variations:* continuity with the landscape.

Spaces are arranged by a more detailed set of performative possibilities. One location may provide for clustering and accumulative behavior, while another allows for ease of dispersion and continuity of space. For example, while entertaining, one is able to flow from one space to another seamlessly (figure 14.17). In other instances, the space acts as a resistance to disrupt the flow. This disruption causes unforeseen situations to occur. In addition, spaces are modulated by the transformation of surface specificity, which allows for various

functions: sitting, eating, sleeping, bathing. For example, seating, which may also be used for sleeping, transforms into leaning spaces that can become areas for social interaction (figure 14.18); this gives the opportunity for that particular use or to be reappropriated for various uses in various combinations.

Within system, surface and space, material is modulated at the molecular level and at the scale of enclosure. At the molecular level, continuous variation is possible within non-isotropic (composite) materials; densities or porosities provide a range of gradient effects (figure 14.19). The threshold of the line is moved to a gradient, so that opaque, translucent and transparent effects can occur in one surface in continuous variation. This rearticulates the intention to conflate the internal spatial effects while simultaneously producing
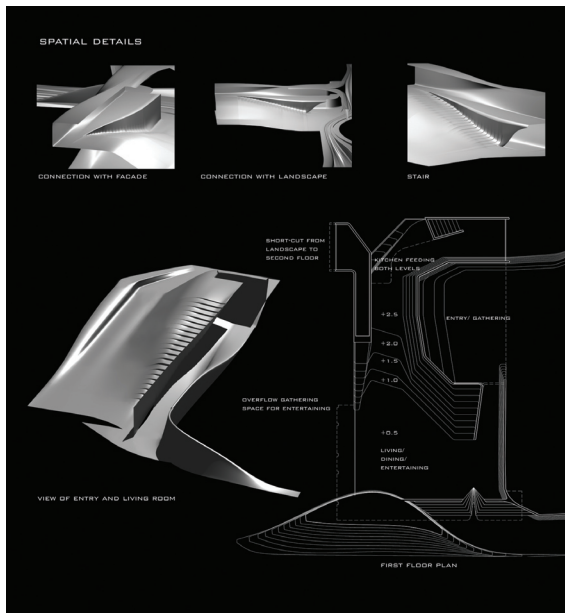
14.15. *Variations:* spatial details.
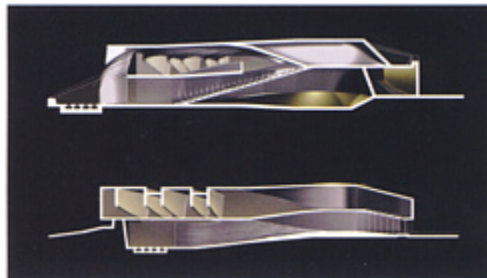
14.16. *Variations:* longitudinal sections.
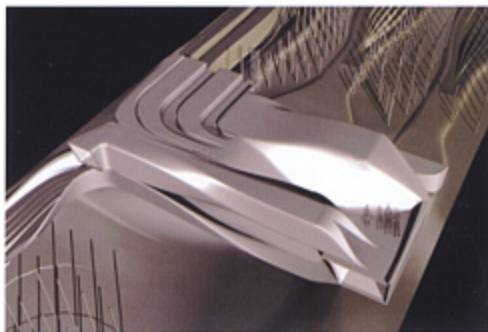
14.17. *Variations:* perspective view of the south façade.
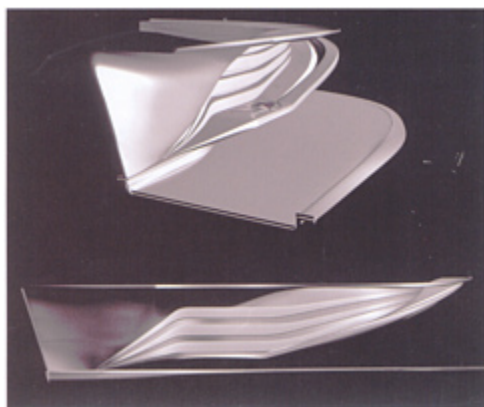
14.18. *Variations:* bedroom elevation and perspective.

aesthetic effects of various transparencies and colors. At the scale of enclosure one can vary the thickness of the surface, dependent on its own material logic for strength and for levels of opacity (figure 14.20). By twisting the material, one is able to produce a range of lighting effects (figure 14.21).

The emerged organization is made of an aluminum structure, which is clad with composite materials that range from opaque to transparent in appearance (figure 14.22). This relies on the technological and material manufacturing capability of contemporary cultural proliferation currently used by the aeronautics industry, which has been recontextualized to produce new architectural effects. The structure develops through the process simultaneously with its material counterpart, and affiliates itself with varying levels of porosity. This aligns different densities of structure with different intensities of program. In the process, the structure is decoded and freed from dependency on point-load transference to one determined by the difference in load-bearing pressures. It provides for an open
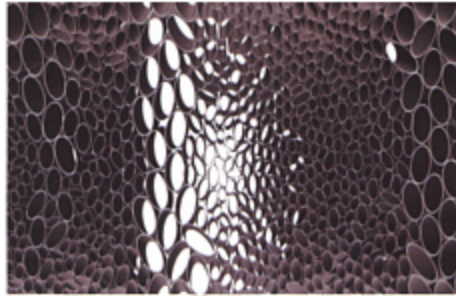
14.19. *Variations:* material modulation.
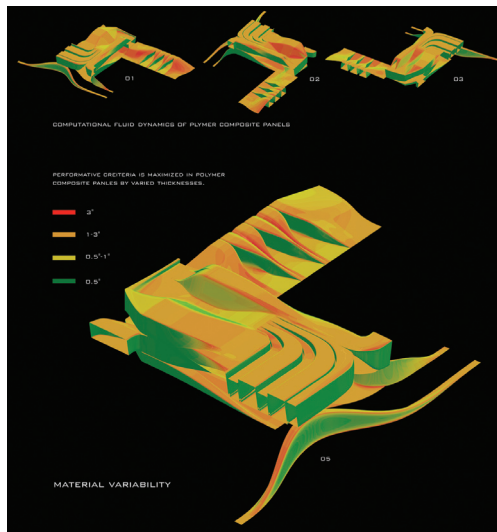
14.20. *Variations:* material variability.

organization, which is specific while simultaneously producing another layer of ambient effects. This potential, when combined with differing densities of composite material panels, provides for a series of emergent lighting effects. This spatio-temporal organization is performative, and seeks variability at all scales-within program, space, structure and material.

Material processes, however abstract, depend on a linear correspondence between concept, form and representation. Continuing the tradition of architecture's relationship to signification and form binds architecture to exhausted rules and potential. The determinate nature of these approaches uses time in its quantitative manner and has carried architectural processes and their resultant static forms producing predetermined effects as far as they could, only to fall short of participating in the dynamic changes continually occurring in contemporary culture. We need to shift this ineffectual model to one that corresponds to cultural evolution where time is qualitative, and consists of duration. This process
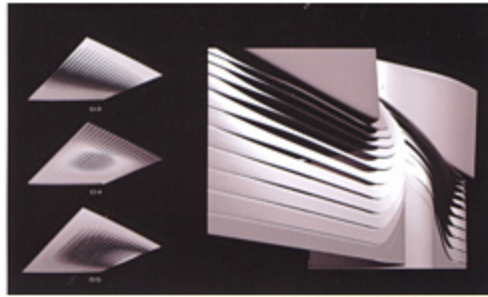
14.21. (far right) *Variations:* louver detail.
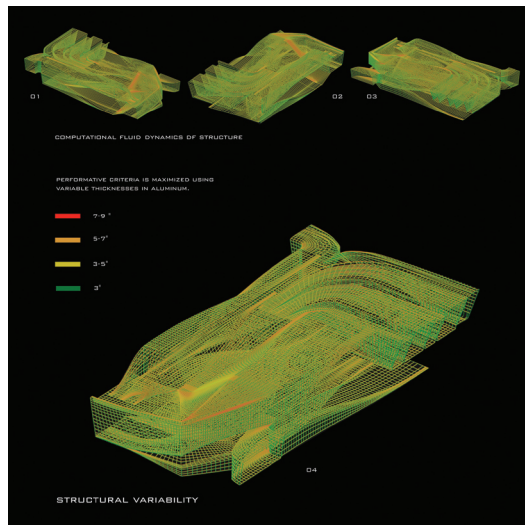
14.22. (far right) *Variations:* structural variability.

sheds the burden of causality by using generative machinic processes of cultural proliferation as a model and removes linear correspondences from concepts to form. Within this temporal animation, objective reality shifts to a potential world of possibility that limits and controls specific combinations of techniques. This meets the quantitative subjective experiential world by shaping a dynamic spatio-temporal organization that produces emergent behavioral effects that influences culture.

These contemporary techniques develop a new sensibility, one of geometric ambiguity, new composite forms and new ways of occupation in space. This spatio-temporal organization guides the subject's experience with mixtures of different programs creating new events, differentiated spaces and composite materials to organize experiences that affect the subject. This organization influences the behavior patterns of the subject qualitatively, resulting in the transformation of culture altering cultural development, and reformulates consequent effects to produce new techniques.

NOTES

1 Larry A.Hickman. *Philosophical Tools for Technological Culture: Putting Pragmatism to Work.* Bloomington, Indiana: Indiana University Press, 2001.

2 Andrew Feenberg describes how the invariant elements of the constitution of the technical subject and object are modified, socially-specific contextualizing variables, in the course of the realization of concrete technical actors, devices and systems. Thus, technologies are not merely efficient devices, or efficiency-oriented practices, but include contexts as these are embodied in design and social insertion.

3 A lineage is the evolutionary path demarcated by a single or combination of cultural entities, through time, as the result of replication.

4 Stephen Jay Gould. *Bully for Brontosaurus.* New York: Norton, 1991, p. 65.

5 Kant's transcendental synthesis of intuition and concept, responding to the empiricism of Locke and the rationalism of Leibniz, claims that knowledge results from the organization of perceptual data on the basis of a priori cognitive structures, which he calls categories, or pure concepts of the understanding. These structures act as rules by which our (ideas) sense impressions and come to constitute our experiences. In other words, the categories govern and shape our understanding of the experience of objects in space and time, for example cause/effect.

"As far as time is concerned, then, no cognition in us precedes experience, and with experience every cognition begins… But although all our cognition commences with experience, yet it does not on that account all arise from experience."

Any changes and adaptations within us incurred by the world would take place within the structure of the categories. It is important to understand, however, that the categories and intuitions remain static. Since all human beings share the same categories, this model of representing the world and our reception of it is determinate and absolute. In other words, our concepts create not only a coherence to one another, they cooperate in constructing a corresponding reality. It is simply the case where one is the product of the other, the casting and the mold, a familiar condition that placed a dominant hold on the entire mode of spatial and material thinking. See Immanuel Kant. *The Critique of Pure Reason* (translated and edited by Paul Guyer and Allen W. Wood. Cambridge (UK): Cambridge University Press, 1998, p. 136.

6 Henri Bergson. *The Creative Mind* (translated by Mabelle L. Andison). New York: Philosophical Library, 1946, p. 197.

7 Roger Caillois. *The Necessity of the Mind.* Venice, California: The Lapis Press, 1990, p. 91.

8 For further reading of collage processes see Jeffrey Kipnis' article "Towards a New Architecture" in Greg Lynn (ed.). *AD Profile 102: Folding in Architecture.* London: Academy Group Ltd, 1993. Here Kipnis posits that "the exhaustion of collage derives from the conclusion that the desire to engender a broadly empowering political space in respect of diversity and difference cannot be accomplished by a detailed cataloguing and specific enfranchisement of each of the species of differentiation that operate within a space" (p. 42). He further explains that "collage is used here as a convenient, if coarse umbrella term for an entire constellation of practices, e.g. bricolage, assemblage and a history of collage with many important distinctions and developments" (p. 48).

9 Constructivism assumes that all knowledge is formed without a mold by way of the process of learning. Nothing is given, neither empirical data, nor a priori categories. Understanding is

accretive. The role of cognition is adaptive and serves our organization of the experiential world. This model is based on fluctuating adaptations and transformations occurring within its system, but is not limited to it. Constructivism utilizes the concept of an epistemological evolution, the notion that the development of knowledge is an ongoing process. Our experiences build upon each other and, consolidated together, build a heterogeneous body of knowledge. This provides for us a framework for inference and adaptation to changing conditions in our environment. The determination of our understanding is based, then, upon the indeterminacy of our experiences, and not the other way around. In this manner, the constructed framework maintains unity, while being able to transform and mutate according to new conditions. The constructivist analysis provides contemporary processes with an opportunity to develop creatively within a mode of abstraction. See Humberto Maturana and Francisco Varela, *Autopoiesis and Cognition: The Realization of the Living* in Cohen, Robert S. and Marx W. Wartofsky (eds), *Boston Studies in the Philosophy of Science,* Vol. 42. Dordecht (Holland): D. Reidel Publishing Co, 1980.

10 See Henri Bergson. *Creative Evolution.* New York: Henry Holt and Co., 1911, pp. 5–6.

11 Lines of external observations and internal experience can be seen as the convergence of lines of both objectivity and reality. Each line defines a qualitative probabilism, and in their convergence they define a superior probabilism that is capable of solving problems and bringing the condition back to the real or concrete. See Henri Bergson. *Mind-Energy.* New York: Henry Holt and Co., 1920, pp. 6–7.

12 Henri Bergson. *The Creative Mind, An Introduction to Metaphysics.* New York: Philosophical Library, 1946, p. 21.

13 Poincaré founded the modern qualitative theory of dynamical systems. He created topology, the study of shapes and their continuity.

14 For more specific discussion on this double articulation, refer to my article "Machinic Phylum: Single and Double Articulation" in Ali Rahim (ed.). *Contemporary Processes in Architecture.* London: Wiley, 2000, pp. 62–69.

15 In a dynamic system, such as that of an oscillation between two trajectories, we generally find a mixture of states that makes the transition to a single point ambiguous. Dynamic systems are unstable and all regions of such systems, no matter how small, will always contain states belonging to each of the two types of trajectories. A trajectory, then, becomes unobservable, and we can only predict the statistical future of such a system. See Ilya Prigogine and Isabelle Stengers. *Order Out of Chaos: Man's New Dialogue with Nature.* New York: Bantam Books, Inc., 1984, p. 264.

16 Gilles Deleuze specifically says that "it is no longer a question of imposing a form upon a matter but of elaborating an increasingly rich [and consistent] material…. What makes a material increasingly rich is the same as what holds heterogeneities together without their ceasing to be heterogeneous." Gilles Deleuze and Felix Guattari. *1000 Plateaus, Capitalism and Schizophrenia.* Minneapolis: University of Minnesota Press, 1980, p. 514.

17 According to the Second Law of Thermodynamics, all natural systems degenerate when left to themselves and have a tendency toward entropy. Time here is a directional continuum and cannot be reversed. This is exemplified in meteorological situations such as the development of clouds before a thunderstorm. See Norbert Wiener. *Newtonian and Bergsonian Time, Cybernetics: Control and Communication in the Animal and Machine.* Cambridge: MIT Press, 1948, p. 32.

18 Instants themselves have no duration. The state of an artificial system depends on what it was at the moment immediately before. See Henri Bergson. *Creative Evolution.* New York: Henry Holt and Co., 1911, pp. 21–22.

19 Here I am taking the idea from the French philosopher Henri Bergson, who wrote a series of texts at the turn of the last century in which he criticized the inability of the science of his time to think the new, the truly novel. The first obstacle was, according to Bergson, a mechanical and linear view of causality and the rigid determinism that it implied. Clearly, if all the future is already given in the past, if the future is merely that modality of time where previously determined possibilities become realized, then true innovation is impossible.

20 Gilles Deleuze. *Difference and Repetition* (translated by Paul Patton). New York: Columbia University Press, 1994.

21 Adolf North Whitehead argues in *Process and Reality: An Essay in Cosmology* (New York: Free Press, 1978) that there are different stages in the act of becoming conscious of potential—and that we cannot pinpoint the actual instance, as temporal increments are able to be subdivided and are dependent upon earlier and later moments to make up this act. As duration is not reducible to points or instants, we are unable to pinpoint this act.

22 What makes a form machinic is when it intermingles with the subjective time of bodies in society. Gilles Deleuze and Felix Guattari explain it as "attractions and repulsions, sympathies and antipathies, alterations, amalgamations, penetrations and expansions that effect all bodies and their relation to each other." Gilles Deleuze and Felix Guattari. *1000 Plateaus, Schizophrenia and Capitalism.* Minneapolis: University of Minnesota Press, 1980, p.90.

15
GENERATIVE CONVERGENCES

SULAN KOLATAN

15.1. *Virtual Terminator*—themed ride.

What do corporate mergers, the new Boeing 888 and infomercials have in common? All are artificial constructs of the late twentieth century. All are products of a network of effects precipitated by forces of global dissipation and aggregation. And each of the above constitutes a new composite entity, forged from elements of already existing entities. In the case of the merger, these elements are the former companies and their array of holdings, their respective managerial structures, their logistical organizations, their physical accommodations and more. In the Boeing's case, they are parts of the bodies of two Boeing 999 fuselages, including seating, storage and mechanical components. And in the case of the infomercial, as the term itself indicates, the composite is formed by crossing an informational television program with a commercial one. The elements here are defined by the conventions and protocols of each program.

These random samples are chosen from the realm of business, technology and popular culture as a way of introducing the notion of *chimera* through an everyday context. Our culture, at present, encourages the formation of such organic hybridity in many different arenas. In fact, organic hybridity is one of the defining productions of late twentieth century culture; a development due to the "structure-generating processes"—a term borrowed from DeLanda—of network techno-logic coupled with bio-logic. While the chimera attains its hybridity through the effects of network logic as seen in the deaggregation and reaggregation of previously sedimented institutional hierarchies, programmatic entities and so-called types, it acquires its organicity through the effects of bio-logic which enable these reaggregations to operate as polyvalent but unified systems.

In his essay *Cooperation and Chimera,* Robert Rosen argues that natural chimera formation—"in which a new individual, or a new identity, arises out of other, initially independent individuals—is a kind of inverse process to *differentiation*—in which a single initial individual spawns many diverse individuals, or in which one part of a single individual becomes different from other parts."[1] According to Rosen, chimera formation is triggered by environmental change and is, therefore, a system's adaptive response when its

15.2. Stills from a range of TV advertisements with houses from the *Housings* project by Kolatan Mac Donald.

survival is at stake. This response is based on modes of cooperative behavior in a diverse and competitive environment. The diagrams underlying chimerization processes are not limited to nature, however. Similar adaptive responses between "graft" and "host" cultures have been noted in recent post-colonial studies, for example, whereby "creolization" and "pidginization" are but two distinct forms of hybridization of language and cultural practices through which a new cultural identity is forged. And while the underlying impetus for the creation of the Boeing 888 might be of a different order, one can see how an argument can be made that corporate mergers and infomercials are forms of adaptive response to changes in the economic and cultural environment.

Architecture is competing in the cultural and commercial fields with the enhanced powers of themed environments, branded products, advertising, the Internet, and the music and film industries (figure 15.1). As we can see, it does not fare very well in competition. It has been argued that under current pressures it will become obsolete eventually or that it is already obsolete. I would like to propose a different scenario, whereby architecture would adapt itself to the new paradigms by adopting a cooperative mode at all possible scales to the extent of forming selective, precise and tactical chimerical systems with the categories listed above (figure 15.2). I believe the conditions for such mergers exist not only in the general flow of contemporary "structure generating processes," but also specifically in the close context of architectural tools and activities.

After a brief discussion of chimera, its definitions, behaviors and formative techniques, this chapter will therefore attempt to show here some of the chimerical potential of CAD/CAM software and engineered materials as well as building programs.

15.3. Mythological *Khimaira*.

15.4. Plant chimera consisting of two or more genetically different tissues—variegation chimera on grape leaves.

WHAT IS A CHIMERA?

The *ur-chimera* is first heard of rearing its multiple heads during Antiquity. Greek mythology registers her as a fifth generation offspring of the Pontus and Gaia union. Said to be of female gender, the *Chimaíra* is represented in the form of a three-headed, fire-spewing, fearsome beast, a monstrous configuration of parts of a lion, a goat and a serpent (figure 15.3). She was the mother of beastly monstrosity, as it were, even by the standards of the Ancient Greeks, who were not timid about conjuring hybrid progeny. Present day references list two of the subsequent meanings that have evolved over time as "incongruous union" and "figment of the imagination." In other words, chimera came to mean a composite so incongruous as to be only existent in the realm of the mind.

In her essay entitled *The Chimera Herself,* Ginevra Bompiani notes: "Although she was unique, her proper name has always been preceded in translations by the definite article, making it a common noun, a multiple entity. Her destiny is embodied in that article: the single character in a single story has become the prototype of every possible composite, every hybrid (including contemporary hybrids of genetic engineering)."[2] In a different passage she continues, "Chimera is a composite but an unstable composite…[that]…tends to decompose and recompose in a thousand different ways." And again elsewhere, she writes, it is the *Chimera's fate* to "never acquire a definite shape or identity" but to oscillate between the unique and an "infinite variety of forms."[3]

Taken together, these passages seem to suggest that the impossibility of ever unambiguously defining the *Chimera* is, in fact, a productive problem because what is at stake here is less the proper and finite categorization of a composite mythic monster but more—and more interestingly—the question of "compositeness" itself.

The compositeness in question possesses two qualifiers among others: organic and nonserial. The Chimera is animal and multi-cephalic, of course. The term organic will be used in a broader sense here, however, namely to denote a systemic connection and coordination of parts in a whole. Such an organic model of the composite would represent "a functional *and* structural unity in which the parts exist for *and by means of* one another."[4] The combined presence of functional interdependence and structural oneness between the heterogeneous components in the organic model of the hybrid markedly differs from that of a mechanical one that is based on "a functional unity in which the parts exist for one another in the performance of a particular function."[5] For the latter system to hold together, transitions between the individual components must generally occur through the introduction of intermediary pieces that afford connections and adjustments within the system overall and locally between the parts. In the former, on the other hand, transitions generally take place by way of transformation of, and between, the components.

CHIMERA AND CONTIGENT OR MOMENTARY NORMALITY

A biological chimera constitutes an artificially produced but, occasionally, also spontaneously occurring condition in which individuals are composed of diverse genetic parts (figures 15.4–6). The purpose for this line of experimentation generally falls into two interconnected categories: one, the generation of new identities more viable under certain

circumstances than their predecessors, and two, the advancement of knowledge pertaining to normative types through the study of pathological forms. As we have seen above, spontaneous chimera formations in nature are almost always a result of an adaptive response to environmental change.

Let us discuss here, briefly, the terms normative and pathological in connection with chimera. As a hybrid, chimera falls into the category of pathologies. Canguilhem, however, in his book *The Normal and The Pathological,* makes some significant and helpful distinctions when he writes:

15.5. "Geep," naturally occurring animal chimera between a goat and a sheep.

15.6. "Zedonk," naturally occurring animal chimera between a zebra and a donkey.

15.7. *Warhead I,* artist Nancy Burson.

15.8. *St. Bernhard (Misfit),* taxidermic animal chimera, artist Thomas Grunfeld.

No fact termed normal, because expressed as such, can usurp the prestige of the norm of which it is the expression, starting from the moment when the conditions in which

it has been referred to the norm are no longer given. There is no fact which is normal or pathological in itself. An anomaly or mutation is not in itself pathological. These two express other possible norms of life. If these norms are inferior to specific earlier norms in terms of stability, variability of life, they will be called pathological. If these norms in the same environment should turn out to be equivalent, or in another environment, superior, they will be called normal. Their normality will come to them from their normativity. The pathological is not the absence of biological norm: it is another norm but one which is, comparatively speaking, pushed aside by life.[6]

According to Canguilhem then, whether a chimera is considered pathological or normal depends entirely on its capability to perform in a particular environment. He goes on to state: "In biology the normal is not so much the old as the new form, if it finds conditions of existence in which it will appear normative, that is, displacing all withered, obsolete and perhaps soon to be extinct forms."[7]

By chimerizing, one system "normalizes" in relation to another stronger one.

CHIMERICAL FORMS AND BEHAVIORS

Composite Figures

Warhead I (figure 15.7), a digital work by the artist Nancy Burson produced in 1982, is described thus by Fred Ritchin: "Weighting her image to the number of nuclear warheads deployable by each country, the artist made a composite figure which is 55% Reagan, 45% Brezhnev, and less than 1% each Deng, Mitterand and Thatcher."[8] Multiple identities seamlessly and inextricably merging into a new singular identity; neither the digital structure nor the representational function of the image betray any lack of unity. The heterogeneous components that brought forth a non-serial reproduction of variants of the head in the mythological chimera are smoothly blended here.

The startling effect of this image arises at first from a sense of vague recognition, and then, upon learning about its making, from the surprise over its "secret" content, both in terms of the "other" information that is indirectly represented through the weighting, as well as in the discovery of the presence of figures that are barely there due to weighting, such as Thatcher, for instance.

"Wolf in Sheepskin"

Is the artist Thomas Grunfeld's taxidermic *Misfit (St Bernhard)* a highly evolved version of the "wolf in sheepskin" (figures 15.8– 15.10)? This is an insidiously monstrous hybrid, both in the meticulous, dare I say loving, execution of the taxidermy, as well as in the cunning matching of the initial components. Thus, at first sight, this hybrid is so subtle as to appear perfectly familiar. The triangle of interrelations between wolf, dog and sheep, which seems to be hinted at here, is full of ambiguity. The wolf and dog share a common genealogy, although in relation to the sheep their roles are antagonistic. The sheep are the wolf's

prey and the dog's herd. The *Misfit* is rendered in a restful pose and with a docile look, as if belying its appellation, and the conflict between its initial identities. How will this animal behave? Will the sheep heed its inner dog? Will the herd roam around in packs?

Fantastic Unity

This time the object has a fantastic unity as it appears before the viewer: it reposes on pebbles, neither with the pressure of a foot nor that of a boot, but with a weight all its own, suggesting uncanny functions which cannot be associated with any known ones. The container (the boot) and the thing contained (the foot) have achieved an entirely new reality as a new object.[9]

15.9. *Mutter und Kind (2 Misfits),* taxidermic animal chimera, artist Thomas Grunfeld.

15.10. *Untitled (Misfit),* taxidermic animal chimera, artist Thomas Grunfeld.

15.11 *Le Modèle Rouge,* artist Rene Magritte.
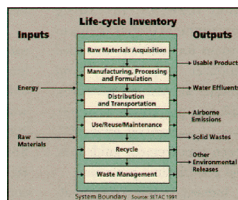
15.12. Industrial Ecology Diagram.

The object thus described is the subject of a painting by René Magritte entitled *Le Modèle Rouge I* (figure 15.11). Actually, he did a series of paintings on the same subject with the same title. It is possible that he did so because he was interested in formulating problems through his paintings, specifically, problems concerning the commonly accepted "normality" of things, like "the problem of shoes." Considered in this way, these paintings might be seen as variable speculations on the relationship between shoe and foot, inextricably fused, as it were, through a logic of elective affinities that appears throughout Magritte's work.

What we see in the painting is an exterior view of the front of a pair of feet *invisibly transforming* into the heels and ankles of a pair of boots. The precision and literalness of the detailing, particularly in the general areas of transition, provoke a host of speculative questions, of which I would like to pose a few here while taking the image at face value. First, if this foot/boot-object existed, what would be the implications and conditions of its existence? Judging from what we see, the object is held together by the structural unity between skin and hide, that is, between live and dead skin. When this kind of fusion is produced biologically, between two live host and donor skins, it is achieved through a technique called *grafting*. Over a certain period of time, the two skins grow into a singular one and operate as a continuous structure with qualities of both. If we imbue the visual blending in *Le Modèle Rouge* with the operational qualities of grafting, how would the skin/hide register the effects of time, wear and tear, aging? Would the "footness" of it allow the "bootness" of it to heal its cracks?

15.13. *Patagonia* jacket made from recycled plastic bottles.

What we do not see is the interior of the foot/boot-object, which poses questions of even greater mystery. At least, on the exterior we can see the transformation, but what a section might show we must conjecture, as the painting denies us the assumption of "normal" interrelations of inside/outside, full/ empty, space/skin, thick/thin, heavy/light.

It is important to note that the boot/foot object is not a problem of generic container/contained relations but a very specific one in which the container and contained do not only share a "material" similarity, but in which the boot is made to fit around the foot as a second skin, in which the sole of the boot duplicates the sole of the foot, and so on. Far from being a chance encounter, this incongruous coupling was carefully engineered by Magritte based on affinities between an object and a human body part.

But What Does It Have To Do With Architecture?

I have tried to show above how the chimera's significance stems from its provocation of speculations on (organic and non-serial) compositeness on the one hand, and its putting into question of the normative through pathological or experimental form on the other. The introduction of this notion into the field of architecture can be productive as an analytical means, provided the contemporary city is a culture conducive to chimera, and as a methodological tool if the computer is an instrument with a special capability for chimerization.

CHIMERIZATION IN ARCHITECTURE

On a macro-scale, a chimerical logic binds architecture into a cultural, commercial and industrial ecology (figure 15.12). It considers architecture in terms of product-systems and related processes. Viewed in this way architecture is but one system organically interconnected with many others, such as man-made object-systems and infrastructures as well as natural eco-systems.

One of the benefits of considering architecture as a product-system embedded within a world of other systems is the possibility of a so-called "cradle-to-grave" evaluation. Such long-term lifecycle assessment reveals opportunities for convergence between different systems at various stages. The field of industrial ecology thrives on such convergence. Its operating mode, simply put, is based on the assumption that machinic and biological processes both involve the transformation of matter and energy, and that, therefore, industrial

15.14. *Mercedes-Benz Vario Research Car* (VRC). "Four Car Concepts in One. Imagine the following scenario: You and your family go on vacation driving a luggage-packed stationwagon. Once you arrive at your destination, you drive to a Mercedes-Service-Station. While you are having a cup of coffee, your stationwagon mutates into a convertible. For the trip back home, the car is re-equipped as a stationwagon." (From mercedes-benz.com)

15.15. Still from the *Con Air* movie (1997). Final scenes with the plane flying over the Las Vegas strip about to crash into the Dunes Hotel…

manufacturing processes can perform like—and together with—natural eco-systems. Some of the goals of this line of thinking include a more effective use of natural resources and energy as well as the elimination of waste. Thus, co-production, combined waste treatment and recycling, in which waste from one product system is used as a secondary resource in another system, are some of the most frequent methods of merging initially separate processes belonging to distinct product-systems into chimerical meta-systems (figure 15.13).

Many times these systemic hybrids engender chimerical forms in the product itself as well. Let us examine *cross-platforming,* an increasingly popular kind of co-production. The *Mercedes Benz Vario Research Car* (figure 15.14) is an interesting case in point. Following the question "what do a sportscar, a sedan and a minivan have in common?" the designers proposed what they call a "universal chassis" as a platform from which to launch a whole "family" of interchangeable vehicle bodies. As a result, the *Vario* can transform over the course of an adult life, metamorphosing in response to the periodic needs and desires of the owner while conserving materials. I would argue that their chassis is chimerical rather than universal. It is not so generalized that any and every car body can be mounted on it. Rather, it is multiply indexed in relation to the specific body types it seeks to accommodate.

Cross-platforming as a form of production is inherently chimerical insofar as it operates on the basis of finding and exploiting affinities between diverse systems. The multiple identities of the *Vario* are variations within the same product-category but cross-platforming is not confined to product-categories. In fact, one of the big Japanese auto-companies is currently cross-platforming between the manufacture of their cars and their prefabricated houses.

An example of this type of ecology between architecture and film occurred in the making of the movie *Con Air*. It was more a matter of creative recycling than co-production, when the interests of the film producers and the owners of the *Dunes Hotel and Casino* in Las Vegas, who were in the process of replacing the building, coincided. The *Dunes* was taken down in the movie's final crash scene (figure 15.15). It was a win-win all around, with the hotel crew saving on demolition and the film crew saving on the construction of costly temporary scenery. The convergence here goes beyond mere economic calculus and into the socio-psychology of human fascination with the spectacle of demolition or demolition as spectacle. To the extent that every mundane demolition is a potential cinematographic event, there is a latent systemic connection when it comes to parallel cradle-to-grave assessments between architecture and film. (Sadly, none of us could help but notice that an enormously more complex and twisted version of this connection has been borne out in the recent World Trade Center attack.)

HOW ARE CHIMERA FORMED?

Becoming

In choosing to work with software specifically created for industrial design and for film animation rather than for architectural design, our studio explicitly engages the issue of cross-categorical pollination by problematizing it in the design process itself. In this way, the architectural design process is affected by what I call a "productive inadequacy." The design tool is not entirely but somewhat inadequate in that it has not been made to address the conventions of architectural design but rather those of another kind of design. It is, as

it were, like having to write with a knife. One has to rethink "writing" through the logic of "cutting" to arrive at "carving." The idea of inadequacy as a trigger for inventive and continual categorical transformation is intriguingly presented in Deleuze' description of Vladimir Slepian's *Man-becoming-Dog* problem. In order to become a dog without resorting to imitation or analogy, the man uses a pair of shoes to trigger a series of responses toward a desired goal of becoming a dog:

> If I wear shoes on my hands, then their elements will enter into a new relation, resulting in the affect of becoming I seek. But how will I be able to tie the shoe on my second hand, once the first is already occupied? With my mouth, which in turn receives an investment in the assemblage, becoming a dog muzzle, insofar as a dog muzzle is now used to tie shoes. At each stage of the problem, what needs to be done is not to compare two organs but to place elements or materials in a relation that uproots the organ from its specificity, making it become 'with' the other organ…[10]

In a similar sense, addressing architectural problems through non-architectural software "uproots" the specified rules of the design process. New rules have to be invented. Insofar as the use of a dog muzzle to tie a shoe produces a complex chimerical system of man-dog categories, the use of simulated effects—to name but one tool of the software—in order to create a building envelop or structure, yields a complex chimerical system of architecture-film-product categories.
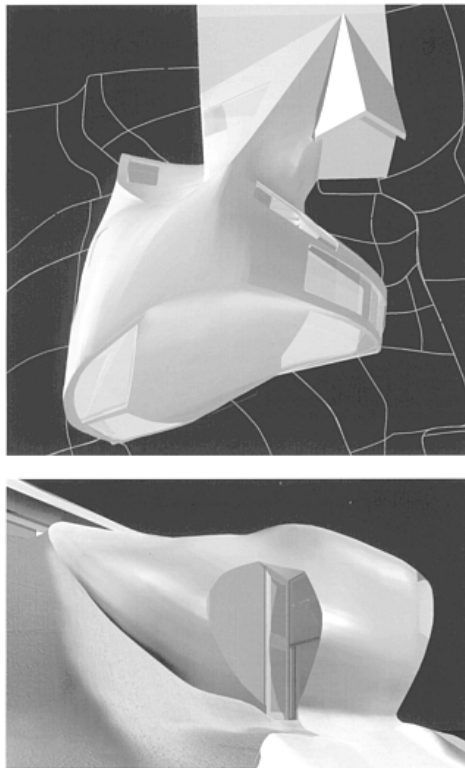
15.16. *Raybould House and Garden* project, architect Kolatan Mac Donald.

This connection between categorical cross-transformation and the categorical transposition of tools again became evident to us during the *Raybould House* project (figure 15.16). The project, a house addition, had been designed by combining parameters derived from the existing house and its landscape. To our delight, the contractor informed us that the construction of the monocoque shell involves the cutting of foam used in the sandwich by a person walking across the house's surface with a kind of lawnmower. Thus, the house is made like a landscape. Not metaphorically, but literally, both in its conceptual generation and in the actual construction process. The quasi-lawnmower operates like the dog-muzzle.

Lumping

The logic of lumping, of bringing together different—sometimes disparate—elements, is one of lateral operations. "Cross-" and "inter-" are its prefixes, as in cross-breeding and interdependence, cross-section and interface, cross-country and interstice, cross-platforming and interdisciplinary. Lumping proliferates horizontally, by blending between already matured systems across different categories. It is clear that lumping as used here is different from an everyday understanding of the term, in that it is not haphazard but significant. Significant lumping affords productive leaps, it has rules. Lumpers are motivated by horizontal or lateral becoming in which *already* complex identities merge into a single body and system.

Co-citation

As noted earlier, a successful chimerization, in which the parts bind together to operate in newly productive ways, requires the precise identification of affinities and similarities between multiple systems. How then are affinities mapped in a heterogeneous environment? Co-citation indexes and maps have been developed in response to this question (figures 15.17 and 15.18). Simply put, co-citation maps are spatial representations of networks of texts related in content. They are used to establish precedent between individual cases in law. They are also used to track cross-categorical connections in scholarly research, as between the humanities and science, for example. These maps have provided a helpful model for us in constructing similarity maps of a different kind. Our "citations" include morphological, performative, scalar, programmatic and process-based attributes. Digital media, with its capacity for similarity-scanning and "sorting" based on attributes, plays a significant role in this process.
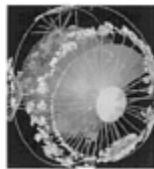
15.17. Three-dimensional hyperbolic graphs of the Internet topology.

15.18. Graph indicating the portion of a corporate intranet that is "leaking" with the Internet.

Tuning

This method of weighting, or tuning, emerges as a significant one in the making of the chimera. Owing to the aforementioned organic quality, the proportion of the ingredient identities in any chimerical construct can be fine-tuned across a theoretically infinite range of hybrid variants (figure 15.19). The potential for (lateral) non-seriality is therefore always given, even if not pursued in each case.

Range

I have defined the chimera as a system of organic, non-serial, unstable composite identities possessing an infinite as well as infinitesimal range. We are particularly interested in working with the notion of process as a kind of "sliding scale," capable of being advanced or reversed along a range of difference, or tuned into a precise instance of variation (figure 15.20).

The eventual actualization of one or more instances of this process does not significantly change this definition. The individual instance or the actualized product is always linked to the "range" provided by the generative system whether actualized or not, thereby shifting the emphasis from the "unique object" to the system and its capacity to produce significant variation. The latter are instances of variance with a new identity in at least one or more of the attribute categories mentioned above.

15.19. The "tuned" VW Golf with single windshield wiper.
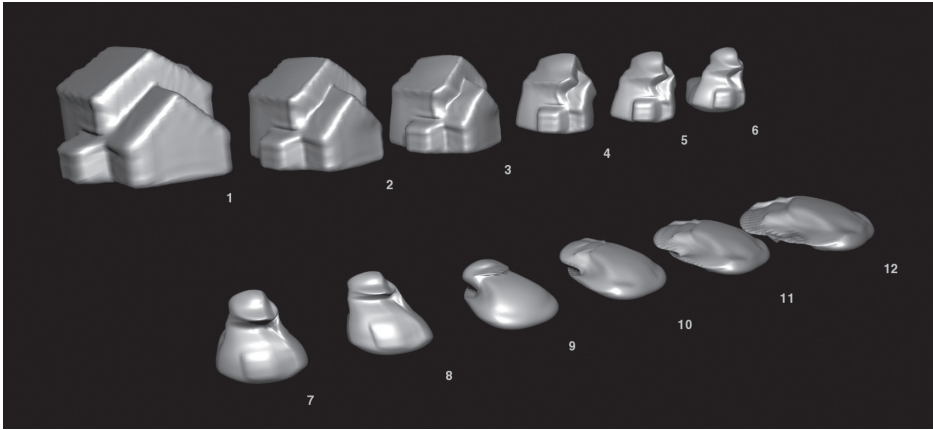
15.20. Chimerical blending operations in the *Housings* project, architect Kolatan Mac Donald. One of many possible transformations using the "Colonial House" as "base" and multiple "target" objects. A concept House for mass-customization.

CHIMERICITY IN ADVANCED MATERIALS

In the realm of materials, a shift from found to engineered qualities is transposing functionality from between the parts of a machine to within the material and its molecular make-up. That is to say, the material itself performs the functions of a machine (figure 15.21). Furthermore, what makes these materials "smart," i.e. what enables them to not only react to environmental stimuli which dumb materials do to some degree as well, but also to learn from their cumulative "experiences," is their composite nature.

A chimerical hybrid is neither produced by an act of balancing, nor one of averaging between the parts. The following passage on the dynamic behavior of ferrofluids (figure 15.22) illuminates the intricate workings of one chimera, and the precise tunings necessary to coax chimerical behavior:

> Pity the gryphon, the mermaid, the silkie, the chimera: creatures assembled of incompatible parts, with uncertain allegiances and troubled identities. When nature calls, which nature is it? When instinct beckons, approach or flee? A ferrofluid is a gryphon in the world of materials: part liquid, part magnet. It is prepared by grinding magnetite—the magnetic lodestone—in an oil. The grinding must be "just enough." If the particles of magnetite are too large, they remember who and what they were and behave like fine magnetic powder, clumping and settling rapidly from the oil. If they
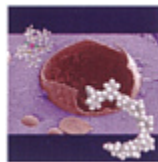
15.21. Graphic image manipulated from a scanning electron microscopic image. The ruptured capsule is red; the fracture plane is light blue. The chemical structure appearing to emerge from the capsule is the polymerized healing agent.

are too small, they no longer show any of the wonderful cooperation between groups of atoms that is required for magnetism. If they are just the right size— if they are small enough that they are.not so different in size and character from molecules of liquid, small enough that they have begun to lose their magnetic heritage, but still large enough that they again become fully magnetic when placed in a magnetic field they develop a useful schizophrenia. Outside a magnetic field, they are non-magnetic liquids; inside a magnetic field, they become magnetic.[11]

 In the case of the ferrofluid there is a finely drawn threshold at which the embedded behaviors of the fluid and the magnetite begin to act in a way that is more than their sum. This useful schizophrenia allows the ferrofluid to do things it was not capable of doing as magnetic dust or as fluid. In order to reach this threshold of useful schizophrenia, the size of the shavings has to approximate the size of the molecules of the liquid. It seems the productive dynamics is triggered when the two components engage at a point of similarity (figure 15.23).

In sociological or post-colonial terminology, this kind of behavior is referred to as "practicing situational identity," changing identification as the context shifts.

Another interesting case of unstable identity produced by composite materials is *Mothra,* a model plane developed by aerospace engineers at Auburn University (figure 15.24), and lovingly named after Godzilla's flying friend. Using a reverse piezoelectric effect, whereby applying an electrical field to the material induces a mechanical distortion, the researchers were able to maneuver a plane in flight by twisting and shape-shifting its wings, thus eliminating the gears, the hinges, and the bearings.

15.22. 1999 *National Science & Technology Week* poster. Ferrofluid has been placed against a yellow background and exposed to a magnetic field (note peak formations!). 226

15.23. This thin, flexible film contains a piezoelectric material that responds to the bend by producing a voltage that is detected by the electrodes seen at the bottom left of the image.

PROGRAM CHIMERA

Perhaps one of the fastest changing areas in response to external socio-cultural and economic pressure is program. The current dynamics is that of a reactivated sedimentation, as it were, of institutional hierarchies and program-types. These now mobile program components are in the process of deaggregating and reaggregating into new configurations and Identities. However, the new identities are chimerical not only due to their compositeness. They are less fixed more tentative configurations that remain in a flux contingent on external and internal stimuli.

A design studio I ran a couple of years ago first drew my attention to this phenomenon. The students and I were visiting the New York Police Department headquarters in Manhattan, where we discovered that the 911 operations—which were, until then, integral to the police department program—had become very large and were therefore going to be moved to another borough where real estate prices were lower. Since this component of the police department was operating more like an office, and since it did not need a physical adjacency to the other functions, it could physically deaggregate from the department and reaggregate with other programs with which it shared its office-like operations and logistics. Furthermore, it was linked to a translation service located in New Mexico. The office-like structure in this case plays the role of the particle size in the ferrofluid to the degree that it provides the mechanism of linkage between two foreign systems. Similarly, we saw a Starbucks/Cosmo chimera emerge before the premature demise of the latter company last year. Starbucks is a ubiquitous network of cappuccino franchises. Cosmo was an internet-based video rental company. The deal was that they would deliver your video within an hour to anywhere within the city, and you would later drop it off at any Starbucks location, and perhaps pick up your cappuccino in the process. If economics was the force driving the chimerization above, convenience was the force behind it here.

15.24. *Mothra,* the first plane to fly with "smart control surfaces."

HOUSINGS

Housings constitutes the initial portion of a long-term project that focuses on experimental designs for mass-customized prefabricated housing (figure 15.25. shows a set of six houses). These six houses were selected from a series of digitally-designed variants. All variants originate from the same "genetic pool." Information for the "genetic pool" was generated from a normative three bedroom, two and a half colonial house plan as "base," and a range

of object-products as "targets." Subsequent digital blending operations between "base" and a varying number of "targets" in turn produced a large range of chimerical houses.

15.25. Six "supreme" variants sampled from a range of *Housings,* architect Kolatan Mac Donald; exterior envelopes shown.

Housings sets out to explore the question of non-serial and organic compositeness in architectural design on three parallel tracks. One, in relation to digital processes with their capacity for variable iterations, organic transformation, and cross-referencing. Two, in regards to issues of viability—can a hybrid outperform existing normative types in a particular social, cultural, economic, ecological, geological and climatic life-context? And three, vis-à-vis an emerging generation of composite materials and digital production technologies.

Remarkably, CAD/CAM software now constitutes, in effect, cross-platforms from which such diverse products as coffee machines, running shoes, cars, films, virtual and physical environments, and architecture are being launched. In other words, the tools for making, the processes of mental and material creation, can no longer be assumed to differ fundamentally between product categories of the man-made. Contemporary theory and practice has no choice but to concern itself with this "generative convergence" and its consequences. The established terms of classification of so-called "second nature" must be reevaluated.

NOTES

1 Robert Rosen. "Cooperation and Chimera" in J.Casti and A.Karlqvist (eds), *Cooperation and Conflict in General Evolutionary Processes.* New York: John Wiley and Sons, 1995, pp. 343–358.

2 Ginevra Bompiani. "The Chimera Herself" in M.Feher, R.Nadaff and N. Tazi (eds), *Fragments of the Human Body Part One.* New York: Urzone, 1989, pp. 365–409.

3 *Ibid.*

4 *Ibid.*

5 *Ibid.*

6 George Canguilhem. "The Normal and the Pathological," translated by C.R. Fawcett. New York: Zone Books, 1991, p. 144.

7 *Ibid.*

8 Fred Ritchin. *In Our Own Image: The Coming Revolution in Photography: How Computer Technology is Changing our View of the World.* New York: Aperture, 1990, pp. 136–137.

9 Anna Balakian. *Surrealism: The Road to the Absolute.* Chicago and London: University of Chicago Press, 1986, p. 205.

10 Gilles Deleuze and Felix Guattari. *A Thousand Plateaus,* translated by Brian Massumi. Minneapolis: University of Minnesota Press, 1988. pp. 258–259.

11 Felice Frankel and George M.Whitesides. *On the Surface of Things: Images of the Extraordinary in Science.* San Francisco: Chronicle Books, 1997, p. 57.

16
OTHER CHALLENGES
ANTONINO SAGGIO

16.1. *Saint Paul's Conversion* (1600–1601), Santa Maria del Popolo, Rome, artist Caravaggio.

The first issue to be addressed is the difference between our public image—what we represent—and what we really think. This chapter will try to describe not the result but the process, not the theory but the spirit, not the object but the subject.[1]

I will start with a word that is very important for me. That word is "sostanze" in Italian, and "substances" in English. It comes from Edoardo Persico, who borrowed it from Saint Paul. In the conclusion of his 1935 Conference titled "Profezia dell'architettura," Persico said:

> For a century, the history of art in Europe has not merely been a series of particular actions and reactions but a movement of collective consciousness. Recognizing this means discovering the contribution of current architecture. And it does not matter if this premise is denied by those who should most defend it, or betrayed by those who, in vain, most fear it. It still stirs up the secret faith of the era all the same. The substance of things hoped for.

We are facing a very important moment of transition, and because of that transition, we are at the same time facing a crisis. The industrial society is being replaced by an information society, and that transition is changing completely the rules of the game—of all games, including those of architecture. If the dynamo for the former was large industry and the machine, then for the latter it is the places of the tertiary sector. The machine of today is the computer—it is driven by the systems of formalization, transmission and development of information. If the very rich then were industrialists, today they are the producers, not even of hardware, but of software for software. This, of course, has all been well known since Alvin Toffler wrote *The Third Wave*.[2] But today we have begun to understand how that wave is transforming the terrain of our discipline.

We have to understand that the current transition also presents opportunities for new visions and new aesthetics. Facing these challenges and understanding how to transform the crisis into new values is the potentiality of Modernity that I care the most about.

   I used the "Postmodern" table by Charles Jencks as a background for what I call the "Philadelphia Chart" (figure 16.2) to emphasize a key difference—I think that our task as architects and critics is not to engage in the labeling of various "stylistic" movements, but to delve into the reality of the contemporary. I used "Drillings into the future" as a subtitle for my book on Peter Eisenman;[3] in my view, his half submerged *House XI* embodies the idea that the contemporary condition deals simultaneously with both the past and the future.

URBANSCAPE

What then are the new substances? Architecture is blooming again. Interesting buildings are being built everywhere (except in Italy). New ideas are emerging from the crisis of transition; we have new architectural methods.

   I will start with the simplest example to illustrate the new condition—the phenomenon is known as "brown areas" and the key word is "urbanscape." The information society has less and less need for great tracts of land to produce manufactured goods, particularly those located in the cities. The vegetables we buy at the supermarket are 90% "information;" the same, only more so, is true for electrical appliances or automobiles. More and more people produce goods that are "pure" information. Throughout the Western world, large land areas are liberated from factories (which could become increasingly smaller, less polluting and less destructive); great resources are once again put into play, first of all, those abandoned by industrial production. Designing today within those "brown" areas implies a profound reconsideration of the city and its functioning, simultaneously opening up new methods of both expressive and aesthetic research. The morphological typologies and categories of urban analysis, derived in the 1960s and 1970s from studies of a consolidated, structured city, have become more and more ineffective and indeterminate if used to define the design parameters. New methods of looking at the city have emerged that examine the complexity, interchange and interweaving of architecture and the environment. It is only natural that architects should move further away from the metaphysics of De Chirico, of a city of archetypes fixed in the memory, and look at the research of artists more attentive to the phenomena of stratification, residuality and hybridization—towards the sackcloth and cracks of Burri, the torn posters of Rotella, the American neo-expressionism of Pollock or Rauschenberg, and obviously the toughest battlefronts of Pop-Art or "Arte Povera." Architecture insinuates itself into the weave of existence. It uses and relaunches pre-existing objects, such as the ready made ones. With its dynamic declarations, it creates spaces in the cracks "between" the new and what already exists. But beyond the expressive choices, or the frightening "twisted scrap iron," a very different idea of architecture for the city is being acknowledged.

   Consideration of the most successful works leads to their definition as operations of "urbanscape." They are the great works of rethinking the city, its intersections, its dynamic flows, its complex links. There are two key works: one is in Bilbao—seemingly a plastic exercise along futurist lines, in reality an urban intersection which

creates new civic spaces; the second one is in Tourcoing—an apparent conservation of pre-existing structures that actually invents a interstitial space between a new shelter and the pre-existing roofs in a fluidly mediating, multimedia, digital vision of Piranesi-like winding ravines.
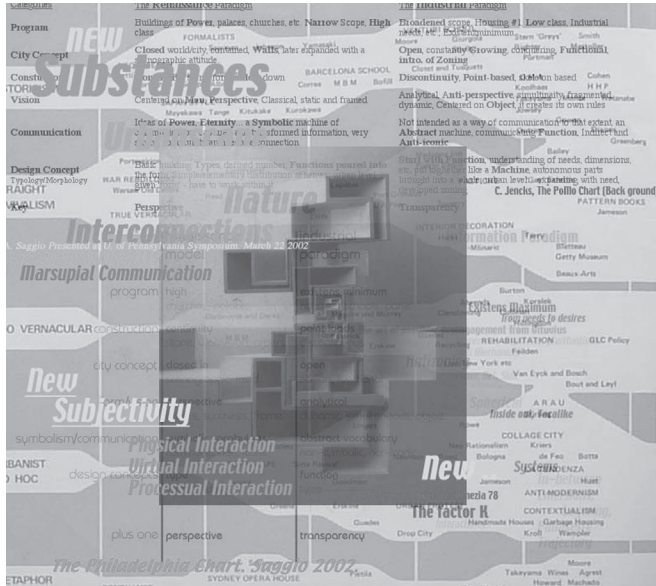
16.2. The *"Philadelphia Chart 2002"*—the image is a combination of notes, key words and concepts. Background—the chart by Charles Jencks (*The Language of Post-modern Architecture,* New York: Rizzoli, 1977); foreground—*House XI* (1978), architect Peter Eisenman.

It was Frank Gehry who selected the actual site where the *Guggenheim Museum* was to be built (figure 16.3). He chose the most untypical site that was incredibly depressed, very messy. He selected an urban junction that would be impossible to select if one were to use "normal" architectural parameters. But those parameters are changing now; we now understand how to deal with complexity, how to use architecture to address problems and reshape spaces in an urban fashion. That idea was not clear at all 15 years ago. It has become very clear now, as projects by my students at Pittsburgh's Carnegie-Mellon University and Rome's La Sapienza show (figure 16.4 and 16.5). We know what "urbanscape" is, we can teach that approach clearly.
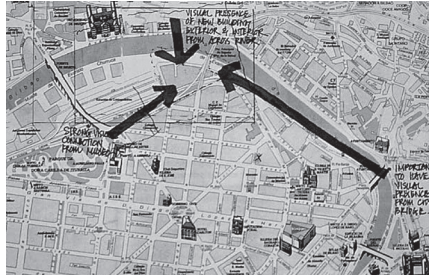
16.3. Frank Gehry's sketch on the map of Bilbao showing the future location of the Guggenheim Museum.

UN-NATURE

The second "substance" is related to our understanding of nature. Because of information technology we have a great opportunity to deal with nature again. Our idea of nature is in some way "unnatural;" we are recreating it with a set of completely new tools. The motto of "rebuilding nature" captures our half artificial, half ecological attitude.

The relationship between the new conception of nature and information technology is at least fivefold. First, the post-industrial man of the electronic civilization can resettle his accounts with nature; if manufacturing industries had exploited natural resources, then information industries can appreciate and value them within new production systems. Second, this structural change of direction opens in the inner cities of the West (and in other regions) the opportunity for a "compensation" of historical proportions. We can now insert greenery, nature and recreational equipment into the high-density zones. Third, the idea of the "fenced park" tends to be substituted by new parts of an integrated city in which—alongside a substantial presence of nature—interactive activities of the information society are also present. If homogenous zoning was the method of planning the industrial city, then multifunctionality and integration define the needs of the information city. Fourth, aside from creating these opportunities, computers also allow their concrete realization.
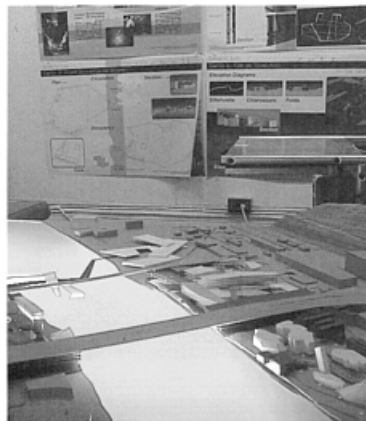
16.4. Liquid Strips Exhibition, Fitz-Gibbon Saggio Studio IV, Carnegie-Mellon University, Pittsburgh, December 2001.

Interactive systems of illumination, information, sound and other controls can make these new parts of cities active, lively, participatory, and rich in events. Fifth, the nature shaped by these forces is no longer one that is floral, or art deco, or even that of the masters of organicism. It has become much more complex, much meaner, much more "hidden," as Heraclitus once said. It is investigated by architects with an anti-romantic eye through the new formalisms of contemporary science (fractals, DNA, atoms, the relationship between life and matter). In other words, different categories of complexity have emerged. The figures of flows, waves, whirlpools, cracks and liquid crystals are born within this context. The key word here becomes "fluidity;" it describes the constant mutation of information and puts architecture alongside the most advanced frontiers, from biological engineering to new fertile, overlapping areas of morphogenesis, bioengineering, etc. The fifth level of connection between the nature and the computer is crucial, because the computer becomes not only the driving force that initiated the change, as understood in Marxian structural terms, but at the same time it shapes this new hybrid concept of architecture and nature. How to otherwise design a building as a cloud, or campus as a telluric crack?

The key work here might be one of the rejected projects from the Competition for the Church of the Year 2000 in Rome—a project by Peter Eisenman (figure 16.6) that saw the church as a terrestrial dance between continental plates that deform the land, patterned around a zigzagging canyon which recalls the ravines dug out by streams of water in soft rock.

16.5. Reusing of the Tiber's Edges, student I.Benassi (advisor A.Saggio), La Sapienza University, Rome, 1999.

16.6. Peter Eisenman's competition entry for the Church of the Year 2000 in Rome (1996).

MARSUPIAL COMMUNICATION

Another thing that we are starting to understand is what I would call the "marsupial communication." Information technology is also about communication. Architecture has much in common with other disciplines, from advertisement to art to other forms of communication. Instead of manifesting an absolutely objective logic (separation of structure and content, coherence between interior function and exterior form, division into zones appropriate for different uses), inherited from the early Modernism, we can start to readdress the issue of communication. The functional is substituted with narration; a building is no longer good if it just works efficiently—it must both give and say more, and even rely on symbols and stories when that is useful. Can we dig in our heels and call upon a different ethics, a different morality? Perhaps, one more time; the central question is merely "how?" The communicative moment could certainly be that of the large Disney hotels with swans, seven dwarfs and cowboy hats, but it cannot be an artificial application of forms and contents symbolic of a boxy architecture, which are entirely foreign to this notion. It requires a narration that pervades the essence of the building and intimately ingrains itself into its fiber. In other words, we need to see "what" communication is desired and possible; we need to seek one that does not just follow the weak, half-hearted celebration of economic or political power.
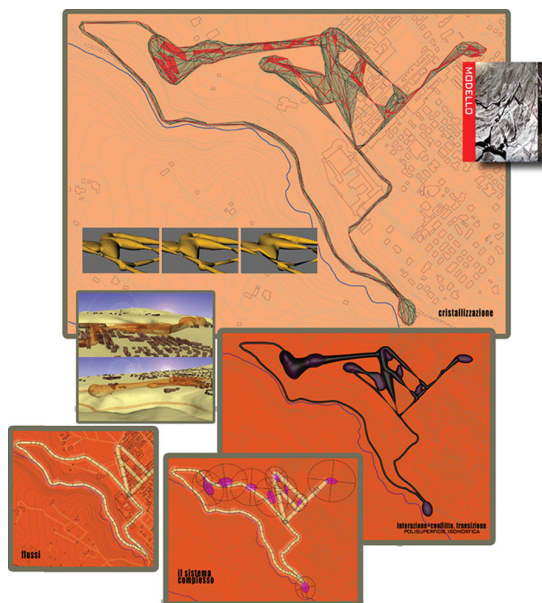
16.7. Campus for the Research of Volcano Laziale, Grottaferrata, students F.Ceci and M.Rucci (advisor A. Saggio), La Sapienza, Rome, 2001.

16.8. THE KIASMA MUSEUM (1998), HELSINKI, FINLAND, ARCHITECT STEVEN HOLL.

The key work that captures this new spirit of communication might be in Helsinki, where a new museum (figure 16.8) has been conceived by Steven Holl using the same layered structure that the optic nerves have in the brain. The anatomical metaphor is placed over the rhetorical figure of the same name. The operation has been so successful that it has been confirmed in the very name given to the museum (Kiasma).

But why "marsupial"? Well, that word captures the fact that architecture is on one side part of the great world of communication (so it cannot be divided from cinema, advertisements, music, etc.), and, on the other side, it uses communication as a tool of its new essence. Content and context, inside and outside, are naturally merged.

16.9. *Stone House,* Stendorf, Austria (1986), architect Günther Domenig.

SUPER-FUNCTIONALITY

The buildings mentioned so far are in fact "communication machines." Their primary value is in their capacity to employ rhetorical figures, to communicate metaphorically, which does not detract at all from what I call "super-functionality." If we compare functionality of the museum in Bilbao with its namesake in New York finished in 1959 by Frank Lloyd Wright, we can see how much we have gained in terms of pure functionality. The modernist architect had to have a closed system of consistencies: form follows function, construction reveals form, the key spatial concept (i.e. the ramp of New York's Guggenheim) creates a clear hierarchy of all subsequent choices. Contrary to that, we operate today in a system

liberated from the obsession towards consistency. Design today is akin to a network of integrated processes rather than an assembly line; each stratum of architecture finds its own optimum in the points of contact with other strata. We know that the exterior image may differ from the interior spatiality, because they have not only to tell different stories, but also adhere to different reasoning for different functions. In one case, spaces had to be shaped in ten differentways to show artworks properly and, in another, provide fifteen

16.10. *Exhibition Play* (2002), Rome, by _maO/emmeazero: the world of videogames.

different ways to intersect the urban context. There are many ways to build architecture, each one depending primarily on the economic reasoning, and not at all on an "inner" ethic of the design. As a result of this process of liberation, we have a greater ability to create efficient and really functional architecture. The relationship with urban space, the conceptual and expressive research into image, the organization of different uses, the most efficient methods of construction, the optimization of the technological machinery, they all frequently manage to attain a much higher level of efficiency if liberated from the cage of a final destiny of immanent coherency.

SYSTEM/SPACE

After addressing urbanscape, un-nature, marsupial communication and super-functionality, I want to conclude the first part by discussing the changes in spatial conception. I would argue that we are moving away from the idea of an "organ/space" towards a concept of "system/ space" using a synthetic formula.

    The New Objectivity spirit of the 1920s sought a direct relationship between space and its function, leading to the notion of a "spatial organ." (The meaning of this term is associated with traditional medicine, which maintains that organs perform specific tasks.) That explains the centrality of the interior space, the idea of interior space as the motor of architecture. It is precisely this idea that has been de facto modified and enhanced in a number

of recent projects. Over the last ten to fifteen years we have seen the emergence of a spatial concept of interiority and exteriority that makes public space an equally fundamental element in architecture. Interior life is spilling over into the exterior; new figures are emerging in the "in-between" space: the emersion, the crack, the topological figures of non-linear equations, the figures of the palimpsest, spiral, partial immersions, etc., supporting an idea of space as a system of interacting forces. These systems are not just machinic manifestations of their own internal logics, but rather expressions of interrelations that exist within and outside a given context. If we take these new positions to an extreme, we could argue that there are no more primary elements, but only "connections." Architecture is made in concert with the space it shapes; interior life spills over naturally into exterior life.

16.11. The *Nord Holland Pavilion* (2002), Floriade, architect Kas Oosterhuis.
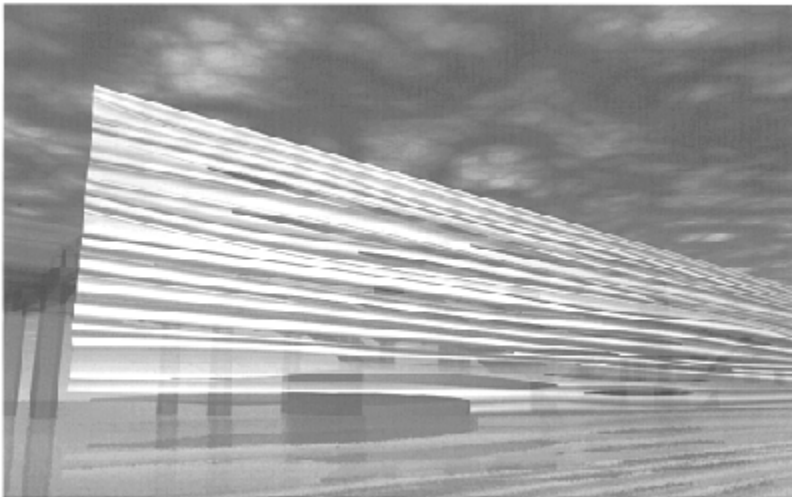
16.12. *Tukuba Express Station* (2002), Kashiwa-shi, Chiba-ken, Japan, architect Makoto Sei Watanabe/Architect's Office.

Interior and exterior are annulled as distinct entities in a continuous flux that dizzyingly spins on itself, as manifested in the *Stone House* in Stendorf, Austria, a continuous work in progress designed by Günther Domenig (figure 16.9).

THE CHALLENGES

In this second part of the chapter, I will move towards a more unstable territory, where new ideas, new desires, new hopes live. To articulate a framework for operating within that new territory, I will focus on an important contemporary shift from "object to subject"—a change on a macro scale that has direct impact in architecture: from the standardization of needs to the personalization of desires, from a formal language based on abstraction to the new use of narration, from the syntax of the mechanism to the presence of metaphorical figures, and, in the context of construction, from the point structure system to structural ribs, from a serial way of creating identical objects to highly customized pieces, from the overall, consistent engagement of form, function and construction within a piece of architecture to the disengagement of parts and elements in order to pursue specific goals. Even more importantly, the way in which we think and design is changing accordingly, as the center shifts away from the objectivity of the machine to the subjectivity of information. We do not adhere any more to the notion of theory "transferred into reality," as was the case with Functionalism, Rationalism, Neo-Plasticism, and also Cubism and Surrealism, and even Fascism and Communism. Today, we tend to take on an extended and generalized "what if" approach. The world of anti-dogmatic thinking, "hypotheses," and "the principle of contradiction" is embedded in the contemporary approaches to architectural issues. It is exactly this epistemological shift that provides a very strong link to information technologies.

INTERCONNECTION

The essence of information technology is not the singular bits of information (their immense number and the speed and easiness of their transportability) but the fact that the bits are "interconnected." We can regroup the bits and organize them into hierarchies of innumerable relationships. We can introduce variations; change the order or interfacing of the connections; form different worlds.

An interesting line of thinking connects the rhetorical figures of speech, the metaphorical use of images in contemporary architecture, and the free paths of the hypertext The rhetorical figures of speech create actual interconnections, a method of relating various data in order to send messages, convey meaning, and convince. The metaphorical use of images in contemporary architecture marks a new phase in which architecture moves from the "objectivity" of the machine to the "subjectivity" of information. The hypertext is one of the most powerful structures of information technology because it allows the user to create and navigate metaphors at the same time, as the Internet shows.
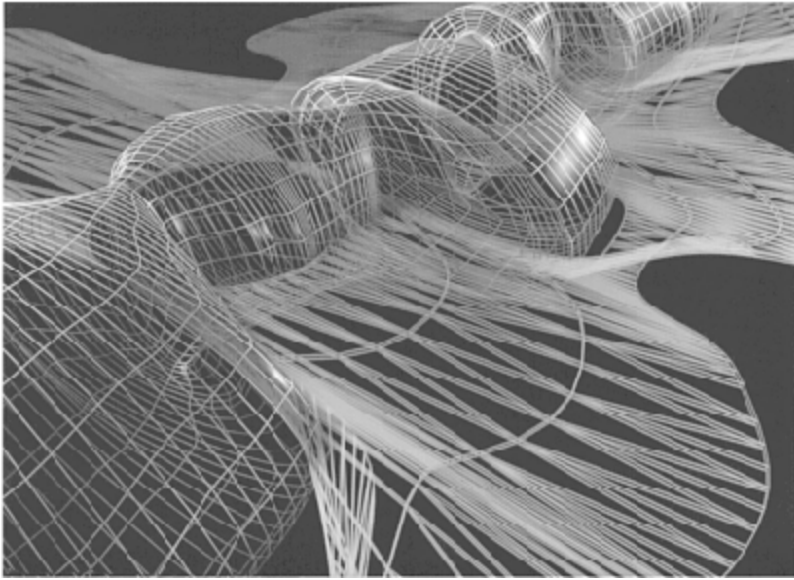
16.13. *Lehrter Bahnhof* (2002), Berlin, Germany, architect Pongratz Perbellini Architects.

Interactivity is the key element of that conceptual chain. It offers the possibility to arrange and organize information as a mobile web of data that can be manipulated by a "what if" approach. In design, interactivity opens the possibility of working on an architecture that is not only metaphorical, but is also a "creator of metaphors," leaving its own decodification open, free, structured or non-structured, and suggesting and offering the user a possibility of constructing his or her own "story."

There are at least three levels of interactivity in architecture, with physical interactivity being the most complex and encompassing the other two. Physical interactivity means that the architecture itself changes; the building's environment is modified according to the situation. We are starting to see its uses not only in some of the recently designed houses (for the wealthy), but also in exhibition halls, museums and other buildings. New experiments are demonstrating not only the modification of an outside situation (i.e. the number of visitors, intensity of natural illumination, various characteristics of exterior climate), but also an architecture that changes according to the variations in moods and feelings of the inhabitants.

The second and simpler level of interactivity combines reality and virtuality in ways that would have been inconceivable in the past. Advances in projection systems, used almost under the building's skin, allow us to intervene in ways that resemble new mass-media illusionism, bringing vitality to degraded situations or circumstances in which interventions were impossible. Projects of this kind were carried out on archaeological sites, in
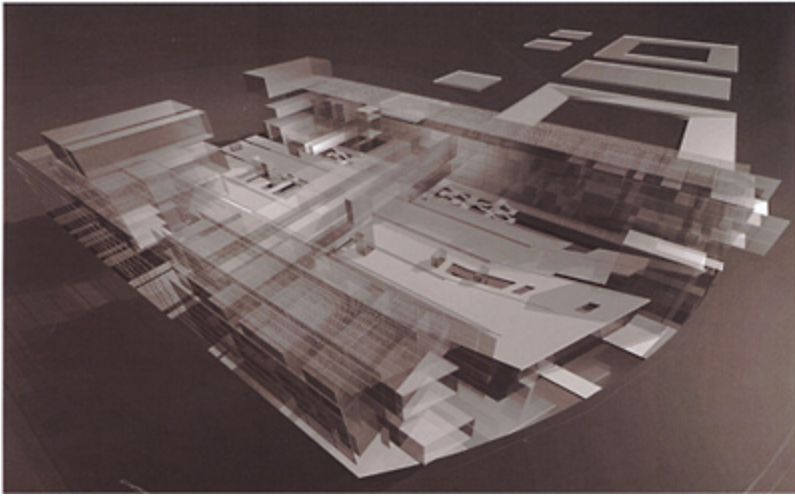
16.14. *Housing Complex* (2002), Eur Velodromo, Rome, architect Nemesi Studio: the winning competition project.

degraded suburbs and historic city centers, representing a decisive step towards the presence of information technology in the city landscape and scenery.

The third level of interactivity is perhaps even more widespread—it is the interactivity within the process of architectural design itself. It is that "what if" way of thinking discussed earlier. Efficiency is not the only advantage here; interactivity in the design process also means creating an increasingly fluid way of achieving the best possible architecture on every occasion.

TRANSPARENCY VERSUS INTERACTIVITY

The crucial aspect of interactivity is its role as a catalyst for a new aesthetic condition in architecture. Under new aesthetic I am not referring to a new stylistic condition, but a condition that captures the very complex and articulated technical, ethical, scientific and functional data of a contemporary situation, moving it to a higher level of synthetic, emotional, intuitive knowledge.

Interactivity will be one of the key architectural paradigms in the future. It will play a role similar to that of transparency in the Modern movement; transparency in the 1920s defined both an aesthetic and an ethic—it showed what the new industrial world really was and what it has to be. The implications of transparency were functional, spatial, hygienical, constructive and aesthetical, all at once. Thus, the shift from objectivity to subjectivity again comes to the forefront. If transparency provided the aesthetics and the ethics, the reason and the technique for a world that rationally wished to see the progress of civilization and better standards of living for the vast masses of workers in industry, interactivity may serve to focus contemporary thought on an architecture that, having overcome the objectiv-

ity of our needs, can respond to the subjectivity of our wishes. New experiments show that the new subjectivity implies not only user's desires, but also a fascinating path that brings life, knowledge and intelligence to the buildings themselves.

NEW AESTHETIC

Interactivity is therefore a central challenge in the territories explored by the new architecture these days. Living in the solid substances of urbanscapes, in the un-nature system

16.15. *Wind Lounge* (2002), Fiumicino Airport, Rome, architect Lightarchitecture Gianni Ranaulo.

space, a few architects-pioneers are digging into a tough terrain. The real challenge is not of technical nature (although difficult and deserving all our attention); the real problem is, the crisis is, the interesting question is: what is the aesthetic meaning of interactivity? How can we build an architecture that has the consciousness of being interactive?

It is one thing is to understand this as a very promising direction, and another to really understand how to address the crisis. As a comparison, I think we are in a situation similar to that of Bruno Taut's *Pavilion* at 1914 Werkbund. Taut realized that transparency was the issue at stake, but his half literary and half romantic approach was exactly the opposite of what emerged ten years later within the "Neue Sachlichkeit." It is interesting to note that

the technology of Taut was basically the same as that of Gropius' *Bauhaus,* but it was the thinking behind the technology that needed to make leaps.

With interactivity as a catalyst, we should try to contemplate the elements of the new aesthetics of information technology. Some interesting possibilities emerge around the issue of "vision;" the macro shift from object to subject brings with it, in the field of vision, the shift from an externalized vision to some kind of internalized vision. The horizon of typical functionalist architecture was flattened on the ground, as if architecture were to be seen from an airplane. The *Bauhaus* building was fully understood when its rotating wings were perceived together with the screws of an airplane. That "object-building" was in its machinic perception conquering the world. Contrary to that, we are today in a world that has moved its viewpoint "inside" itself. Our horizon is not flattened on the ground, but is revolving within itself, as some kind of a Möbius strip. It is like the vision of a probe exploring our own body. The object and the subject, the thing and our perception of it, are not divided, but are indissolubly merged together. This approach was already very evident in some works of architecture that were looking at more extreme tendencies of Expressionism (Johnson and Gehry were discussing endlessly the influence of Kiesler in their Lewis House project of the mid-1990s). But the really interesting thing begins to happen when information technologies start to permeate the design thinking. We know how much architecture is influenced today by the topological geometry, by the mathematic logic of
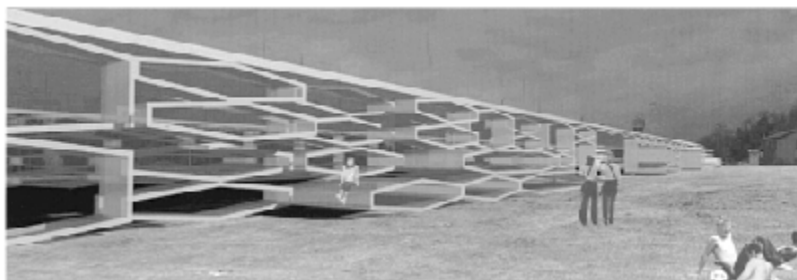
16.16. *Parking building* (2002), Nuovo Salario, Rome, architects Ian+, L.Negrini: the winning competition entry.

non-linear equations, by a world of hypotheses that can be tested only using a computer and that postulate the "non-difference" between inside and outside. Object and subject are merged together in the contemporary vision that goes from our feeling of landscape and nature to the new geometry, each time defining its own "territory."

PERSPECTIVAL/MECHANICAL/INFORMATIONAL

When dealing with information technology, particularly interesting is the fact that architecture embodies our understanding of space; in many aspects it "builds" what our scientific knowledge is. To put it to an extreme, architecture mirrors knowledge. But then, how can

one understand the pyramid without having the feeling that some basic issues of trigonometry were to be known? How can one imagine the perfection of Roman architecture if not with some kind of geometrical calculation, which, of course, could not have been done with the impractical Roman numerical system?

The tools and the objects built with those tools are extremely connected and mutually influential. This means that architecture transforms itself to adhere to a new level of knowledge when it emerges. The invention of perspective required a complete change

16.19. Steve Jobs looking at an early Apple circuit board (circa 1976).

in the conception of architecture. Symmetry, proportions and unified systems of elements were conceived to make a "perspectival" architecture. The concepts of gothic architecture had to be completely modified to adhere to the philosophical, scientific and even social understanding of an "all" real, an "all human" space. And again, later on, the perspectival idea of architecture had to be completely dismantled to adhere to the industrial and mechanical, analytical and non-perspectival space of the functionalist architecture.

To start thinking of an "informational" architecture, we have to look inside the scientific paradigms of information technology. This movement towards the "inside" also has an opposite one. The conceptions of space changed dramatically in various moments of history, and it is always almost impossible to "imagine" what a new space can be. It seems inconceivable when we are immersed in one condition that somewhere "out there" is another type of space, another way to conceive and make things.
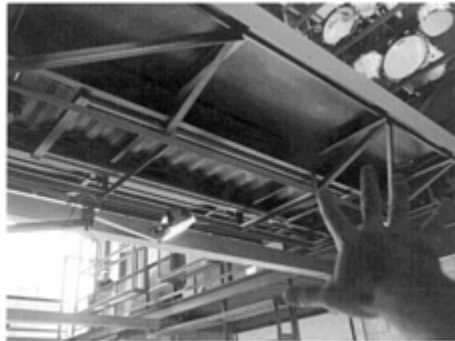
16.17. *Rob Brill Residence and Studio* (1998), Silverlake, California, USA, architect Jones Partners Architecture.

Nowadays, we are creating an idea of space that still does not yet exist completely, but one that we begin to intuit and begin to shape. Consider the wonderful metaphor of fish presented in the *Architecture of Intelligence* by Derrick De Kerckhove.[4] Fish know only the fluid that, just like air, surrounds them. They know nothing either of what the sea or lake or river really is, and know even less about the space in which we humans live. Only a jump beyond that aquatic surface can open up the sensation of another space that definitely exists, even if it is neither frequented nor understood.

We need to make that jump, to move out of the condition of a mechanical space to start conceiving the space of information technology. Throughout history we have lived in different spaces, and architects, using different sets of rules and different knowledge, have given them form: the informal space, gestural and primitive, pre-Miletus (and pre-alphabet); the space arterialized and geometrized by the Greeks and Romans; the sacred and mystic space before Giotto; the perspective space of the Renaissance; the industrial and mechanical, analytical and non-perspective space of the modern Movement. Each new space on arriving has required new principles and new alphabets that have been created through difficult, exhausting, rough but exciting processes. That is our task too.

16.18. *Miyake* (2002), Paris, France, architect Ammar Eloueini Digit-all Studio, with C.Parmentier.

16.20. The Amerzone, Casterman Microids, Benoit Sokal (1999).

I will close the chapter with two citations. The first is the famous quote by Martin Luther King: "I have a dream."[5] The second one is by Jaron Lanier: "Art is about people not committing a suicide."[6] What this means in the end is that the information technology must act as an intensifier of our basic tendencies: if we want a new architecture that incorporates the crucial and mobile aspects of our time, if we believe that art is the highest form of knowledge and of salvation, if we think that technologies must reinforce a consciousness of progress and of widespread rights, then we must first have the courage to dream it.

NOTES

1 The text and images of my presentations, whether they are course lectures or symposium speeches, are immediately accessible through the Internet at http://www.citicord.uniromal.it/saggio.

2 Alvin Toffler. *The Third Wave.* New York: Morrow, 1980.

3 Antonino Saggio. *Peter Eisenman: Trivellazioni nel futuro.* Torino: Testo & Immagine, 1996.

4 Derrick De Kerckhove. *Architecture of Intelligence.* Basel: Birkhåuser, Basel, 2001.

5 Martin Luther King, Washington, August 28, 1963.

6 Jaron Lanier, Pittsburgh, September 19, 2001.

17
EXTENSIBLE COMPUTATIONAL DESIGN TOOLS FOR EXPLORATORY ARCHITECTURE

ROBERT AISH

This chapter starts by discussing aspects of the current architectural computer-aided design (CAD) paradigm, and then reviews how and why computer programs created for other design disciplines are being used in exploratory architecture. The lessons distilled from these first two discussions will then be used to suggest how we might create a new type of architectural software better matched to the exploratory design process. Finally, the results from validation projects conducted with a new prototype CAD system specifically intended to better encourage creative architectural exploration are presented.

One of the common issues implicit in the chapters and designs presented in this book is the nature of the relationship between the designer and the chosen computational design tools. What are the particular tools of choice? What characteristics differentiate these tools? How are these design tools being used relative to their intended purpose? How has their use influenced or changed the architectural design process? Are designers getting the most out of these tools? And, most fundamental of all, is there a meeting of the minds between creative designers who use CAD systems and the software engineers who create these systems? Alternatively, is there some intellectual or creative "impedance" mismatch? And if so, how can we have overcome this?

THE CURRENT ARCHITECTURAL CAD PARADIGM

Perhaps the most striking aspect in this book is that none of the authors are actually using CAD applications specifically intended for architectural design. As a software developer with a leading vendor of CAD systems for the building design professions, I find that this has a particular significance. This observation implies no criticism of the outstanding design work presented in this book or the authors and designers represented. But it should be a severe "wake-up" call to software engineers, because it more or less implies a failure to understand what creative design is, or how to develop design tools to support this exploratory process.

Conventional CAD applications either operate at a very low semantic level (lines, arcs and circles) or present a higher level, but predefined, semantics (walls, windows and doors). The "low semantic" approach is very general. It does not constrain expression, but captures little meaning. It is fine as a substitute for a hand drafting. The "higher, but predefined, semantics" approach can be extremely useful and productive if one is working within a

design or engineering discipline with well-established conventions, and with agreed components and inter-component relationships. In fact, the vast majority of architecture and construction works in this way, with standard construction methods and details. This conventional approach to design also provides the main market for the software vendors.

These existing applications are a reasonable response to conventional notions of design, with established architectural semantics, simple part/assembly hierarchies, and the production of drawings that are subject to human interpretation within a craft-based construction industry. The problem, which is widely recognized, is that this approach treats architecture and construction as a bounded or "closed" domain, which can be sufficiently described (and automated) by a finite set of application entities and operations. There are reservations, in particular voiced by influential practitioners and academics, that CAD applications, which encode design and engineering conventions in this way, could be viewed as a very conservative force that reinforces conventions.

By contrast, the design work presented in this book can be characterized as exploratory in a geometric, fabrication and cultural sense. This architecture challenges conventional notions of form and design semantics by generating and exploiting geometry that is radically different from that found in conventional buildings. The challenge that the software developers should be keen to accept is how to create a new type of design tool that can respond to the opportunities presented by these new, more exploratory approaches to architectural design.

An important aspect of exploratory design is its relationship with various fabrication and construction processes. Conventional construction methods are encoded in graphic representations that essentially constitute an abstract "shorthand language" for communicating design intentions in terms of standardized components and craft-based construction techniques. The physical realization of exploratory architecture requires the communication of vastly increased amounts of data to contractors (e.g. the coordinates defining a complex curved surface) or significant modification and/or abandonment of conventional fabrication methods. When fabrication methods are adopted from other industries, the conventional "shorthand language" for communicating architectural design to manufacturers and contractors may no longer be useful or appropriate precisely because that "shorthand language" presumes a finite set of constructive options. So, not only is current architectural CAD software not useful for generating exploratory architectural designs, but its emphasis is on the generation of graphical notation based on drafting conventions, and this does not address the new requirements to digitally communicate unconventional forms directly to fabricators and contractors.

THE ADOPTION OF SOFTWARE FROM OTHER DESIGN DISCIPLINES

The adventurous architectural practices represented in this book are essentially using three types of software: (a) general geometric "foundation" software; (b) solid modeling software for mechanical design; and (c) animation software. What can architectural designers and software developers learn from this?

General Geometric Foundation Software

Most CAD systems include modeling commands (curves, surfaces, solids) that are often far more general than those combined into specific architectural entities and operations. For the designer with conceptual understanding of geometry, the general modeling commands give a degree of expressability and freedom not usually available with a specific architectural application. These general modeling commands require some skill to use, and do not necessarily leave behind a "semantically" appropriate data set, but they have the advantage of supporting the key requirement of exploratory design, which is to allow geometric freedom. In addition, hidden within most CAD systems are general modeling functions, which are not necessarily "exposed" to the designer via commands (and icons) on the user interface.

For the designer with programming skills, this provides an extremely powerful resource, as the work presented by the Foster studio demonstrates. There is a price to pay for this. The designer must have reasonable programming skills to harness this potential (at least at the moment). Although some might view the need for programming skills as a disadvantage, the emerging discipline of "programmatic design" has already demonstrated this potential and the rewards that follow from these skills.

The lesson here is that geometric generality and end-user programmability are key constituents in a set of computational design tools for exploratory architecture, but that aspiring designers have to develop appropriate skills to harness the full potential of these tools.

Solid Modeling Software for Mechanical Design

Mechanical CAD systems extend the general geometric functionality of foundation software to include full solid modeling, including Boolean operations. These can be used at a number of levels within architectural design: first, to model the overall form of the building and the volumes enclosed and, second, to model individual components. Mechanical CAD software can interface with computer-aided manufacturing (CAM) programs and devices to a much greater extent than is the case with foundation software. While models created in most foundation software can now be output to three-dimensional prototyping devices such as laser cutters and stereolithography machines, mechanical programs can generate data that enables much more sophisticated communication with the full spectrum of advanced manufacturing devices used on the factory floor. This truly reconnects the virtual world of design to the physical world of manufacturing.

Mechanical CAD systems certainly provide powerful geometric tools. The problem here is that these tools are embedded within an application primarily intended to support a mechanical design "workflow." This workflow can be characterized by the use of parameterized features linked by "feature trees" and part/assembly hierarchies based on rigid body transformations. Many theoreticians, practitioners and software developers working in architectural design have concluded that the relationship between the overall form of building and the systems and components used to realize that form are significantly more complex than what can be supported by restrictive "tree-like" relationships or simple geometric transformations. Therefore, from an architectural designer's perspective, these

interesting and powerful tools often appear to be "trapped" within an application with a very prescriptive and inappropriate workflow.

The important lesson here is that computational design tools for exploratory architectural design need all the geometric generality and functionality found in mechanical CAD systems, but more flexible and extensible relationships than those supported by "feature-trees" and other devices associated with the mechanical design workflow.

Animation Software

Animation software offers important advantages and disadvantages when used in architectural design. Let us consider the disadvantages first. We can classify computer graphics systems into those where the visual results that appear on the screen *are* the end result and those where the visual results are a representation of a design intended to be physically realized. In the first case, the virtuality of the medium is the same as that of the resulting product. Animation and paint systems fall into this category.

We can contrast this with other computer graphics systems used for design, where what appears on the screen is not the end result, but an aid to the creation of some other (physical) object or system. Here the physicality of the medium is different from that of the product. Both the animator and the architect share a common objective, to create an emotional response, but a building has to be physically realizable to ultimately achieve this effect. This requirement for "physical plausibility" imposes constraints on the design process, which ideally should be reflected in the behavior of the design medium. These constraints may be substantially reduced or completely ignored in animation systems. Animation software suits its intended purpose by making it possible or even desirable to suspend or modify physics, and to avoid or be unconstrained by the need for dimensional accuracy. But, while using software where these constraints are relaxed or absent might contribute to the exploratory phase of architectural design, such a system is unlikely to adequately support the planning or the physical realization of the resulting design.

It is also important to note that animation software is intended to facilitate the delusion or deception of those viewing its end results. This capacity is often embedded as a means of generating the desired result more efficiently from a computational standpoint. For example, if we focus on a specific issue such as rendering, it is quite possible with computer graphics to give the illusion of a continuously curved surface by simply smoothing a facet model. But the underlying simplified geometric representation and the corresponding faceting rules used in a dynamic rendering algorithm have no relation to the possible alternative panelization and fabrication processes which could be used in the physical realization of the building.

However, the really significant contribution that animation systems has brought to architecture and other design disciplines is the proper integration of notions of time into the design process. Conventional CAD tools often presume incorrectly that a designer first creates a model with one set of tools, and then subsequently animates that model with a different set of tools. This paradigm completely fails to recognize that the dynamic malleability of form is an essential part of an exploratory design process.

So, the important lesson here is that the notion of "time," which is found in animation systems, needs to be properly integrated into computational design tools for exploratory architectural design, but with more dimension control and geometric precision.

CREATING A NEW TYPE OF ARCHITECTURAL SOFTWARE

The development of application software depends on establishing some general, recurring pattern, which has some underlying logic and which is capable and worth computerizing. If our chosen domain is architectural design, what are these general and recurring patterns that are worth computerizing? Are these based on "lines, arcs and circles?" No. We have already established that for a CAD application to be based purely on a "graphical reflection" of the results of the design process is an insufficient foundation for a coherent computational design tool. Are these based on predefined representations such as "walls, windows and doors?" No. We have already established that to encode existing construction conventions into design tools unnecessarily "forces" the designer to think in a specific and detailed way about the design before he has established the design concept or overall configuration or form. So what is "general and recurring" about something as nebulous and as an open-ended as the exploratory design process? The common characteristic, the recurring pattern, is the "creation and manipulation of geometric relationships."

We do not have to hard code the specific geometric entities or the specific relationships. Yes, we can provide some base classes that encode the typical design conditions, but we must also allow the designer to invent and to extend the repertoire with his own geometric entities and relationships. But the common foundation, the recurring theme, is that we have geometric relationships, which the designer will want to create, manipulate, assign meaning to, break, reform, and assign new meanings to. If we could formalize a system that understands geometric relationships in the same way a creative designer does, then this would be worth computerization, because it is with such a system that the designer can create and express his own architectural semantics. In this context, the software framework has two roles: first, to enforce consistency on the system of geometric relationships, as relationships are added to, modified or removed by the designer and, second, to maintain the integrity of these geometric relationships during parametric modification and direct manipulation of the model by the designer.

To test these ideas, we created a prototype computational design tool called *CustomObjects*. We might describe this system as "a model-oriented end-user programming environment which combines direct interactive manipulation design methods based on feature modeling and constraints, with visual and traditional programming techniques." The *CustomObjects* framework is the first Bentley application written using and fully harnessing the potential of the Microsoft.NET technology. *CustomObjects* has been developed with the close cooperation of leading Bentley user organizations and represents Bentley's response to the requirement for a "programmatic design" environment that is a fusion of geometric modeling and software development.

How does this work? Stage one, we start with a set of base classes of geometric primitive components and relationships (in this case developed by the software vendor). Stage two, we use the currently available components and relationships to create a model where

the relationships between the components define the behavior of that model. Stage three, we capture the model as the definition of a new component, add that component to the set of available components and repeat (starting at stage two) until we have a satisfactory design.

The way we create a new component, which can extend the repertoire of available components, is also the way we create a model. The definition of such a "model-based" component is, in fact, a "behavioral aggregation." It is, of course, possible to create a new component using conventional programming, just as the original base classes of geometric primitive components were created. A model can consist of any combination of "model based" or programmatic components, and any model can become the definition of a new "model-based" component. So, we have two ways to extend the semantics of the CAD system: first, by modeling (therefore accessible to designers with good modeling skills, but no conventional programming skills) or, second, by programming (therefore retaining additional advantages to those designers who are prepared to invest in these specific skills).

Within one model, it is possible to include components defined by and used by different disciplines within a multi-disciplinary design team. Therefore, this model not only has the potential to represent the interaction of the different building subsystems, but also to model the dependencies between design decisions made by different team members. In effect, it becomes the forum for exchange between members of the design team.

CUSTOMOBJECTS VALIDATION PROJECTS

One of the most appropriate ways to evaluate new software is to engage in projects with designers who are experienced but unconstrained by convention, who have strong exploratory motives and who do not hesitate to demand the best computational design tools. The development of *CustomObjects* was validated by retrospective studies of geometrically complex projects, such as the *Waterloo International Terminal* by Nicholas Grimshaw and Partners, and by collaborative application to current building design projects with such studios as Foster and Partners, Gehry Partners, KPF London and Arup. We have also been working closely with small firms exploring new architectural possibilities and with leading researchers in digital design and construction at institutions such as the University of Cambridge, University of Virginia, Royal Melbourne Institute of Technology (RMIT), the University of Illinois (UIUC), and the Construction Engineering Research Laboratories (CERL).

The particular study reported here is the design for a conservatory (figure 17.1) created by Kevin Rotheroe from the FreeForm Design + Manufacturing Studio in New York. The objective was to use this project to explore how a series of nested "user-defined" geometric construction *(CustomObjects)* could be created to realise the complex geometry of this design. We also wanted to explore how the designer could iteratively manipulate the entire form of the building within a wide array of possibilities, and simultaneously receive immediate feedback at the component level in order to assess the manufacturing implications of a particular iteration.

The overall design concept is a series of angular "wedge" constructions that form a radially configured whole. The problem therefore breaks down into the design of a

"genotypical" wedge whose angular spacing is dependent on the intended number of wedges in the whole form.

We start by defining the primary compositional geometry as a series of radial rings and a vertical axis, on which the genotypical "wire-frame wedge" construction will be built. A series of defining "key points" are constructed by intersecting these rings with sets of compositional planes. The radii of the rings and the angular spacing of the planes are all parametric (figure 17.2). Other genotypical wire-frame constructions (the compositional arch and rib) are placed onto this primary framework. These arch and rib constructions

17.1. Conservatory enclosure, architect Kevin Rotheroe, FreeForm Design + Manufacturing Studio: shown in inverted form.

are controlled by other radii and angular parameters, and include various planar and tangency constraints. Separate to this construction, a genotypical "blend surface" construction has been defined, which in turn is defined by a series of "bulge rib" constructions. These bulge ribs are driven by a "bulge factor" (or chord depth) parameter, which effectively controls the bulge (or sag) factor of the "blend surface." These "blend surfaces" are then attached to the "wireframe wedge" to create the full "surface wedge" construction and this, in turn, can be radially replicated around the axis according the parametric number required to create the "composite model."

Within this model there are six separate *CustomObject* definitions (defining the different "genotypes"). Each definition is composed of instances of other *CustomObjects,* giving a total of 720 instances within this model (figure 17.3). This structure of *CustomObjects* allows the parameters, which define the behavior of internal constructions, "to be exposed" within the definition of a higher level *CustomObject,* indeed right up to the parameters used

at the top level "composite model." One such parameter in this model is the "bulge factor." By varying this parameter over time, it is possible to create a dynamically malleable design model, which allows the designer to explore subtle alternatives in a way that would be impossible with conventional digital design tools or physical models (figures 17.4a-d).

Other manipulations that we explored included moving the central compositional axis away from the vertical, and draping the whole composite model over an undulating site terrain model, and then varying that terrain model and observing the response of the composite model.

As the conservatory project illustrates, design often involves the conception of some totality, and then the definitions of constituent components, which, when combined, can realize that totality. The critical skill is to understand where the natural "fault lines" are, where the boundaries are within the total concept that suggest appropriate components. Of course, in this presentation we only have the scope to describe the results of Kevin Rotheroe's exploration rather than the full process, but there are some important generalizations that are worth noting. We are very much used to the idea of components with fixed or modular dimensions, where the compositional rules are quite restrictive. What is interesting about this project is that the design process required a search for appropriate component boundaries not based on dimensional systems, but rather on unifying geometric relationships, for example, based on continuity (or discontinuity) of curvature. Of course, a delightful aspect of these relationships is that they can be maintained with a variety of dimensions and, thus, we can create "progressions," for example, of scale. Here some aspects (or parameters) are being varied (possibly in a systematic way) while other "dimensionless" parameters, such as bulge (or chord depth), are being held constant. We can therefore play with the creation of systems of components that can respond to adjacent components, that can appear to flow but, by sharing other parameters, can maintain essential commonalties of form, which gives unity to the total composition.

Two points are worth noting. First, no special software was written to build this model and the constituent components. All the *CustomObjects* were created through modeling operations with standard geometry types and geometric relationships. Second, one should not underestimate the mental resources required to create an apparently "effortless" result. However, the initial effort required is more than justified by the subsequent opportunities to experiment with geometric "what ifs," which opens the possibility for numerous iterations and refinement, which is of course the essence of design.
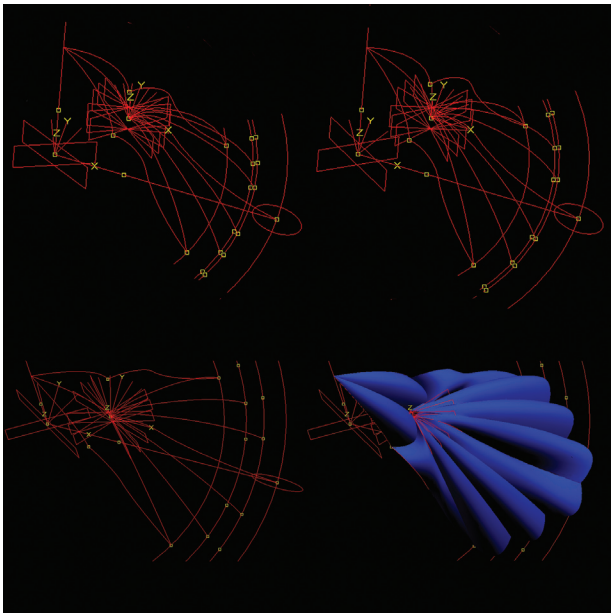
17.2. Various parametric alternatives of the radial compositional generation of a single "surface wedge" construction.
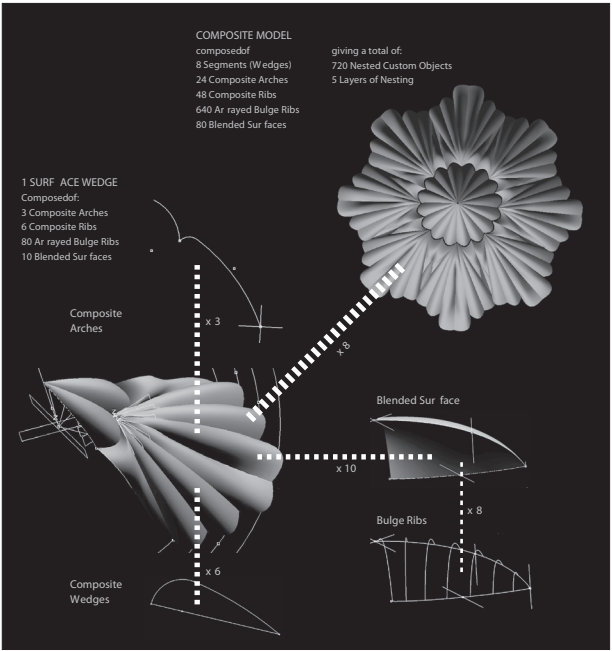
17.3. The compositional structure.
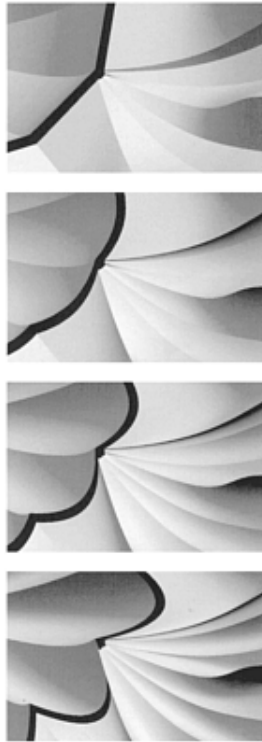
17.4a–d. Four frames from the animation model.

CONCLUSIONS

Once built, architecture resists change. Conversely, software is inherently adaptable. The widespread use of commercial software instituitionalizes the underlying abstractions on which that software is based. If these abstractions encode existing or fixed conventions, then software (which is inherently adaptable) ends up being unnecessarily conservative—something which is as much resistant to change as a concrete and steel building—an unfortunate paradox.

What I am searching for in the development of *CustomObjects* is the minimal abstraction of design that, when implemented in software and used by creative designers, provides for the most expressability, the most extensibility. The immediate motivation is to provide appropriate design tools for an exploratory architecture (and to avoid this paradox), but there are other, broader objectives. When software leaves the development lab, with its freshly minted CD and shrink-wrapped manual, it is only complete in a restricted sense. We have to recognize that as a system, it only reaches full completion through its use and extensions added by creative users. Paradoxically, in the domain of software design, the ultimate mark of success are those extensions the original developer did not anticipate, those which extend or refine the underlying abstraction.

18

BUILDING INFORMATION MODELING: CURRENT CHALLENGES AND FUTURE DIRECTIONS

JON PITTMAN

The progression of my career—which has taken me from architecture to manufacturing to the world of software development—has afforded me a very unusual cross-disciplinary perspective on the evolution of building industry technology. In my early days of working at Hellmuth, Obata 4-Kassabaum (HOK) and Skidmore, Owings & Merrill (SOM) back in the 1980s, I can remember when computing was just a small outpost within a large professional firm. From HOK, I went on to a company that developed animation software, and I learned much about the form-making programs that have been widely discussed throughout this book. I then entered the arena of manufacturing, working for a mechanical engineering firm that was very much concerned with the connection between product design and the actual process of manufacturing or "machining" those products. It was at this juncture that I was struck by some startling differences between the two industries.

To mechanical engineers, "design intent" referred to a set of very precise dimensions, constraints and parameters that drove the design concept. Their focus was on ensuring that the manufacturers would fabricate the products according to absolutely defined tolerances and specifications—with no ambiguities about what was manufactured.

When I returned to the building industry, I heard a different meaning for "design intent." Architects sought to express their design intent more broadly—clear enough for a contractor to construct the building without explicitly providing directions for how to do so. Why the purposeful ambiguity? According to some, ambiguity is necessary in order to minimize the architect's own liability in case something goes wrong during the construction process. Others say that purposeful ambiguity allows our industry to tap into the distributed intelligence of the community—i.e. that the collective knowledge of how things get built as embodied in designer, builder, manufacturer and tradespeople, is far richer than the knowledge embodied in any one individual or group. Further, limitations on the architect's compensation made finding efficient ways to depict the building necessary.

As we move forward in our discussion of how technology can support the integration of the design and construction process, I think it is important to keep these two distinctive perspectives in mind.

BUSINESS PRACTICE EVOLUTION

A review of a recent AIA Survey (2000–02) yields some interesting insights into how our practice has changed. In the past five years, firm billings have grown by 67%, as opposed to

a 14% growth in the US economy over the same time period. This means that architectural firms have been making more money recently than they have traditionally earned—so, for some reason, which we need to explore, it has been a heyday for the profession.

Another series of statistics reveals a growing bifurcation in the profession:

- firms with 20 or more employees grew from 5% to 13%
- 40% of all work is in large firms (100 or more employees)
- intradisciplinary work has increased.

So, we are finding that the small-size firm—which used to be the mainstay of the profession—is disappearing, while large firms and mid-sized practices are flourishing. But what is most interesting to us as a technology provider is the fact that 90% of all firms use electronic transmissions of digital design information.

DESIGN TECHNOLOGY EVOLUTION

When I first left architectural school in 1980, the state-of-the-art technology was "layered production"—or what we now call manual drafting. Very few firms used computers, or if there was any computer activity at all, it was taking place in the very large firms or "avant-garde" practices. The technology that existed was experimental and expensive—about $100,000 a seat per workstation (hardware and software combined). Few could afford it.

At my job at HOK in the 1980s, I remember that we had retained an employee whose sole responsibility was to schedule use of the "machines." We had many projects going on and had many architects who wanted access to these machines that were extraordinarily expensive relative to human labor costs. So this person's whole day was spent in negotiating with different project managers to make sure they received the appropriate amount of hours to accomplish their tasks on the computers. I remember saying to him one day, "Michael, in three years, your job won't exist. The cost curves are going to cross and we're going to buy enough computers for everybody so we won't need someone to schedule machine time. Instead of people being cheap and machines being expensive, we will have the opposite." He couldn't imagine it. This was about 1985 when the personal computer came on board— the classic disruptive technology. It was first viewed as a low-power technology that was not taken seriously by mainstream businesses but it quickly gained enough power and promise at a low enough price that it became ubiquitous in firms. By the early 1990s, machines were cheap and people were the expensive resources.

During the 20 years that followed, we refined production-based drafting. And, though, I hate to make predictions, I would say the production drafting problem is largely solved. So where do we go from here?

As we see it, the key to integrating design and construction is through modeling and collaboration. And very closely tied to this next technological evolution is the potential for the architect to reemerge as a master builder—one of the themes of this book.

RESEARCH EVOLUTION

Once again, let me digress into a bit of history, this time within the research community. In the late 1960s and early 1970s, Nicholas Negroponte at MIT was exploring the relationship of the computer to the design process in his book, *The Architecture Machine,* where he identified key stages in this process (accommodation, adoption and evolution). At that time, mainframes were state-of-the-art in computing, and there was a lot of investigation into design methods, to which Bill Mitchell has alluded in Chapter 6. In the 1980s, the focus of research shifted to rendering and visualization, with much of the seminal computer graphics research taking place in that decade. That is when ray-tracing and radiosity were invented, leading to dramatic advances in visualization and a wealth of great imagery. But these techniques did not become mainstream for about another decade.

In the early 1990s, investigations into model-based design first began. In the architectural community, the theoretical underpinnings of "blob" architecture were emerging, while in the computing community work was beginning on pen-based input devices.

Ten years later, we are seeing investigations into four-dimensional computer-aided design (CAD), where the dimension of time is added, as well as collaboration platforms, mobile devices, and the ability to manipulate and display images on very large-scale color screens.

How long will it take for these research advances to become mainstream? By and large, the lag between research and implementation is not for technological reasons but rather for business and economic concerns. How willing are design practices to disrupt their processes and try something new? It will be interesting to see whether the new generation of students that we have talked about will be able to shorten that lag because of their willingness to adopt technology more quickly.

BUILDING INFORMATION MODELING

When most people hear the word "modeling," they immediately think of three-dimensional form modeling for rendering and visualization. And while that is certainly an important component of modeling, what we are envisioning is something broader and richer. It is closer to the way the term is used in the manufacturing or mechanical engineering industry—a model that takes into account performance characteristics, cost and other issues related to the construction and operation of a building, as well as its design. A model is not just a three-dimensional picture of geometry, but a rich representation of the building that contains all kinds of interesting and useful data.

To better understand how "modeling" is used in this context, we will examine the building industry process—for we are now exploring how technology can impact the entire building lifecycle, not just the design phase but procuring, building and managing as well.

One might graph the amount of information understood about a building across the phases of design (figure 18.1). In this graph, the horizontal axis is time and the vertical axis is the amount of information that is available about a building project. We start with no information and, over time, we build enormous quantities of information: schematic

designs, options and alternatives, sketches, analysis, estimates. Much of the information is in digital format; much remains in the designer's mind. What happens when we go to construct a building in the traditional process? All of that information gets smashed down, plotted out, and printed on dead trees. Turned into paper form, the rich digital design information is lost. As architects, we are afraid of risk and liability, so we do not want to pass all of the information along to the contractor even though some of it may be very important.

So what does the builder do? Well, the builder tries to analyze that information in order to reconstruct the architect's intent. How much is the building going to cost? How should construction be sequenced? From whom should the construction team buy materials and components and subsystems? And if it is a competitive bidding process, then multiple contractors and their multiple sets of subcontractors and suppliers are going through this same process at the same time. So a tremendous amount of information is being generated to determine how the building is going to get built and how much it is going to cost.
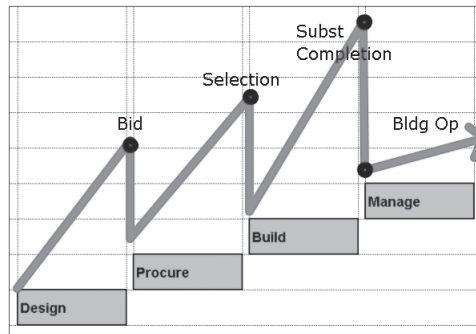
18.1. Creation and loss of information.

Ultimately, someone is selected for the job. And what happens? You lose a lot of information since the losers in the bidding war toss it all out. Then construction starts and a tremendous amount of information is generated once again. The builder is trying to decipher the architect's design intent, and as the construction team actually tries to construct the building, they find ambiguity in the design. There is a considerable amount of back and forth communication in order to clarify what was originally meant and reconstruct the information. Record drawings may be finally created so that once the building is occupied, the owner does not start from zero but can at least refer to a reasonable set of "as-builts." Of course, these record drawings are often wrong and quickly get out of date.

What is most important here is to realize that we are losing information throughout the entire building industry process. And that is the problem we are to resolve: how to maintain the integrity of information throughout the building lifecycle. Building information modeling, therefore, goes beyond form creation and image generation; it is the creation of digital assets—digital information that is actionable. A paper-based production drawing set does not provide much actionable information in itself; the value of the information lies in a human being's ability to interpret it.

Our challenge is to embed information within the data so that the information is actionable in future phases of the building lifecycle. Building information modeling seeks to fill in the holes, tying in design components with procurement systems and estimating systems. Obviously, both a contractor and building owner are interested in construction costs, and it is very difficult to determine costs from a static two-dimensional drawing. So we are examining ways of actually embedding more information in the design data that can be extracted later on to yield, for example, a more reliable cost estimate.

In my role as a technologist, I often have the opportunity to speak to both architects and contractors, and, as mentioned earlier, the discussion often turns to the issue of "risk." The lens through which they view the world is one of managing risk or being at risk financially. As Jim Glymph said in Chapter 8, in Europe, there seems to be more of a sense of shared risk among building industry professionals than in the United States, where architects operate within a very litigious environment. One approach to this problem is to develop clearer and better building information, closer to the manufacturing engineer's concept of design intent than to the architect's traditionally more ambiguous design expression. As we have just shown, such information could then be used in construction not only for assembling building components but also for such issues as how to best stage construction. The entire construction process is really a design problem in and of itself—and to be able to use digital design information to help resolve these issues would be a tremendous advantage to all.

Of course, a second dimension of risk is compensation. As designers through building information modeling provide more extensive, complete and actionable data to the building enterprise, they should get paid for it. In fact, a model-based approach provides one of the most important opportunities for designers to charge more for their work.

COLLABORATION: THE CONNECTIVE TISSUE

We have been discussing building information modeling and how to create rich, semantic information in a model that goes beyond form to also include function, performance and cost—all of the elements that truly define a real building. To create an environment where design and construction are knitted together, however, a collaboration infrastructure is also needed. Collaboration is a broadly used term these days in technology, and it sometimes occurs in some very mundane and crude ways. We believe, however, that there is a tremendous potential through online collaboration to bring the architect back to the center of the building process and to knit together the various different players in our industry.

Within the design process, the players are usually used to working together within an individual firm with a unified information infrastructure and with work processes that are quite similar. People tend to work with each other in a high bandwidth way; there is a lot of collegiality; a shared vocabulary, language of drawing (in plan, section and elevation) and methodology, and their styles of interaction are clearly defined.

Within the construction process, it is a different story. Typically, the players are a much more loosely knit group. They are often geographically distributed in different places; their relationships may be contentious and adversarial; and they typical use a different type of information technology infrastructure—indeed, multiple types of communication—than the design team, so the solutions for these two groups are often not the same.

But they are both trying to resolve information problems—issues around ambiguity and how to best work together. Even today, collaboration for the most part is handled by printing drawings out on dead trees, marking them up, and shipping them via overnight mailing services. Last year, FedEx made about $500 million on shipping construction drawings around the world. It is a tremendous waste of resources, particularly when you can send information digitally.

The current leading-edge technology for project collaboration involves the sharing of project information via project websites. These online project collaboration services are the first wave of collaboration technology solutions and they are helping project teams to efficiently manage data throughout the design and construction of a project. However, they are using today's processes as their paradigm. These services automate the process of moving around documents, but they do not enable the fundamental, deep collaboration that takes places among individuals on a building project team.

As we envision it, this deeper form of collaboration will begin with a design environment in which we have multiple kinds of information: information on the building form and structure, relevant data for construction staging and assembly of building components, product information sheets, and even a job camera to view the construction site. This is how professionals will work—not from the vantage point of a tiny window but by assimilating massive amounts of information in various forms. As professionals, we will add value by making sense of the information and applying it to the particular task at hand.

FUTURE DIRECTIONS AND CURRENT CHALLENGES

We suspect that it will take another 15 to 20 years before building information modeling and collaboration solutions reach the same level of maturity that we have attained with production drafting. So, how can we reach this future? As mentioned, many of the impediments are economic, social and legal concerns that can only partially be resolved by technology. Nevertheless, as technology providers, it is incumbent upon us to address these issues. Our work now is to develop a building information modeling environment and the collaboration tissue that connects these models.

Buildings rarely exist in a static state. They are in a constant process of creation and destruction as people move in and out. They undergo renovation and change and become a part of a larger urban fabric. So, if you examine the building lifecycle, it is not really a linear process at all. Therefore, we have to begin to think about how we can support such a process that has both vertical (spatial) and horizontal (time) dimensions.

The system we envision offers tools for authoring, editing, publishing and analyzing information. In fact, most of the software in use today is really authoring and editing software that is used to create design content or architectural form. We would like to extend those tools so that the architect can publish information that can be extracted for use by others on the team—the estimators, specifiers, construction managers and building owners who need to analyze that information for future activities.

Our current challenge is to provide tools that let building professionals consume information digitally rather than printing it out on paper where it loses its value. Tools that will let us analyze the performance characteristics of buildings (their viability from life

safety, structural, mechanical, thermal and acoustical points of view, for example) will result in better coordinated, longer lasting buildings. We are working to provide the ability to analyze a building according to its systems: the site, structure, skin and services. The development of rich building information models with the connective tissue of collaboration techniques and tools will allow us to navigate through this complex building space through time, knitting together design and construction. We are convinced that this process transformation will have a startling side-effect. The architect will reappear on center stage as the master builder of information, the key figure upon which all of the other players in the process depend.

19
IS THERE MORE TO COME?

CHRIS YESSIOS

Is there more to come? The answer to this question is, of course, yes, there is much more to come, which will appear as much, and even more, miraculous than what we have experienced over the past couple of decades. (While this chapter is definitely about what is in the future of the digital tools in general, it may well have a bias towards what we are exploring and anticipate specifically for form•Z. Much of what is presented is still in a "wishful thinking" stage and should not be taken as definite and guaranteed promises.) Before elaborating on what more to expect, it is worth reviewing the milestones of the past.

Needless to say, talking about where computer-aided design (CAD) will be going is a risky undertaking. Our experiences over the past 20 years show that, while we were able to predict quite a few developments, we also missed some more, which came as "pleasant" surprises. At the same time, we made many predictions and promises that never materialized. These may actually offer us a proper starting point in considering what to expect in the future. So, we will examine these promises and observe whether they are still valid, i.e. whether they are mostly desirable and how feasible they are. But even before discussing these pending promises, it is worth reviewing the highlights of the progress we have made. Those of us who have been involved with CAD for a few decades quickly recognize that the progress made is quite impressive. This realization is even more significant when we note that the younger generations take many of these developments for granted.

Today we have systems that are *competent, affordable, accessible* and, last but not least, *accepted*. They are everywhere in the design professions, especially in architecture. For so many years, as we were debating the issues, those of us in academia were trying to persuade the professionals that CAD was the way to go. The argument was frequently requently about the economics. Not too long ago the cost of a single CAD station was about a quarter of a million dollars. Today it is a few thousand dollars and continues to go down. So, nobody argues about affordability anymore. While there is a continuous debate about what more the CAD systems should be able to do, nobody denies that they already do a lot, or at least enough to be productively usable. This leads to their broad acceptability. Today, no professional considers practicing without the use of a CAD system, which means there is no argument anymore about their validity, even though there is still frequently heated debate about the type of usage one should make of them; part of it is the "old" argument of "drafting" versus "design."

The chapter is in three sections: surpassed expectations, developments that were not predicted (but had a major impact), and still pending promises. The first two sections deal with what has happened, and the last section with what has not, but may happen in the future. My prediction is that, in the future, the emphasis will be on design-oriented tools that will be capitalizing on artificially-creative techniques. We see hints of these directions already today in the ways younger designers are using the available digital tools.

SURPASSED EXPECTATIONS

It is fair to say that nearly all the CAD applications we have today have significantly surpassed what we thought would have been possible some 30 years ago. The following are a few of the most notable developments:

Computers are used Effectively Beyond Production, for Design

Over the years we have debated what CAD means—whether it is computer-aided drafting or design. We concluded it is both and it is used in both capacities today. While its use in drafting as a production machine is easy to recognize and appreciate, what is especially significant is the acceptance of CAD as a design tool. Computers are used in a manner that allows us to explore forms that go beyond what we can handle with the traditional manual means. They enhance our creativity and even lend themselves to artificial creativity and this will be discussed in more detail later in the chapter.

The Manufacturing End of CAD/CAM

Computer-aided manufacturing (CAM) is valuable from two distinct points of view: it offers means for making physical prototypes from virtual models quickly and it helps us build complex forms.

Physical models or prototypes are critically important in the design process. Designers, including architects, like to build as many of them as possible, as their design explorations proceed. While virtual models on computer screens come close to substituting for the real models, the need to view and touch physical models remains. However, taking the time to build physical models by hand is an essentially self-defeating process. By the time the model is completed, the chances are that the design has already evolved into its next stage and a new model is called for. The rapid prototyping or three-dimensional printing methods that are available today can make physical models directly from virtual models in a fraction of the time that it would have taken to construct it by hand.

The second aspect for which CAM is valuable is that it helps us manufacture the complex forms that computers now inspire us to incorporate in our designs and virtual models. Even though CAM has already grown beyond our initial expectations, it also appears that it has yet to be fully developed. That we already use manufacturing processes to build forms that initially we did not think were buildable must qualify as a pleasant surprise that evolved during the last couple of decades.

The Warm Reception of the Digital Tools by the Younger Generation

For me this is the most significant development relative to CAD. It is a common observation these days that student designers are frequently ahead of their professors when it comes to the use of digital tools. As they feel a lot more comfortable with them than the established

middle-aged professionals, the students' learning of design is closely associated with the computers and they develop intuitive ways to be admirably creative with them.

DEVELOPMENTS THAT WERE NEVER PREDICTED BUT CURRENTLY HAVE A MAJOR IMPACT

There are probably many developments that came as pleasant surprises over the recent past, however, there are two that are of particular significance: the explosion of the Internet and the wide success of electronic games.

The Internet

Even though it existed in some form even before CAD made its first steps, its explosion, current popularity and impact was never fully anticipated. As it has evolved from a rather exclusive means of communication between academic researchers and government agencies into a daily means of communication for the vast majority of common people, the verdict about its significance is still out. However, its impact on CAD is already visible and quite deep. Whether it is the easy access to valuable information it offers through hyperlinks and other means, or the possibilities for collaboration between design professionals located far apart, we all sense its importance but have yet to fully comprehend how deeply it will affect the design professions.

Electronic Games

It sounds almost strange to talk-about games as something significant for design. They are significant because they help the young people feel at ease with electronic devices. This is one reason why computers come so much easier to the younger generation than they do to middle-aged people. The electronic games have prepared them well. However, the electronic games are contributing in additional ways. As wars help the development of technology, so do the games. To perform well they need technological advancements in hardware and software that make them run in real time and look real. These are all technologies which are very instrumental in the development of CAD tools, which have benefited significantly from the technologies initially developed for games.

STILL PENDING

This section will touch on items that were promised but have yet to materialize in a complete sense. This is possibly the category of the highest interest, as we attempt to explore whether the promises are still valid and desirable today. We shall be looking into what was called automated design, which is based on artificial intelligence and knowledge-based systems, parametrics and CAM. As we talk about promises, we also have to remember those about equal partnerships between humans and machines.

Automated Design through Artificially Intelligent and Knowledge-based Techniques

Automated design was one of the very first ideas formulated when the computer was still in its infancy, in the 1950s and 1960s. The idea was that, given a set of requirements, relationships and constraints, a program can be written that can process the information to derive an architecturally sound and correct solution that satisfies the given requirements.

Ever since the early age of the computer, architects in particular wanted to use it for all those tedious tasks they did not like doing. Many programs were written that were attempting to do design according to the above paradigm. Many were written even before we knew how to do graphics, and used character matrices to represent spaces and plans. Their emphasis was on functional criteria and relationships and they never considered aesthetics. Even though some of them were quite successful in generating efficient layouts, they were never accepted by the design communities. As we observe to what forms CAD is taking us today, we can also start seeing why the "drawings" of the early days could not have been accepted.

In architecture, however, the need to lay out spaces efficiently is real and occupies a major portion of an architectural firm's labor, especially when it deals with projects where functional efficiency is a high priority, such as hospitals, libraries, schools, etc. These designers would love to have a machine that can derive a solution for them in little time; as they are freed from a major headache they can spend their time on more pleasant and productive design tasks.

Because there is a need and demand, we can expect that a lot more work will happen in this area; the results are going to be a lot more impressive than they were 20 to 30 years ago. There are a few, rather simple reasons for this; today we have much more computing power and storage available to us, which make techniques such as extensive heuristic searches a lot more feasible. We also understand these techniques much better, as demonstrated by the chess programs that are capable of beating the masters of the game. We also understand how to combine the heuristic searches with knowledge bases, and are willing to recognize that every problem is not a new problem but it is one for which significant knowledge already exists, so we can capitalize on it.

<div align="center">

Parametrics

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This is almost a buzzword today. While there is a lot of talk about parametrics, there is little understanding about what they really mean for architectural design. It is, once again, a term derived from engineering; as a technique, it has yet to become native to architecture. Transferring techniques from one field to another, without adopting them fully, is a dangerous undertaking, as it contains the risk of appearing foreign to the users of the second field, which typically leads to unproductive situations.

Initially, a parametric definition was simply a mathematical formula that required values to be substituted for a few parameters in order to generate variations from within a family of entities. Today it is used to imply that the entity once generated can easily be changed. This is where the parametrics becomes significant for CAD. Parametric entities carry their attributes and properties within their representation, which allows them to be manipulated and transformed according to these properties. While this works quite well for

the engineering type of entities, it leaves a lot to be desired for architectural entities. The nature of architectural design is such that individual elements of a structure are manipulated and evolve as the whole structure evolves. Thus, they work best when their character is embedded within their internal representations, rather than being handled as more or less externally attached attributes. To develop such parametrically complete representations of architectural elements, one needs to evaluate, understand and interpret the inherent behavior of these elements; this process may actually be quite subjective, which is a rather typical occurrence in architectural design. At the risk of sounding pessimistic, allow me to suggest that all the commercially available architectural structures that claim to be parametric are of the engineering type and fail the above criteria. However, work on true architectural parametrics is in progress and is expected to become available commercially in the near future.

Manufacturing

As mentioned above, manufacturing is one area which developed in directions that were beyond our initial expectations. At the same time, it is an area for which many predictions were made, such as computer-driven machines making buildings, which have yet to materialize, and this is why I am mentioning it again as an area where we can expect even more impressive developments in the not too distant future. Earlier, I underlined two areas where CAM's success has been the most impressive: automated physical model building as required during the process of design, and computer-assisted manufacturing of building components that have complex forms. Our expectation for the future is that these will be combined into a single automated construction method. We can expect large CAM machines to be constructing—or should I say manufacturing—buildings such as those that Frank Gehry has popularized in recent years. That means big machines, driven by computers, and putting together real, full-size buildings.

Equal Partnerships between Humans and Machines

Those who have been around CAD for a while should recognize that this refers to Negroponte's *Architecture Machine*. After observing three possible ways in which machines can assist the design process, Negroponte considered only one, according to which the design process, considered as revolutionary, can be presented to a machine, also considered as evolutionary, and a mutual training, resilience and growth can be developed: "By virtue of ascribing intelligence to an artifact or the artificial, the partnership is not one of master and slave but rather of two associates that have a potential and a desire for self-improvement."

It is no surprise that such equal partnership between humans and machines never materialized, simply because the machines are not even close to being intelligent enough to be considered as potential partners. Of course, as debated rather extensively in the 1970s, there are also all kinds of ethical issues that may make the idea of an equal partnership between humans and machines undesirable. But there are fewer objections to accepting the machine as an assistant that enhances the human intellect, so we can expect quite a bit of that happening in the foreseeable future.

Artificial creativity

Machines collaborating with humans in design requires more than artificial intelligence—it requires artificial creativity, which can be defined similarly to artificial intelligence. We know we have a manifestation of artificial creativity when a certain activity done by a machine would be considered creative if it were done by a human being. Within this rather circular definition, and provided we are not looking for miraculous manifestations, I would like to suggest that artificial creativity is already occurring, when we use tools that reinforce our creativity, tools that make us capable of doing designs that would be hard to do, if at all possible, with traditional manual means.
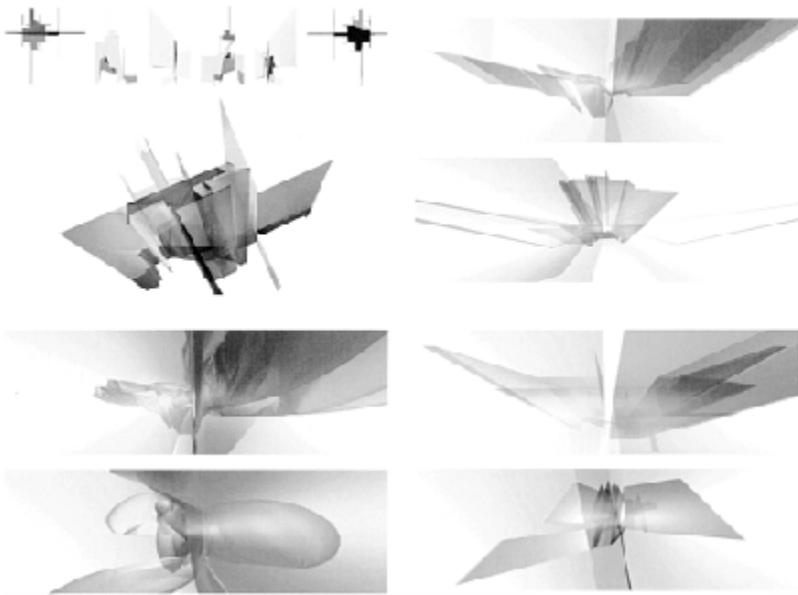
19.1a–d. The "Mies-reading" project, by Sam Jacoby, a Diploma 4 student at the Architectural Association in London, UK.

There is much work that can be done to produce tools that will take artificial creativity to the next level, tools that are researched systematically with that goal in mind, rather than being byproducts of other endeavors. This is where our main effort is right now. Determining the exact nature of those exploratory tools is, of course, no trivial task; we have once again to look at designers and how they design. Copying their mannerism blindly would repeat mistakes of the past all over again. We have to observe how designers respond to the possibilities offered by new digital tools, and find ways to reinforce their spontaneity. Thus, it should come as no surprise that the best groups for making these observations are the students and very novice designers.

Figures 19.1a–d to 19.5a–c, which are images from student projects, illustrate this point. Below I will describe the design directions that were apparently encouraged, and perhaps even completely inspired, by the new digital tools. As a conclusion, I offer that those directions would not have been approachable without them.
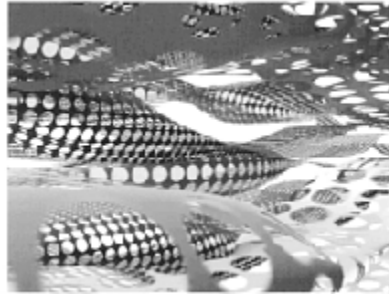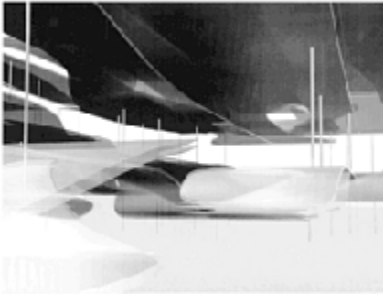
19.2a–b. "Dynamic Territories," by Rok Oman and Spela Videcnik, Architectural Association, London, UK.
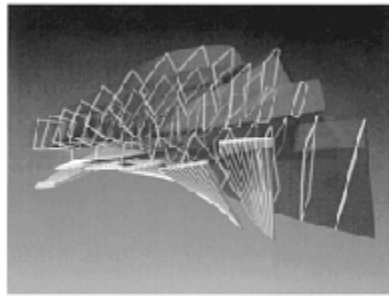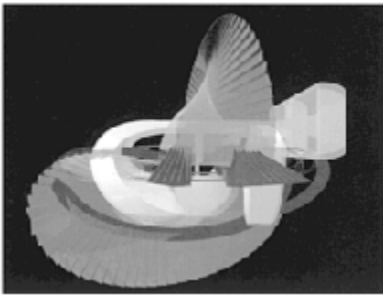
19.3a–b. "Differential Topologies," by Abbey Chung and Robb Walker, Southern California Institute of Architecture (SCI-Arc), Los Angeles.

RULES
- Start with a point and draw the figure
from this point.
- Take the figure with a visible point and
draw another of the same figure rotated
5 degrees and 95% the size of the
original.
- After the last step drop the
visible point from the
original shape.
- Repeat for more
iterations.
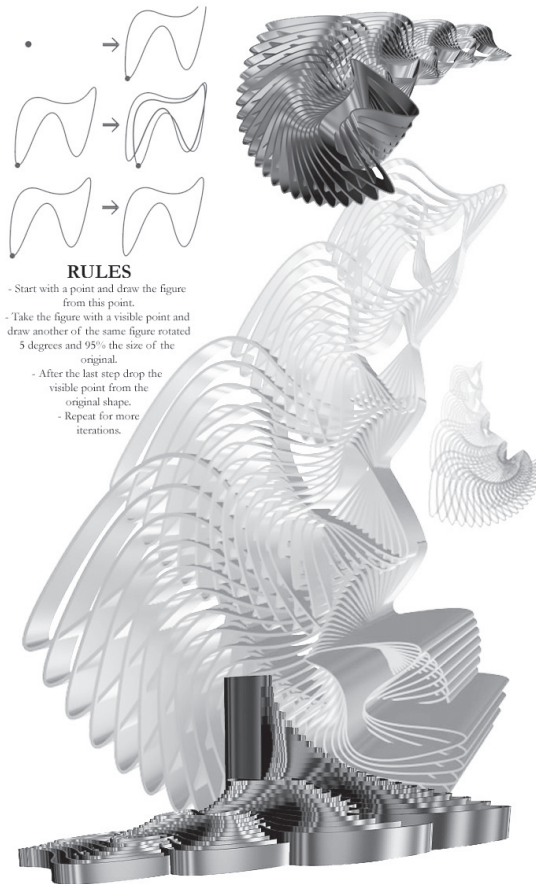
19.4. Generative design by Stan Arnett, University of Colarado, Denver.

The "Mies-reading" project (figures 19.1a–d) by Sam Jacoby is a reinterpretation of the production of Miesian space, where stereotomy is used for the analysis and interpretation of form:

> As a device for analysis, stereotomy, as derived by [Phillibert de L'orme] has been utilized, an orthogonal projective method, which is based on the knowledge of three drawings, the plan and two sections. During the projection, a layering and unfolding of these orthogonal drawings takes place in order to interpret the relations of two-dimensional representation of space into a three-dimensional surface/volume and finally back into paper space. The result is a segmented volume, described by exact and measurable traits, giving precise geometric information, and the enclosing,

continuous surface, which is geometrically inexact. Hence, this new volume and surface is both facilitated and generated by the projection, employing three types of folding: rebatement (folding on a horizontal line), rotation (folding on a vertical line), and development (flattening of a curved or faceted surface into a two-dimensional sheet). What this translation of the Miesian space suggests is a new geometry, which relies on the orthogonal organization of space, while simultaneously rejecting the hierarchical structure, enabling the phenomenal effects to become immediate within the construction of space. Geometry here does not only function as a static measure of invariant and unitary characteristics, but also as a plane of consistency, upon which differential transformations and deformations can occur, which are manifested at singular moments of an ever-changing spatial body.

This is an interesting form-generating methodology, which one can imagine producing all kinds of unexpected shapes, once digital tools are employed for applying these rather complex compositional undertakings.

The next project is "Dynamic Territories" by Rok Oman and Spela Videcnik (figures 19.2a–b). While we do not have much textual information about their intentions, their images give us quite a few hints about the type of manipulations and transformations they tend to apply to their objects. As their title implies, they want their objects to be fluent, tentative and changeable at the click of a mouse, sometimes in predictable and other times in unpredictable ways. Again, one can easily anticipate the possibilities, were such capabilities implemented in form-manipulating digital tools.
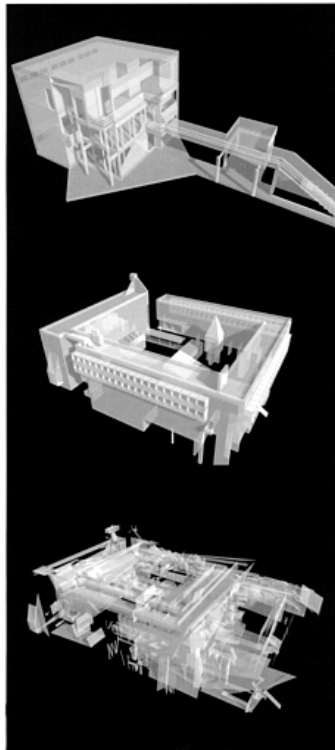
19.5a–c. Morphing of a Graves building (Parent A) into a Le Corbusier building (parent B); the middle image is 50% each.

In their "Advanced Drawing" and "Speed Drawing" classes, students Abbey Chung and Robb Walker are experimenting with what they call "differential topologies" (figures 19.3a–b). These form-manipulation techniques can again benefit from digital implementations.

Shane Rymer of the University of Colorado, Denver, examines the emergence of generative systems by introducing students to the ideas, the software and the strategies of the generative design process through a series of small projects that aim at architecture, as manifested in a project by student Stan Arnett (figure 19.4).

Under the title of "Explorations in Liquid Geometry," Kostas Terzidis and his students at the University of California, Los Angeles, investigate how computers and new media may extend a designer's perception by constructing spaces on the basis of non-Euclidean axioms. For example, how would an inverted perspective representation behave in a hyperbolic world? Another set of experiments involves morphing (interpolation) between two buildings, possibly from different designers (figures 19.5a–c). Parent A is mapped to parent B and the morphed result shares characteristics of its parents yet has its own identity. The result is a form that we could not have visualized without the morphing process.

20
THE CONSTRUCTION INDUSTRY IN AN AGE OF ANXIETY

NORBERT YOUNG

I will cover the following five topics in this chapter: first, my own context from which I speak; second, the new experience of a slowdown in economic expansion; third, the incredible boom and bust of the "dotcom;" forth, the impact of the tragic events of September 11; and fifth, a look at our industry and its fundamentals. In closing, I will offer some perspectives on what all of that means.

I have lived and breathed this industry for almost my entire life. I was raised in a very small town in Maine, named Pittsfield, with a population of 3,000, which offered only two options in life, to watch chickens lay eggs (Pittsfield is the egg capital of Maine) or to live and breathe construction, as most of the town was in the industry. Even today, Pittsfield is the home for the headquarters of Cianbro Construction Company, which is one of the top-rated companies on the *Engineering News Record's* list. I trained as an architect at the University of Pennsylvania because Louis Kahn, a great architect and a preeminent teacher, was there. Upon graduation, I was interning and working my way up to the associate in a mid-sized regional firm, Bower Lewis Thrower, and was involved in some remarkable urban projects. I then joined a client, Scott Toombs, from the Rouse Company, and spent the 1980s in the equivalent of today's "dotcom" fever—real estate development. There were great successes in the early 1980s, such as the One Reading Center, but also a near disaster at the end of that period, where the real definition of a pioneer caught up with us at the Princeton Forrestal Village—a pioneer defined as someone with an arrow in his back!

I then made a full circle and returned back into construction as a member of a dynamic New York construction management firm, Lehrer McGovern, which then became part of Bovis Construction. Over a nine-year period, I worked on some really amazing projects and construction programs in 17 countries, from EuroDisney in Paris to Canary Wharf in London to the Twin Towers in Malaysia. However, one program is my personal favorite—I was the officer in charge for the design and construction of all the sports facilities for the 1996 Olympic Games in Atlanta. There I saw firsthand the client's needs for more than just one project—the program or portfolio, and the key asset therein—the information—was truly the currency that produced results.

I joined McGraw-Hill Construction in late 1997, and have been leading the group since April 1999. We are known by the key brands and tradition of F.W. Dodge, Sweets Group, and our publications, such as the *Engineering News Record, Architectural Record* and *Design-Build*. There is also our construction.com Internet portal.

We are now in a downturn, for the first time in over ten years. We have never had ten consecutive years of growth in our industry. That shift means that we are now dealing with

a new world. Many of us who have been through previous downturns will have difficulty recalling lessons learned and how we need to behave.

The debate in April 1999, when "dotcoms" literally exploded on the design and construction scene, was not about the change that was occurring, but rather about the pace of that change. We have heard from some incredibly bright people with MBAs from Harvard, Stanford and Chicago that there was going to be a cataclysmic change to our industry—so cataclysmic, in fact, that if you were not on board, you were going to be dead, or "disintermediated" as they said. We were literally being told by countless companies that they would kill "legacy" companies like McGraw-Hill Construction. That was rather daunting to hear as I was just taking over the group.

A few of us concurred that the change was happening, but we thought it would be evolutionary in nature—after all, our industry moves at its own pace. Companies came out of nowhere with an incredible promise, and most have disappeared. So, what did we miss?

After re-reviewing over 200 business plans we received (each of them was promising our demise, but ironically they all came back to see if we had any money to fund them), I have found that there was very little real research on our industry, our readiness to change, and a lack of understanding of how our industry behaved, particularly its points of pain. Most of the research consisted of a broad statement that the size of the global construction market was $3.2 trillion and that their particular web application could result in an instantaneous savings of significant percentages. All one had to do was to capture eyeballs, and that was supposed to result in a viable business!

Now, let's shift to the horrific events of September 11, 2001. The losses are staggering. I was in our offices at midtown Manhattan and watched everything unfold before my eyes—a nightmare. Over 100 construction industry professionals lost their lives that day. The loss of real estate alone in lower Manhattan is the equivalent to the loss of all the office space in Cincinnati and Northern Kentucky—it was all gone before our eyes: 13,400,000 gross square feet of class A office space destroyed, and another 16,600,000 gross square feet of class A office space damaged.

After that tragedy we have indicators that are clearly negative. The US is now in a recession. Consumer confidence has plummeted. This is important, because two-thirds of the US gross domestic product (GDP) is literally driven by what the consumers buy. The market value has evaporated, to the tune of $5 trillion. While one may argue that this is just a paper loss, it truly has an impact—one only has to consider the impact of Enron's collapse.

But unlike previous recessions, there are still other indicators that are very strong. Who would have believed the federal interest rate would be at a 1960 level? And inflation—what inflation? I still remember the recessions in the late 1970s when we were assigning an inflation percentage to our project estimates of 1.5% per month! When was the last time you needed to do that in project planning? Also, inventories are low—meaning goods need to be manufactured. Many believe that the power of demographics—the age of the population and its spending behavior—will drive us for many years to come.

But it is the shifting indicators that we are watching—their shift and pace will truly determine how long the downturn will exist. First, what will really be the impact of war and terrorism? Next, unemployment in the US is rising, but still below the high levels of previous recessions. We particularly watch government spending and focus on two components: federal spending, which should be strong, and local government spending, or more

importantly, the erosion of local tax bases. Finally, we watch the market sectors that are now battered, particularly commercial aviation and hospitality. The net effect is a fairly lengthy period of uncertainty, as these indicators unfold.

There is a healthy debate now about other trends, such as these dichotomies of increasing and decreasing phenomena: suburbs versus urban downtowns, renting versus owning, dispersing versus centralized operations, collaborative communications versus face-to-face meetings, regions focusing on defense/federal programs versus regions driven by tourism, longer-term versus short-term debt.

So, let's go back now and look at our industry, its fundamentals and how they interrelate. The key ones are as follows:

- inevitably, we focus on the project
- ours is an industry that has always organized virtually
- today we use countless intelligent applications
- yet the industry operates with very little efficiency, and
- we are an industry not yet ready for the web future.

Let us examine each of these in more detail. First, the project lifecycle: although linear in nature, a project is really never done, particularly when you consider that over half the dollars are spent after a project is done in the repair, refit, maintenance and renovation. Every business decision immediately leads to design and construction activity. There is an absolute linkage of our industry with any business activity, which is why our industry follows business cycles. It is also why our industry is such a large component of the GDP—almost 9% in the US alone.

Next, the players: if there is any industry that is ripe for the web, it is the construction industry, because our teams get assembled for every project and become a virtual industry around that project. There is no owner or client out there that has architects, engineers, contractors, subcontractors, distributors, building product manufacturers, and service providers sitting in a room waiting for the project bell to go off. The big question, then, is how many players are there; when we looked at the statistics, we discovered that there are over 1,250,000 companies in the US alone. But when we went deeper, we discovered that 98% of the companies had ten people or less! Therein lies another key characteristic—we are fundamentally a very small business industry operating in local markets. Companies come and go—particularly when we consider that the average life expectancy of a specialty subcontractor in the US is 2.8 years!

Now, if we layer on the intelligent applications we each use every day to do our jobs, we again see a proliferation with little connectivity. We are unable to leverage these applications from player to player, let alone just internally. The net result is that the handoffs of information remain very static. The promise of the web—that of connectivity and enhancing productivity—remains unfulfilled.

When we look at the information needs of our industry, and for that matter any player in the project life-cycle, there are truly only six questions that need to be answered: who, what, where, when, how, and how much. That is all one needs to do the job and drive the intelligent applications. We at McGraw-Hill Construction Information Group focus on answering those questions, and we have organized our focus into three components:

projects, products and industry. We are constantly researching the use of the web and technology within our industry. In a snapshot from July of the top architecture and engineering firms (figure 20.1), we can see that over 98% use the web for communications, and less that 3% use it for some form of e-commerce, and these are just the big firms.

Successful Internet Uses Today

· Communication
· Careers, Employment and Training
· R esearch and Development
· News and Information
· Sales and Marketing
· Design Tools and Collaboration
· Project Management Tools
· Bidding and Procurement Tools
· Product Marketplaces
· e-Commerce

20.1. The use of the web by the top architecture and engineering firms (as ranked by the *Engineering News Record*). The list is qualitative and ranked by most used at the top to least at the bottom.

There are two other factors at play, besides the web. One is the impact of the Moore's Law—the doubling of computing power every 18 months, and the concurrent reduction in cost. This means that now, and going forward, our small-business dominated industry can actually afford computers. It still stuns me that my laptop, which costs about $2,000, has ten times the computing power that NASA used to put a man on the moon. But even with the web and computers in our hands, the third driver—adequate bandwidth—is lacking. This is a particularly important issue for our industry, given the highly graphical nature of our information. With greater bandwidth we should begin to see the convergence of the web, computers and bandwidth.

The change is happening, but how long will it take to truly transform our industry? Huge investment, in the form of venture capital, comes into our industry; we estimate that over $1.5 billion were invested in 1999 and 2000 alone. That investment did drive more research in our industry and its practices than we have ever seen. Old legacy companies, such as ourselves, were woken up, changed and shifted. Even the computer-aided design (CAD) technology companies have changed.

But we still have the cultural and political issues to solve. To address them, I will use Aesop's fable about the tortoise and the hare. I maintain that we are in a marathon. Most of the "dotcoms" literally described the race as being one of a 100 yard dash; in fact, one business plan after another stated that it was a dash for the swiftest. What happened, however, is that most broke through the tape at the 100 yard mark, looked up, discovered that there is 26 more miles to go, and collapsed.

Paul Teicholz, who recently retired as head of Stanford University's CIFE (Center for Integrated Facilities Engineering) has been researching the productivity of the US construction industry since 1969. At that point, according to Teicholz, both US construction and US manufacturing were equally productive. But 31 years later, he finds that while US

manufacturing has become more productive, the productivity in US construction has actually decreased so much that, today, there is a two-to-one gap between the two! I find that perplexing—productivity has gone down as the emergence of intelligent applications has occurred. In 1969, when I started as a young architect, my intelligent applications were a T-square, tracing paper and a pencil.

I have also looked at the research that David Coleman of Collaborative Strategies has done on the impact of technology on various industries. He has found that there are four key factors that matter, and that their relative importance varies from one industry to another. The actual technology is the least weighted. Twice as important as technology is the economics, the ability of a particular industry to afford the systems, which Moore's law should solve. Also twice as important are the social issues, pertaining mainly to behavior. Four times as important are the political issues, which is particularly true in construction, where one of the prime drivers is the transfer of risk down the food chain of the project lifecycle.

Another key driver should be standards for the exchange of information. What if the basic information, the data, could be shared dynamically by player to player from application to application—wouldn't that result in significant gains? We should not be wary of standards. In fact, we, as players, should demand open standards. Imagine the information from CAD documents immediately populating the spreadsheet of an estimating application, then adding pricing for material and labor, and immediately populating a scheduling application because, after all, labor rates contain the time duration of activities, and, then, as the job is contracted, flowing right into the general ledger system. This may sound ideal, but all the necessary technology is in place today to make this happen. It is the cultural and social barriers that inhibit transformation.

There are several key initiatives for information standards, such as the International Alliance for Interoperability (IAI), which has a global focus, through nine chapters, on interoperability and the development of intelligent objects, rather than simply lines, with all their attributes. From that effort we have the XML (eXtended Meta Language) for our industry, referred to as aecXML, which allows the web to transport the attributes rather than just static pages, as is presently the case with HTML (HyperText Mark-up Language). The industry players, and not the software developers, should drive these initiatives.

Instead of assuming that there is a technology solution waiting to solve our disconnections, I argue that we should focus on the players and their points of connection (or rather disconnection). There are two key players in the cycle that absolutely hold the crown jewels, now and in the future—these are the special subcontractor and the distributor. Why? They are the ones who do all the buying and selling. After all, when I was at Bovis, we never did any actual purchasing of goods—we never bought the brick or the concrete. When I ask my contractor friends what their big problems are, they respond that after getting competent people to staff their projects, it is their subcontractors—they are small businesses, do not use computers and they cannot rely on them, because they could go out of business tomorrow.

I asked the building product manufacturers the same question—what are the issues facing them and the response was remarkably similar: the problem is their distributors, which are small, do not use computers and they cannot rely on them. Until we can get those small businesses, which represent 98% of our industry, on computers with very simple

applications that are very intuitive and easy to learn, not much will happen in e-commerce in the building industry.

This, then, is where a lot of our own focus is today. Now, more than ever, is the time to be very, very close to the customers and clients. For us, that means going deeper into understanding who the players are, what they need, and how they need it. After all, an architect is different from an engineer.

To conclude, we are going back to the fundamentals—the project lifecycle and the needs of the players from the industry. That is literally our plan for today and tomorrow. We will watch very closely the shifting indicators, and will get close and stay close to our clients.

21
PERFORMANCE-BASED DESIGN

CHRIS LUEBKEMAN

At Arup, I am known as the foresight and innovation guy. My job is to constantly try to push our sights forward while I am being bombarded with the reality of our practice. But in the terms of this volume, I am going to play a bit of the contemporary guy. I am going to step into this role in order to help frame some contexts for us to begin to be able to build a bit of an understanding of where our practice is, and is heading, with performance-based design.

This chapter consists of three parts. The first is a discussion of context, the second a discussion on performance-based design, and the third a discourse on the future.

PART 1: CONTEXT

Whenever I mention context within Arup, I have a system that I have adopted called the "3Ns." In order to illustrate these, I use the metaphor of flight. If we look back through time, we can see that human-enabled flight, the ability to soar unencumbered by gravity, has been a dream and driver for technological change for many years. It was only about 100 years ago that the Wright brothers finally got off the ground by putting together a bunch of disparate elements into a flying machine through a singular dedication and desire to achieve their goal.

21.1. The *Now:* US Navy jet breaking through the sound barrier.

The first N is the "Now." By this, I mean those technologies and designs that are contemporary and are realizable in our context. Yet, everyone has a different context, within which they work and understand what they have been experiencing. This first N is always changing. As a flight metaphor for the *Now,* think of the jet breaking through the sound barrier (figure 21.1)— which looks futuristic but actually builds upon technology that was available decades ago. I look at this and think of those projects upon which each of us works—which are breaking sound barriers? Not all flying machines can, and if most tried, they would fail. Similarly, most projects in the built environment do not break sound barriers, and if they did, they would fail. Yet, it is crucial that there are those that do and that we recognize them.

The next N is the "New," which, in our professional context, I take to be three to five years away. It is what we are anticipating in practice. I prefer the flying wing by designer Norman Bell Geddes, as a bit of the "back to the future" (figure 21.2). I believe if we are looking three to five years ahead, we also need to be looking three to thirty years behind. Much of the work we are attempting today has been realized in different ways before. Knowing this, we can combine emerging technologies with a solid appreciation of the past to create understandings, potentialities and realities that were only glimmers of hope before.

21.2. The *New.* the flying wing.

21.3. The *Next Project Ornithopter,* the human powered bird.

The last N is "the Next," which I take to be ten or more years away. It is what we are trying to anticipate by looking over the future as well as the future we are helping to create. As a metaphor for this, I use the mythological intention of flight through the flapping of "wings." A particularly interesting example is *"Project Ornithopter,"* which could be described as a human-powered bird (figure 21.3). The vehicle is an attempt to achieve one

of the "holy grails" of flight. Indeed, there are many vehicles of flight that flap their wings. They have been around for a while and the military uses them quite prolifically today. Can you imagine a Boeing that will flap its wings? It was once unimaginable that humans would ever fly, let alone fly faster than the speed of sound.

The building industry has holy grails as well. For the past 30 years, we have been striving for the integration and the manipulation of the digital with the physical. The challenge for us, the next generation, is to redefine and create new holy grails.

At Arup we must balance our engagement of the 3Ns. As a corporation, we have to worry about the *Now,* because without a profit we do not exist. Our clients come to us because we are fully engaged with the *New*. And the *Next* provide us with visions to work towards. Each and every one of us must ensure that we are engaged in each of the 3Ns to some degree in order to maintain a healthy working relationship.

The Arup Context

Arup has about 7,000 employees around the world in 76 offices. We are in 26 countries and you can imagine the number of languages with which we have to work. We have an extremely strong culture, a very strong belief system; we are what you would call a self-selecting organization. Those who join us typically either stay with us for their entire careers or leave us very quickly.

Buildings only make up about 50% of our £450 million turnover. We have diversified quite a bit over the past ten years. Today, we have branched into automobile styling, risk continuity, venue design, and even e-commerce and e-learning consulting. We have diversified in order to survive.

We spend about £8 million—around $12 million—on research and development. This is probably the largest investment by an independent consultant in the building industry. Of those £8 million, more than 85% is spent on projects where we have the privilege to work with individuals and firms around the world who challenge us in ways that are very unusual. We embrace that, because as Sir Ove Arup famously wrote: "No man is an island." We never work in isolation; everything is built by a team. All of the tools that we have today need to enhance the potential for teamwork at both a local and global level. These tools range from simple global access to contact databases to fully integrated project management software to highly precise analytical tools available at a keystroke.

International travel is a large part of my job, as well as for approximately 20% of our workforce. I am on the road an average of two to three days a week. Our clients demand our presence and that presence is both physical and digital. They increasingly demand instantaneous access; the world has become an extremely small place through "instant" communication tools. Video-conferencing is absolutely ubiquitous in our world. I have a web-cam at my desk and I video conference using a high-end system on average two or three times a week. This new definition of proximity has become "normal" for us.

We also connect internally through communities of practice. About five years ago we created what we call skills networks, in order to enable designers of common interest to bridge our geographies (for example, all of the structural engineers). We enable this through a single, searchable intranet that currently contains about 177,000 indexed documents on

it. Every single office is connected to the intranet; some through GigaBit trunks and some only through modems. The key issue is that everyone is digitally connected.

This connectivity means that we have the capability to pose a question to an entire professional engineering community within the company and receive answers back from all over the world within 24 hours. These, for us, have proven very useful. For example, we were bidding for a job in St. Louis and the client was asking about typical art museum loadings. Within 24 hours, we had 17 different museum loadings from 17 different projects that had been completed by Arup within the past three years. These were 17 different legal floor loadings from which we could compare and contrast. Such a precise and fast response is very important, because it allowed our design team to communicate to the client the parameters within which we could work. We won the job.

Globality and Networking

Personal networks, enabled by globality, are particularly important in the digital world. This whole global connectedness woven into our community of networks is crucial to success. The world continues to become a smaller and smaller place as professional opportunity becomes more global. I have just completed a competition in Zurich with the Tokyo-based architect Shigeru Ban. He is working with another Arup designer on an art museum in the States, and in addition, we are discussing working together on a high-rise residential project in Australia and on an educational building in Lebanon. Digital tools for both design and collaboration have enabled this. We could not have done it ten years ago in such a fluid and "normal" fashion.

Benchmarking is another new aspect of knowledge networking. Global clients now expect us to benchmark performance to global standards. How do we get the information about the energy performance of an office building in Sydney or the rail network efficiency between Berlin and Stuttgart or the cost of energy in Tokyo? Our clients expect it and we have to be able to provide it.

Project networking has also been enabled through new digital tools. Our global teams have long needed "instant" access to project documents of all kinds. About seven years ago, we started to look for software that would allow our clients and our teams to be independent from a single software platform. We found none, so we created a piece of software for our own use, which we called *Columbus*. It allows anyone in a project team to read hundreds of different file formats without being masters of the original authoring program. Thus, all members of a project team can view any file of any kind.

Columbus is extremely important for the smooth running of our international project teams. What is standard software in London or Manchester is certainly not standard in San Francisco. For us to work globally, we had to have something that can interface and plug into all the different software programs in use. We joined with Causeway to create a package that has now successfully spun-off commercially, and on which there are a couple of billion pounds worth of construction going on right now.

The last item relative to the context of globality and networking is global consciousness. Today we find the issue of sustainability permeating everything we do. There is the growing realization that sustainability is not just a passing fad that will fade, but an important responsibility for all members of the global society. Our industry consumes the most

materials and energy of any industry, and is also the largest employer. We have an influence that is incredibly far reaching. This is perhaps the singular new challenge that we can, or must, rise to.

In the Context of Speed and Time

All of us understand time compression; clients expect projects to be done yesterday. With the advent of digital tools there has been a reduction in the time spent planning and designing the built environment. The luxury of considering options for a day, week or a month has been reduced to minutes or hours. Digital tools now allow rapid adjustments to designs as they materialize on site before their end use has been determined. This compression is not just in our industry, it is pervasive. Terry Ozan, Vice-Chairman at Ernst and Young, had this to say about speed:

> I think the importance of speed is going to be emphasized and is going to change. For example, virtually every company is worried about speed in a time-to-market sense or a time-to-customer sense. That's going to be faster and more important. But other areas of speed are going to become very important that some companies might not have really focused on before—and that's the speed or time to experience for an individual. How fast can somebody get what we think of today as five years' of experience? What cycle time can we reduce that to? Or time to capability for an organization… how fast can an organization develop capabilities that they didn't have before?
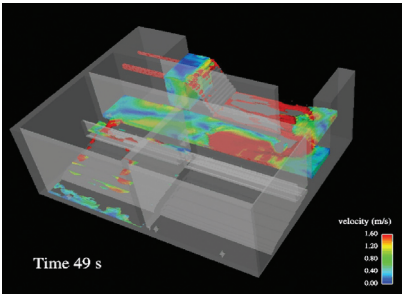
21.4. The CFD simulation of the water flow inside a pumping station.

These three different kinds of speed mentioned by Terry Ozan are critical for survival. One is the speed to market—how fast we can get our objects completed. The second is speed to experience—what are we expecting individuals to come out of school with? What kind of tool sets do they need to have?

If we think back to when we all started in practice, we were not expected to be profitable within the first year—at least, that was the case when I started in the late 1970s. Today, we expect our newly hired employees to be turning a profit within months. What has gone missing in that? What are we losing, what have we gained with our expectations? How do we have to change the way we educate in order to make sure that our students, our professionals, are ready to deal with change? That is a very important issue.
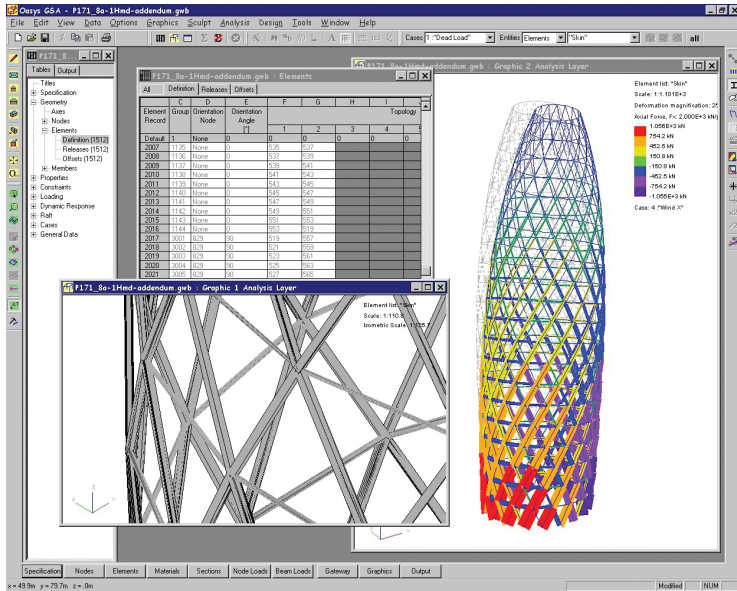
21.5. The FEA analysis of stresses (*Swiss Re* building (2004), London, UK, architect Foster and Partners).

The third is speed to organizational capability. How fast can a company change? How can it learn? How can it adapt to a changing market place? How fast can a global company really take on board the changes that are taking place in its markets? How fast can institutions change to reflect new needs? These are questions that we ask ourselves. One must not change too rapidly as fads and whims have destroyed many solid firms. Yet change is the only constant with which we must work.

PART 2: PERFORMANCE-BASED TOOLS IN PRACTICE

Arup fundamentally supports the development of performance-based design. We believe that this will put design back into the hands of designers. When I recently did a quick Internet search for "performance-based design," it took 0.29 seconds for over 2.8 million hits to come back. I was curious to see what was out there, and came across several definitions.

One that caught my eye implied performance-based design is "an alternative to the prescriptive codes." We believe that this is right on the mark. Prescriptive codes are actually extremely constrictive and do not lend themselves to the kinds of tools and tool sets discussed in this book. Most of the other millions of hits were digressions from this.
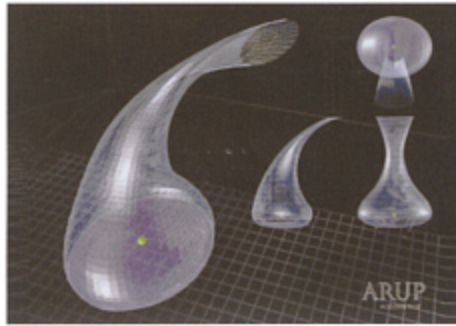
21.6. The acoustical analysis of the debating chamber in the GLA building (2002), architect Foster and Partners.

I also put out a call within the company to find out which digital tools we use today. I quickly closed it down because I found out we have over 150 digital tools just among our structural engineers. These ranged from very simple spreadsheets all the way up to virtual three-dimensional walk-throughs of potential structures. They also included much of our own software which we have been developing for the past 30 years. I took another tack and inquired about the general capabilities we look for in the software. The resulting list was even longer; I realized that scanning all 7,000, asking for their tools, was a futile exercise. I decided that I would discuss a small subset of the tools that we use (bear in mind that this is merely a snapshot of convenience).

We utilize computational fluid dynamics (CFD) software in many areas. We increasingly refer to this as fluid engineering, because it pertains to fluid flows of many densities (figure 21.4). We have been utilizing a related method for structural analysis (finite-element analysis (FEA)) for many years (figure 21.5). We pioneered these methods on the Sydney Opera House. We do acoustic modeling, such as the analysis we conducted for Foster's Greater London Authority (GLA) building, using ray tracing and other techniques (figure 21.6). We simulate traffic flows for automobiles, trains, people and goods in the built environment. For example, we can look at how people would escape from a station when on fire (figure 21.7).
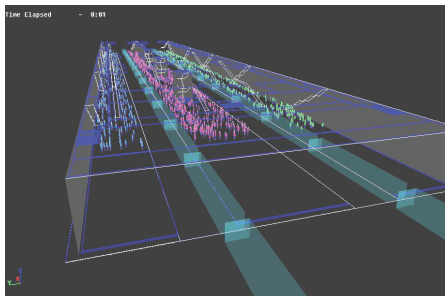
21.7. Traffic simulation showing people escaping from a station on fire.

The link between codes and analysis must be recognized. In the past, we have worked on developing tools that allowed one to satisfy code requirements. This will not change as they move towards performance. We found that most commercially available products have been inadequate to deal with the real complexity of the phenomenon found in the built environment. But things are changing. We are, for example, working with VTT of Finland and the Australian government to help evolve a performance-based fire code for Australia that focuses on getting people out of buildings rather than door sizes. This will enable, and sometimes force, designers to implement effective safety measures, rather than simply following a set of rules.

We are also looking at digitally modeling linked physical phenomena, for example, in the analysis of fires or acoustics. There are interrelated factors that we have known about for many years, but have not been able to model because the variables are too numerous. With the advent of performance-based tools, the computational capability is catching up with the need. We are starting to see what has been considered unseeable.

We do many infrastructure projects. A typical issue, for example, might be looking at how fire spreads in a subway and how people get out. We need to account for the smoke and its build up, and how people react and attempt to get out. It is a great way of using digital means to get that information across that could not happen otherwise.

We also use what I call "machined reality." We do a lot of work for London Underground and, because it is underground, you do not see it. We have been printing parts of the underground system (figure 21.8) to show them what they have—I think this is the first time that London Underground had seen a physical model of some of its own infrastructure.
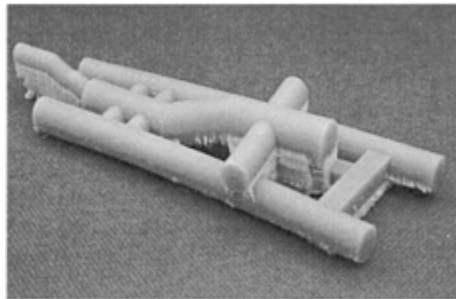
21.8. A machined physical scale model of part of the London Underground infrastructure.

Digital tools can also be used to find mistakes that we could not find before. We had a 300 m high tower project, which the architects had developed fully in three dimensions. We imported the digital model into our software just to check if the columns were lining up and discovered that there were some misalignments. This is a fairly bad thing for a structure, because it produces a lot of unnecessary shear and moment. The architect was not aware

of the problem, which raises some important questions about the digital design process. In this case, the tools can also provide a check.

We work with the analysis of highly dynamic phenomena as well. Our capability to perform dynamic analyses started with crash tests of nuclear fuel flasks. We subsequently expanded this to building structures and the automotive industry. Using dynamics simulation, we can now test all sorts of things, such as the wobble on London's Millennium Bridge. In doing this, it is also crucial that we conduct physical testing. This ensures that our algorithms and our performance simulations are correct. As various projects have shown, without understanding the craft of making or building, the digital world is not representing the reality we are trying to create. The same applies to performance. We have to seamlessly check from a systems integration (macro) standpoint, all the way down to the detail of a single bolt (micro) standpoint.

Sometimes we do not know if what we are modeling is real or not, as often happens when we are asked to do forensic work. After September 11, we had many clients very concerned about loading cases that had not been considered before. We investigated different scenarios, often not knowing if they were correct. We cannot know if our simulations do represent reality, because the calibration has been limited. But from the limited calibration available, the dynamic models appear to be very good. We have taken dynamic analysis even to the molecular level. Through this, we are now starting to build an understanding of how certain failure phenomena initiate. When the railway tracks caused a series of significant crashes in England, we were asked to look at the problem. We found this to be what is known as rolling contact fatigue and results from the wheels rolling on the rail (figure 21.9). We were able to solve that problem with absolute assurance and confidence in our dynamic models (figure 21.10).

Another area that one cannot see is the soil-structure interface. It is all but impossible to be inside the earth to "view" what is happening. We can put optic fibres down and begin
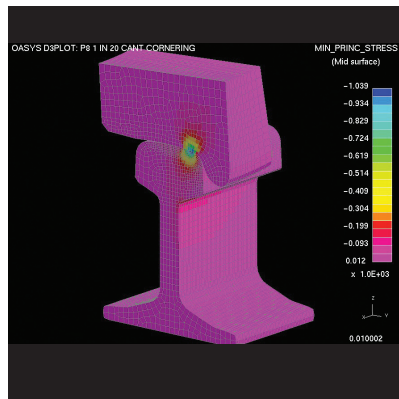
21.9. The analysis of the gauge corner cracking in the rails.
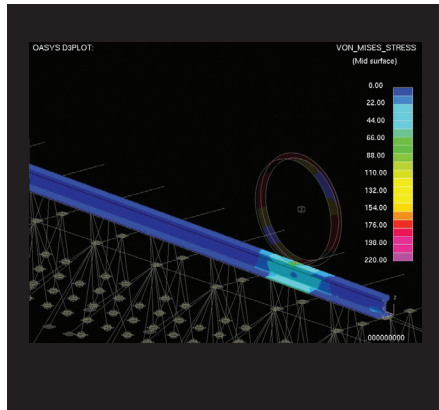
21.10. Simulation of the rolling contact fatigue.
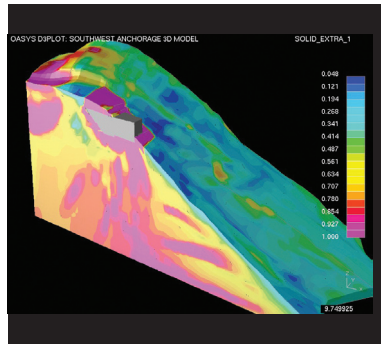
21.11. Analysis of the soil structure interface.
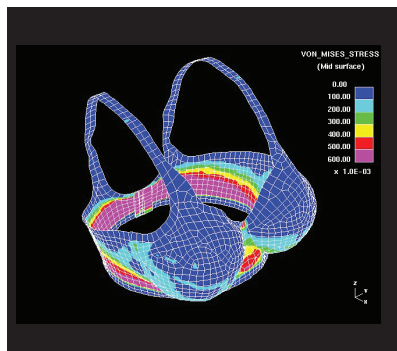
21.12. FEA study of a brassiere under dynamic stresses.

to assess stresses in foundations (figure 21.11). We can only digitally "see" what is going on, then feed this into our digital model to confirm our assessment of what is going on. This interface knowledge was used when we were asked to redesign a brassiere (figure 21.12). In this case, it was about understanding the behavior of the fabric and the structural system. It was essentially an issue of a dynamic system.

21.13. A cross-section through the cargo-handling building in Hong Kong, designed by Arup in collaboration with Foster and Partners.
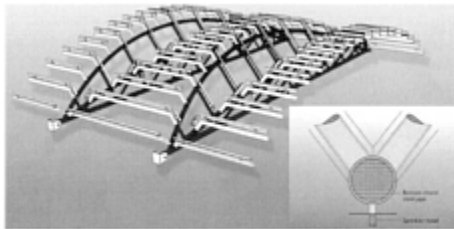
21.14. The digital model of the V-shaped trusses.
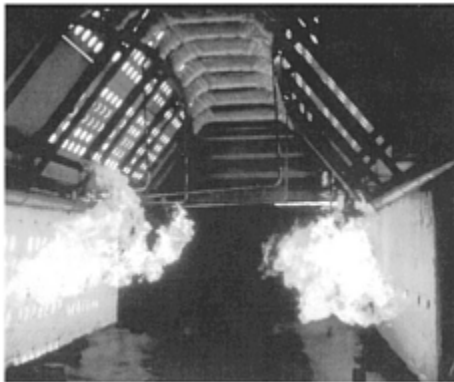
21.15. The fire testing of the V-shaped trusses.

The mixing of the digital and physical is particularly relevant in performance testing. In a project at the Chep Lap Kok airport cargo-handling facility in Hong Kong (figure 21.13), which we did with Foster and Partners, we designed V-shaped trusses (figure 21.14) to span the interstitial space between the long-term storage and the short-term storage. The clever bit was storing water within the trusses as an integral part of the fire-protection system. The water would supply the sprinkler system and cool the trusses in the event of a fire. Both are important aspects that enhance the performance of the system. However, the authorities in Hong Kong did not believe it would work. So, we built full-scale models and burned them (figure 21.15) to prove that they did perform as we anticipated. This is the kind of design that one can achieve with performance-based design that is precluded from prescriptive design codes.

There are numerous examples of how prescriptive codes actually result in questionable performance. The Hong Kong building code, for example, requires that every room in an apartment building should have access to air. This, in itself, is a good idea. However, when we completed a CFD analysis of the air circulation in some apartment building patterns (figure 21.16), it revealed that there were still some terrible places within the building. The prescriptive codes forced the ventilation to be done in a certain way, which, from the performance standpoint, was simply the wrong approach.

A Case for Performance-based Design

Performance-based design allows for a dialogue between clients, engineers and architects about appropriate performance objectives. It is a fundamental philosophy that embraces the concept of evaluating the functional aspects of entire systems and not just the components. It is extremely important that we engage in systems thinking and not in elemental segregation.

Performance-based design is really about going back to basics and to first principles, taking into account the experience one has gained over time as well as field and laboratory observations about the non-linear behavior of elements and components. It is the combination of first principles with experience and observations that is the fundamental potential of the design philosophy. It places the design imperative back into the hands of the designer. And, more importantly, it also places responsibility and accountability back into designer's hands in a very obvious way. One can no longer hide behind building codes.

There are two professional areas in which performance-based design is becoming accepted—fire engineering and seismic design. In both of these, a client can demand a certain performance and expect to get it. This requires that the design partners sit together with the client at the beginning of a project in order to define the performance characteristics in addition to the associated risks involved with the level of performance for each.

Thus, this requires that we look at the entire range of options and combinations. It is really about understanding and managing risk. For most design engineers, and for building code officials and clients, this is a radical departure. Performance-based design also acknowledges the interfacing of multiples of variables. At Arup, we developed a tool called the SPEAR diagram (figure 21.17) to look at sustainability as a multivariable issue, mixing

both objective and subjective information. Once the levels of performance are accepted, then the design team can begin to discuss ways in which to achieve them.

In closing this section, another point must be raised. For which percentage of the industry is this discussion valid? About 90% of our industry probably does not care about it at all. Is this technology and knowledge only for the privileged or should it be for all? In my view, performance must be the foundation on which we build the environment, and so it must be for all. We must find a way of getting these ideas into the small- and medium-sized enterprises that make up the vast majority of practices that manipulate the built environment.

PART 3: BACK TO THE FUTURE

In the final part of this chapter, I will offer some thoughts about which direction this may be heading. Consider the members of a design team. Without doubt, the boundaries of the professionals that make up the team are blurring. Ten years ago architects did not have access to structural analysis packages, project costing tools or CFD software; nor did engineers have access to three-dimensional modelers and behavioral animation tools. Today, all of these are available to any and every member of a team. Students are being taught to use these tools as a part of a "normal" education.

Blurring boundaries forces one to face up to different issues. Architects are pushing back at the engineers and saying: "I do not accept that because I have my own structural analysis program, and according to my assessment, that's not right." And the engineers are saying: "I don't accept that because I have made a spatial model and the ideas just do not stack up."

Clients and owners are doing the same thing. They can take their three-dimensional rendering package and have their son or daughter work up a rendering at home. They can then play with the renderings until they like them and then "push back" at the architect. These changes are having a tremendous effect. They must have an effect on the way we work and the way we interact with each other.

The number of engineers required to complete the design of a complex project is steadily decreasing as tools become more powerful and automatic. However, as projects increase in complexity, the knowledge required to bring the design through to completion also increases. How will this increase be met? Who will fill the gaps in the team? Will it be a new type of project manager, architect or engineer, or a mixture of the three in one, or a team of multiskilled individuals?

I believe there is a resurgence of craft, a challenge that is being made to craftspeople. We are at the beginning of a return to the master builder of days long past. Yet the new master is a master of a different skill set. There is a demand for the confluence of the accurate digital design and crafted objects. Hopefully, we can meet the demands of this resurgence. We are at a very exciting stage because we have almost achieved the holy grail of those who have worked towards digital design for so many decades. They have worked towards this vision of a new kind of mastering.

One future that we may consider for design is experiencing a space examined through the filter of total performance-based design. When we get to the point where

one can go into a room and actually see and feel what is being designed, we will be approaching the new mastery and a new era. Imagine a design space, a climate chamber with completely digitized surfaces, where one can physically and virtually experience anything one creates. We will then have a five-dimensional design world—point, surface, volume, time, with the fifth dimension being performance (figure 21.18)—in which one can manipulate the performance variables and feel the effects in real-time. Can you imagine…?
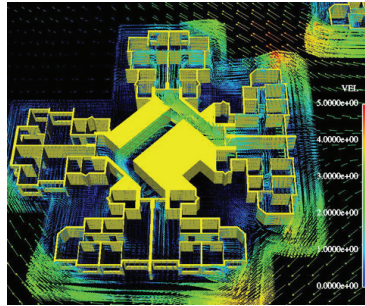
21.16. The CFD analysis of the cooking air circulation in a Hong Kong apartment building.
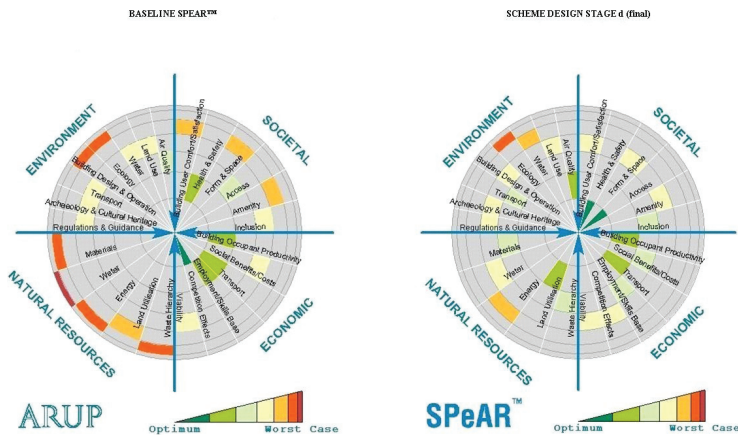
21.17. The SPEAR diagram.
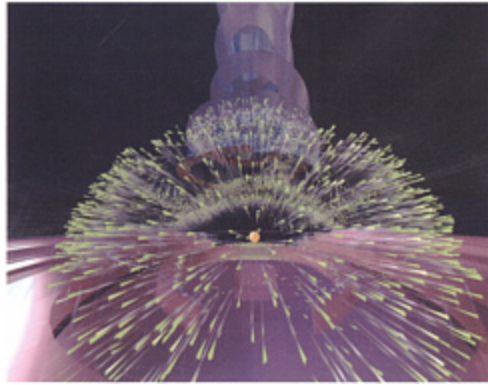
21.18. The five-dimensional design world where performance is the fifth dimension.

The Future is Oversold and Under Imagined

And finally, I would like to develop the theme that the future is oversold and under imagined. It is routinely oversold by authors, who need to fill our imaginations as well as pages, and by technology companies, who are trying to sell us the widget, gadget, mobile phone, laptop, or other "must-have upgrades." Science fiction writers long ago "predicted" many of these items in books that were often scoffed at by those in the know. Those early books of fiction are becoming significantly more interesting through their prescience.

Whenever I read an advertisement for new technologies or hear someone from a design software company talking about their latest and greatest, I ask: "How much of this is sales and how much is real?" The response varies depending upon the honesty of the presenter. And in this vein, I ask myself, how much of what we read in this book is overselling? And where are we under imagining?

Consider the following, recently a tabloid British newspaper described a camera the size of a pill that you can swallow. Hard to imagine in March 2001, but only one month later a product came out, and just recently it has been made mainstream. I find this fantastic. Imagine, if you have a problem with your stomach, there are only three ways of getting in there. To most, one path does not even come into consideration; and of the other two, I would much rather swallow a pill. Seriously, it is incredible to think that we can send a pill inside of a human today to "investigate" our physical inner world. When the movie *Fantastic Voyage* came out, this was the most extreme science fiction that was all but impossible to really imagine would one day be possible. Even if someone had asked me if we would ever be able to do this just ten years ago, I would have said no. I was obviously under imagining.

I could also never have imagined what I recently found on my children's breakfast cereal box. When I grew up we had sports heroes adorning the packaging. Each box was covered with images and statistics of individuals who would jump higher, run faster and

chase their dreams of being the world's best; the message: a healthy lifestyle led to success. Today, I found instead a CD embedded within the cardboard touting a tutorial to win *Who Wants to be a Millionaire?* It blew my mind at two levels. One was the sociological message that it implied: eat the cereal and be a millionaire. The greedy value system that this implies is quite unpleasant. Secondly, the fact that a CD is basically worthless is amazing. I remember when blank CDs cost $10 each. What this further implies is that memory is essentially free. It was not that long ago when memory had high value. Now, memory is packaging. Where will we be in a few more years? What will we get as a surprise nestled within a cereal box? Will we be collecting components of what we think of today as computers? Will the box itself become a computer?

Bill Gates predicted early in his career that "640K ought to be enough for anyone." My *Sony Memory Sticks* each have 128 megabytes. According to Jim Spohrer, a distinguished scientist from Apple Computer, "very shortly, we're going to be able to build a computer chip into everything. A Coke can will have a computer chip in it and it will be so cheap—just like it's cheap to print the Coca-Cola picture on it now." Can you imagine when everything that we produce in the physical world will have a chip embedded within it? Can you imagine what would happen if we really knew what went into every element of the built environment? Can you imagine if the element would be able to communicate when it needed to be cleaned or replaced? What would the design process become when everything contains information?

In 1953 Winston Churchill said: "All great empires of the future will be empires of the mind." I like this quote since I am part of a company that is essentially an empire of the mind. Imagine if one combines this with the recent Sony advertisements in which a person has a memory chip "slot" in the back of their head. I have a mechanical engineer, John Moss, who is retiring soon. I believe that he has not forgotten anything since he was about 16 years old. He has been with Arup for many years and has experience that is absolutely irreplaceable. I would love to be able to download his memories onto a "stick." I would love to be able to only download the mistakes he has seen! It is hard for me to imagine that I will ever be able to do this, but I do know that research is pushing hard to allow one to do just that. Research is penetrating boundaries in ways that terrify me as a humanist, and absolutely fascinate me as a technologist, scientist and engineer.

At the end of the nineteenth century, the Royal Society of London—the most eminent scientists of their day—stated that the study of physics was basically completed. They only had one little item to sort out and that was the electron. That little item changed the world in ways that they could not have dreamed. Quantum computing is probably going to change my children's lives the way the electron changed my grandparents' lives. I cannot begin to imagine the implications because I simply cannot get my head around how a cat can be alive and dead at the same time. But I sincerely hope that those who can are exercising their imagination.

Albert Einstein said: "Imagination is more important than knowledge." I cannot agree more with the statement. I would take it even one step further to say that knowledge is nothing without imagination. We must constantly exercise our imagination so that the knowledge we develop feeds into it in an ascending spiral.

This chapter closes with an exercise in imagination. Take yourself back to the Carolina coastline about 100 years ago. You are walking along the windswept, sandy dunes. You see

Orville Wright getting into his biplane. You stroll over and sagely advise: "Orville, you are going to be successful today. You will be so successful that the flying machine you now made of paper, wood and a bicycle engine will evolve into a streamlined metallic alloys object which will fly many times faster than the speed of sound. You will be so successful that one day these flying machines will fly halfway around the world, so high that nothing can see them, so fast that nothing could ever catch them, without ever stopping to refuel; flying machines whose sole purpose will be to drop thousands of tons of bombs on people with whom you cannot exchange a single, intelligible word."

Imagine how he would have reacted. What would he have said to you? He probably would have had you carted you off to an institution of some sort. I guarantee that Orville Wright, despite the fact that he never had a pilot's license, never would have, nor could have, imagined that scenario. I sometimes wonder what is it that we are not imagining?

22
CHALLENGES AHEAD

ROBERT AISH
MARK BURRY
BERNHARD FRANKEN
MARK GOULTHORPE
SULAN KOLATAN
CHRIS LUEBKEMAN
BRENDAN MACFARLANE
|ALI RAHIM
ANTONINO SAGGIO
BRANKO KOLAREVIC

KOLAREVIC: In this discussion we will seek out common threads in what I believe will be different and divergent perspectives on what the future has in store for our professions. I invite our panelists to summarize from their own point of view the unique possibilities, opportunities and challenges that we are likely to face in the future.

SAGGIO: I have identified five themes, all of which have something to do with the issue of construction. The first theme is engagement/disengagement, related to the Utzon/Gehry comparison that Bill Mitchell talked about. The second theme is classical consistency versus anti-classical movements, or "Foster's Chapel versus Gehry's Hair." We have seen these two very different approaches clearly depicted during the symposium. The third is "let's design a mess and make it anyway," which is kind of a joke, but is really how some architects think. You can design almost anything and then go to Arup's where they will find a way to build it. The fourth one is "bones versus skin" that shows two different approaches to construction. The fifth one stems from the method of working and the role of imagination in it, as in "imagination is more important than knowledge" (to borrow Einstein's words from Chris Luebkeman's presentation), which opens up the whole issue of simulation and the "imaginative" role of computers.

LUEBKEMAN: I will talk about the challenges. I think there are some lessons in the history of technology that are very important to pull out. If you look at the introduction of any new technology, you could argue whether that has been the new technology in the past 30 years. The first phase that it goes through is limitation. The second one is some outrageous or injudicious application, and the third is appropriate application. I think we have come to the point very recently where we are beginning to see appropriate application, and that for me was one of the most interesting challenges, possibilities and opportunities. It is for us to continue to define that appropriate application, the appropriate spatial articulation, the appropriate machine language. It is for us to push for that appropriate application, which

will be different for all of our different contexts. We have to guard against the continuation of the outrageous or injudicious. It is absolutely crucial to go through that phase, so one can then say "no, let's find out what is right." This has happened repeatedly through history.

KOLATAN: I would hope though that this kind of categorization of appropriate use is not misunderstood. Design intelligence exists at different levels. Some outrageous or injudicious application might be very intelligent indeed. I am not sure that one wants to already begin to become so regulatory about it.

The last time there was this much joy and optimism in architecture was probably in the 1960s. However, it seems to me that we are in danger of falling into some of the same holes that the 1960s generation fell into. One of them is perhaps an extreme reliance on technology. We ought to be careful about trusting a new technology to create perfect solutions on its own. The other one is the projection of a prescriptive future. I might be completely wrong in this, but my sense is that despite much talk about flexibility, for instance, or unpredictability, there is a tendency toward the prescriptive. I think this is also a potential danger that we must avoid. Perhaps you can be more specific in terms of your definition of what is an appropriate application versus a non-appropriate application of this technology.

LUEBKEMAN: What is appropriate is for each one of us to determine. It is the unique aspect we bring to our profession. It is crucial to understand and respect the context in which one stands or from which one wants to speak. We have seen in the symposium presentations some amazingly appropriate applications of technology, as a design methodology, a design language moving into a machine language, as Bill Mitchell said. That is entirely appropriate for what it is and how it is. Those things could not have been done in any other way. For me, that is incredibly powerful and incredibly strong. It is something we have to continue to push for.

GOULTHORPE: I sense that as the technology is more clearly understood, there is a tendency to fall back into techno-rationalism. I think several speakers have said that architects have to use their tools in sensible ways. I think that is insufficient for a cultural discourse. I think that it is entirely valid for architects to be dreaming or using technologies in "inappropriate" ways. The presentation by Ali Rahim dreams of a giant stereolithography machine, or giant particle cintering machine, that can distribute material as a density in space—what a delicious thought! It is probably unattainable, except in crude form at this point, but I think it is perfectly valid that architects should be dreaming in that sense. There is no 'right' way to use technology! One might as well say that there is a 'right' way to use a pencil!

I find that we are increasingly moving in our work from a scriptural paradigm to a digital one. I think architects must concentrate on what is that shift. It is a shift in creative thinking, in creative process, which I don't think is being articulated well enough in schools. Brendan MacFarlane says he wants to manifest his idea. Increasingly, I work without an idea. I am trying to generate open-endedly, release a fluid and creative process, which I am then sampling and editing. You have to go beyond what is prescriptive. There are many people increasingly working in non-linear, cyclical creative ways, which seems to me wholly appropriate to these new technologies.

I think digital technologies are essentially technologies of communication and not simply of manufacture. They have changed entirely the possibilities for the way architecture is developed and conceived. Every day I am in contact with technical specialists around the world. I think that creates an entirely different paradigm for architectural production. The gathering of dispersed expertise gives us all sorts of new possibilities, such as the dynamic architecture that I hinted at, which would be unthinkable if I was working in a traditional manner. Once you have stitched together a different way of working, it prescribes a wholly different creative attitude from architects.

One remarks that in the current generation of emergent offices very few of them have a single name, a signature. That marks a huge psychological shift. dECOi operates as a sort of anonymous rubric, a leitmotif that functions beautifully to allow people to gather without feeling they are being dominated by a single, creative mind. They seem happy to work in clusters on things.

I think all of these things demand changes in education, in practice, which is why I think it is a philosophical shift. The shift to a digital paradigm is the most fundamental technological shift humanity has probably ever encountered; the change from hieroglyphics to alphabetics codification, or the invention of mechanical print, are both seemingly minor by comparison. This is an extraordinary change, happening very quickly—a philosophical change, properly speaking. I think if it was addressed as such in academia, not simply as an appropriation of technique, then I think we would be witnessing a far more felicitous practice emerging than simply how curved are the panels, etc. We should be addressing, fundamentally, patterns of creativity, patterns of association, etc. I think that is the challenge.

KOLAREVIC: Chris Luebkeman called for five-dimensional design worlds, where the fifth dimension is meant to be performative. I think that Ali Rahim's presentation actually hinted at those five-dimensional worlds in a very poetic and convincing fashion. I would argue perhaps that is an opportunity, that is a possibility we should seek out—the creation of this five-dimensional design world.

I also want to ask our panelists to ponder the 1960s Sulan Kolatan mentioned. Peter Zellner wrote in one of his essays that "there is a strange resemblance between the efforts of the digital neo-avant-garde to induce a new state of formlessness in architecture and the now obsolete utopian designs of the 60s." Do you actually see that there is a danger of this becoming yet another Utopia? Or, do you actually believe that it is going to become a reality?

MACFARLANE: I would like to answer that question only through the project we did for Pompidou, because I think we have been accused of being utopian. For us it was a project that is absolutely specific to its situation and its site. It is a project that isn't, we hope, in continual dialogue with its site and its situation. It is possible that it alludes to the 1960s, but I would hope that it takes on a contemporality of its own (the project isn't about that). I think it is the specificity of the situation that is interesting, which is why I was trying to underline its importance. Through abstract interests in the technique we are trying to find a way through to the specific problems, dealing with specificities now, dealing with unique conditions.

AISH: I will address Chris Luebkeman's references to performance-based design. When I worked at Arup's, I participated in the development of some of the first generation of the performance tools. I think that there is a whole area of how we design the design tools. That is my preoccupation, and I am probably the only software developer in this group.

We are looking at things at a different level of abstraction, which I think is quite interesting to you as users of these tools. You are using a disparate group of tools, many of them not intentionally designed for architecture. The kinds of dimensions I consider important are intuition on one side and formality on the other. I think when we look at architecture (my view of it), it is both about dimension and the precision of dimension, and also about things like proportion, which are relationships that you can establish.

Then in performance-based design, there is the idea that when we design, we suspend the laws of physics momentarily (i.e. let's see what the shape is like before we have to build it). But I think time—the fourth dimension—is also something that we have to play with, because, as Hugh Whitehead mentioned, the whole idea of parametric design is to create an editable design history that you can re-execute. So, Ali Rahim's comment about time being irreversible—I'm sorry, but that goes out the window. I have reversed time many times, because I go back, edit something, replay it.

Then, there is the idea of intention versus indirection. We heard about design intent where we actually draw something—but how about actually making a program that we set parameters for and then we look at the end result. We don't directly manipulate something; we manipulate the algorithm, and we look at the result, and sometimes that result produces accidental contributions. It doesn't matter what kind of computer program we produce; this program doesn't execute by itself in a machine in the dead of night when there is nobody around. We are aiding a design process and, therefore, we have to develop a cognitive model of design. There is no point in having some fantastic conditional statement with nested ifs going that deep if you can't understand it; the compiler can understand it. The question is how we present that logical possibility in a way that a designer, who also wants to be spontaneous, can combine that type of thinking into a design process.

BURRY: I think we do risk being in a little bit of a vacuum or a closed circuit, where we think it is appropriate to discuss whether we misappropriate or appropriate software that is designed for other people and whether that is clever or foolish. I think we do risk getting into situations where folk will chase the cause, having gotten the effect. I don't think these are the issues. I think the issues are actually how we expand our horizons and work with people who actually do know how to use the tools properly. I am not saying that we shouldn't mess around and break things—that is our instincts.

One of the things that I have appreciated most over the last few years working with Mark Goulthorpe, particularly working with the interactive wall, was working with a very deep and wide multidisciplinary team. What is fundamentally missing is that we can't really communicate with other designers yet. You have other designers performing design activities that are entirely consistent with our own aims; they are just working in a different way.

What I see as an opportunity is the possibility of revising the whole academic environment. When you look at other designers, who aren't architects or interior designers, but are aeronautical designers, boat designers or graphic designers, they are physically in other

parts of the university; they aren't actually sharing time. When you look back at the history of how we actually do our education and practice, we find that the laboratories or the workshops associated with particular design activities are discrete, so that a printer using acid doesn't necessarily want to work with a die-maker in another workshop. But now we have all these tools, such as rapid prototyping, which are consistent across the disciplines. Yet I am not aware of anybody, apart from our own institution, trying to get all the designers, who are actually involved in the creative act of taking an idea through to an artifact, to share physical space and actually start sharing knowledge. So if you see somebody using a computational fluid dynamics (CFD) software, rather than tinkering with it yourself and seeing if you can actually get some cool effects, you can more usefully say: "this is what I want to do; this is what you do, can you help me do it?" I think that is the challenge (letting go) and the opportunity for us (hybrid vigor).

MITCHELL (from audience): I think the issue of software is fundamental. I would argue that software is in fact a deeply conservative force. One tends to think of it as a liberating tool, but mostly it is anything but. The reason comes out of the dynamics of software development. Typically, almost all software begins with the observation of some existing practice, with maybe some incremental transformation of it in mind. Then, by the very act of producing software, you privilege those practices and you marginalize other practices simply by making the ones that you support with software much more efficient, much faster, much easier; so, you introduce this kind of distinction between the privileged practices and the marginalized practices. Then that is reinforced by another kind of dynamic with commercial software: the more software gets used, the more an organization that produces it has to devote its efforts to supporting its user base and the less it can afford to change. You get into a tremendously conservative situation. I think it is really crucial for architects to understand the ways out of that, otherwise you get trapped in this cycle of conservatism that I think is absolutely deadly. One way out of it is just to have a deep critical understanding of what you are appropriating and be prepared to rip it apart and transform it. The other way is to have a more open, modularized structure of software and less division between a closed system that embodies a system of practice and a much more free, open, programmable, and transformable environment. Such an approach enables one to be critical and break out of this cycle of conservatism. You do have to have some mathematical knowledge to do it, some fundamental knowledge of how computation works, but I don't see any substitute for it. Otherwise I think one is trapped irrevocably in this cycle of conservatism that I think one can observe in a lot of work.

KOLAREVIC: I think Bill Mitchell is absolutely right on that theme. I too wish the Microsofts of CAD would take a more progressive role in casting the future for us in different terms.

AISH: I quite agree with Bill Mitchell too. My experience is very much influenced by my work in practice. I have been working with Hugh Whitehead, for example, and if I can paraphrase what he says and what I completely agree with, which is that so much CAD software is pushing a particular semantics of design that is most probably irrelevant except for extremely pragmatic buildings designed and constructed using conventional

practice. But lurking underneath the semantics is a very powerful and general geometry toolkit. If only we can get down to that, and have some programming skills taught alongside of design skills, then you have that general toolkit and you can go and invent your own semantics and you are not constrained. In one sense, the final layer that you currently see is very conservative, but underneath is something very general and we must encourage the students and the practitioners to get down to that layer. To quote Hugh Whitehead again, one of his comments is "what we need is tools to design tools." It is not for the software developer to hard code in a special button on the menu to do some special stadium roof. You have to program that yourself and you need to have skills to do that.

FRANKEN: I want to return to the Utopia question and the 1960s question. I was born in the 1960s and so I am a child of the 1960s. When we started out, we were quite naïve. I think the same goes for Brendan MacFarlane and my generation—the generation of the 60s—that we thought what we did in software was somehow possible to do in reality. Over time, through projects, we lost some of this innocence and we gained professionality. Looking at it now, I rather prefer professionality. I am tired of software that is inadequate, so we started programming our own, out of necessity to get things done the way we want to have them done. We have to do it ourselves because the industry is not supplying the right software.

RAHIM: We need to be inclusive to further the practice of architecture. Different disciplines need to participate in a dialogue and discussion much like this one. This is a start but it needs to span a wide range, from software engineers, building engineers and architects all the way to politicians. These collaborations need to occur simultaneously, compressing the current hierarchy of existing relationships. This is possible currently, given the overlaps and interests of each discipline. Inherently, the feedback between all these constituencies will be collapsed. This is a challenge. A network of resources needs to be established that allows for all the redundancies within the profession to be alleviated. One example includes the transmission of information to the client, the engineers, the building department, and the manufacturers—they all need different forms of information. If there is a way of beginning to evolve certain relationships with all of these partnerships that are networked through a way of working, the redundancies will be minimized. This would position the profession and make it relevant for today's cultural advances. I am not sure if this is going to occur, and if it does occur, what the time lag will be—but to move the profession ahead, as a whole, we have to strive towards rethinking these relationships that can manifest in something culturally relevant.

WHITEHEAD (from audience): I would like to leave you with a question that was put to me the other day as I was walking into the office. Somebody stopped me and said: "Look, in exploring these new forms, are we doing it just because we can, or because it is a good idea?" I was quite shocked to be attacked by one of our own people. I had to come up with something quickly, but I didn't get any further than saying: "Well, actually I think the answer is both. We are exploring it because we want to find out if we can, and the reason why we are doing that is to find out if it is a good idea." Now, this poses a whole set of new questions, because to answer that we need better methods of evaluation. Obviously, when

we look at new forms—and if we want to promote new forms as a good idea—we have to make the energy case. That is something we are now focusing on very strongly. If you make the energy case for new forms, you have to integrate all these wonderful, powerful analysis tools with your geometry controls. That is a question that I leave you with—how do we integrate analysis tools with our geometry controls?

BRUCE LINDSEY (from audience): I was thinking of a moment where the term user may be useful, and I would describe it as an aesthetic addiction. To turn perhaps what might be an observation into a question I would ask—why the differences aren't more dramatic between the projects?

KOLATAN: There is a kind of homogeneity that is a default condition of the kinds of software we use. One could say that it is because we still don't use the software in a sophisticated enough way. In other words, what seems to generate this homogeneity in computational architecture is in part the fact that shape and geometry are often too closely aligned. Geometry becomes genotypic as well as phenotypic destiny, as it were.

While topology is intrinsic to the software we use, it need not become extrinsic. In our own work we are extremely interested in problematizing this difference between form and shape. The Housings project, for example, is a case in point. A single genotype (the colonial house) produced a wide range of phenotypes. A way out of the extrinsic geometry dilemma can potentially be found through the introduction of scalability. If geometric structure is thought of as scalable or fractal, shape does not have a fixed or singular relationship to geometry. In other words, if this structure operates at a micro- or nano-scale in relation to the identifying marks of individual shapes, it becomes invisible. This is not unlike the scalar relationship between a species and its cellular structure. I think it would be radically liberating in terms of the range of formal and spatial definitions to be mapped. Geometry can become backgrounded, deep and sublimated, rather than foregrounded and ''in your face.''

The question of the user is a good one because many other areas are already going into the business of mass customization, as mentioned earlier. There is going to be a great degree of user participation in the future—potentially in our profession too—in the way things are designed and produced. I think we need to provide a much greater flexibility in terms of the final formal, spatial organizational diagrams that we are working with. I don't think that is the case yet.

ULRICH FLEMMING (from audience): I would like to challenge the notion that you program only as a last resort in case the software vendors don't provide you with the right tools. I have been a programmer for more than 30 years and I enjoy it tremendously. I preach to my students that the program is a crafted artifact like many other crafted artifacts that can be crafted well (or less well). Given that, I would suggest that the only software worth using is one that you can program, that you can customize, such that it becomes an integral part of the tool you are using.

I wish architects would abandon this passive stance in which they simply accept what the software vendors offer them. They don't even make suggestions as to how to improve the software; they don't even know what suggestions to make, because they don't understand

the software at the level at which you need to understand it if you want to make intelligent suggestions. And the best way to learn how software works is being able to program it.
I suggest that one should consider software that you can actually program as a positive aspect of practice and not as a means of last resort. You should be ready to program, and it is fun.

FRANKEN: For me, programming was not only a last resort, it was a question of beauty too. In programming it is a resourcefulness, i.e. how much code do I need to achieve something. It is like a mathematical formula. If it is good code, it looks beautiful.

KOLAREVIC: I want to refer to one of the comments that were made earlier by Bill Mitchell. We do not need to code in order to program. What Ali Rahim is doing is programming. A number of people who presented their design work at the symposium are actually programming, but not by doing hard coding.

I would like to conclude this discussion without any remarks that could hint at the possibility of an end, because I think we are at the beginning of an open-ended and exciting search for the future of our professions. So, I would like to leave this discourse inconclusive and open-ended. I hope that we will see numerous answers in the future to the issues of opportunities, possibilities, and challenges of designing and manufacturing architecture in the digital age.

APPENDIX

BIOGRAPHIES

BRANKO KOLAREVIC
Associate Professor of Architecture
University of Pennsylvania
Philadelphia, USA

Branko Kolarevic joined the University of Pennsylvania (Penn) in 1999, where he teaches design and digital media courses. Prior to joining Penn, he taught at universities in North America (Boston, Los Angeles and Miami) and in Asia (Hong Kong). He has lectured worldwide on digital media in design, most recently on the "virtual design studio," "relations-based design" and "digital architectures." In 2000, he founded the Digital Design Research Lab (DDRL) at Penn.

He has published extensively in the proceedings for ACADIA, CAADRIA and SIG-RADI, and has written the textbook *Architectural Modeling and Rendering* (Wiley, 1998) and co-edited with Loukas Kalisperis the *Proceedings of the ACADIA 1995 Conference, Computing in Design: Enabling, Capturing, and Sharing Design Ideas*. He is also the Review Editor in Architecture for *Automation in Construction*. He is the Past President of the Association for Computer Aided Design in Architecture (ACA-DIA). In 1998, he chaired the ACADIA's organizing committee for the first Internet-based design competition for the *Library for the Information Age*. Most recently he organized and chaired a two-day international symposium on "Designing and Manu-facturing Architecture in the Digital Age," which was held at Penn in March 2002.

He received Doctor of Design (1993) and Master in Design Studies (1989) degrees from Harvard University Graduate School of Design. He also holds the Diploma Engineer of Architecture degree from the University of Belgrade, Faculty of Architecture (1986).

http://www.gsfa.upenn.edu/ddrl/

ROBERT AISH
Director of Research
Bentley Systems
Exton, USA

Dr. Robert Aish is the Director of Research at Bentley Systems. He is a graduate of the School of Industrial Design at the Royal College of Art, London. He has a PhD in Human Computer Interaction, from the Man-Machine Lab at the University of Essex. His post-doctoral research was on the development of computer-aided design tools for design participation at the ABACUS research group at the University of Strathclyde.

As a software developer, he wrote building services applications for Arup, architectural modeling applications for YRM and shipbuilding applications for Intergraph. His role at Bentley is to establish how object-oriented technologies can be harnessed to create a more appropriate design paradigm for architecture and building engineering. Rather than focus on specific application semantics, his research is aimed at identifying the common abstractions that underlie the open-ended design process, which characterizes the AEC (architecture, engineering and construction) domain. These abstractions include design dependencies, deferral management and extensibility. His research has resulted in the implementation of a new package called 'CustomObjects' which is intended to be a framework within which the design research community and inspired architectural practitioners can innovate.

http://www.bentley.com/

MARK BURRY
Professor of Innovation
RMIT University
Melbourne, Australia

Professor Mark Burry was born in Christchurch, New Zealand. He is a practicing architect and recently took up a position at RMIT University in Melbourne, Australia, as Professor of Innovation (Spatial Information Architecture). Prior to this post, he held the Chair in Architecture and Building at Deakin University for five years. He has published internationally on two main themes: the life and work of the architect Antoni Gaudí in Barcelona, and putting theory into practice with regard to "challenging" architecture. He has also published widely on broader issues of design, construction and the use of computers in design theory and practice.

As Consultant Architect to the *Temple Sagrada Família,* he has been a key member within the small team untangling the mysteries of Gaudí's compositional strategies for the Sagrada Família, especially those coming from his later years, the implications of which are only now becoming fully apparent as they are resolved for building purposes. He has been active with the project, and the museum associated with it, since 1979. Currently, his time is divided between researching and teaching design and associated advanced computer applications, interpreting Gaudí's *Passion Façade* design for construction during the coming years, and collaborating with other local and international practices, principally dECOi in Paris.

http://www.sial.rmit.edu.au/~mburry

BERNARD CACHE
Principal
Objectile
Paris, France

In the area of CAD/CAM, Bernard Cache started working with Jean-Louis Jammot in 1987 on software applications that would make the concept of "objectile" become a reality. (Objectile is the name given by Gilles Deleuze to a series of variable objects that are industrially manufactured on numerically controlled machines.) Their first experiments were conducted on abstract structures and furniture. In 1995, Bernard Cache and Patrick Beaucé started Objectile, a company that digitally manufactures wooden panels to be used as building or furniture components. Alongside collaborations with other architects, Cache and Beaucé are now working on "fully associative" procedures between design and manufacture at the architectural scale. Their recent projects include a series of demonstration pavilions for Batimat, the international building trade fair in Paris—the *Semper Pavillion* (1999) and the *Philibert De L'Orme Pavillion* (2001).

Bernard Cache has degrees in architecture from EPFL (Ecole Politechnique de Lausanne), philosophy from Institut Supérieur de Philosophie de Paris VIII (under Gilles Deleuze's supervision), and economics from ESSEC (Ecole Supérieure des Sciences Economiques et Commerciales). From 1985 to 1995 he worked as an economist while conducting personal research in architecture theory and in CAD/CAM. His book *Earth Moves* was published in 1989 (MIT Press). His articles have been published in several magazines, including *L'Architecture d'Aujourdhui* and *ANY*. H is research is now focused mainly on a contemporary reading of Gottfried Semper's *Der Stil*.

http://www.objectile.com/

BERNHARD FRANKEN
Principal
franken architekten
Frankfurt, Germany

Bernhard Franken is an architect and engineer pursuing a medial concept featuring a coherent digital process from design to production. Starting out with a creative idea, both form and realization are developed digitally.

Bernhard Franken's independent architectural language and philosophy have solicited broad interest in various international exhibitions—among them, at the Deutsche Architektur Museum in Frankfurt and the Nederlands Architecture Institute (NAI), Rotterdam—and he has received several renowned awards. He has been Assistant Professor at the TU Darmstadt and visiting Professor at Kassel University. His architectural firm, *franken architekten,* develops design concepts through digital parametric design, ensuring both consistency and perfection in all phases of the project. The exhibition pavilions he designed for the BMW group over the past years demonstrate the synergies resulting from digital design and manufacture.

http://www.franken-architekten.de/

JIM GLYMPH, FAIA
Principal
Gehry Partners, LLP
Santa Monica, USA

Jim Glymph joined Frank O.Gehry & Associates (FOG/A) in late 1989. His interest in building technology and how that technology influences design, as well as his understanding of how integration of design, invention and the building process can enhance the development process of a project, complements Frank Gehry's work.

Jim Glymph encourages a special relationship among architects, engineers, craftsmen and fabricators, one that is characterized by design collaboration at a technical level and facilitated by the application of unique computer technologies. The rapid feedback that these collaborations allow creates not only a better understanding of the building process, but also a better control of construction costs, while at the same time permitting the exploration of new design possibilities.

In 1991, Jim Glymph became a principal at FOG/A and since then he has directed projects in the United States, Europe and Asia; notably the "Dancing Building" in Prague, Czech Republic, the *Experience Music Project* in Seattle, the *Stata Center* at the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, and the *Walt Disney Concert Hall* in Los Angeles, California. The principals of FOG/A— Frank Gehry, Randy Jefferson and Jim Glymph—have, over the past ten years, gradually transformed FOG/A from a studio with a skeleton staff of young architects to a firm with an experienced staff of over 100 talented designers and architects. Under the direction of the three principals, FOG/A became Gehry Partners, LLP in 2001.

MARK GOULTHORPE
Principal
dECOi Architects
Paris, France

The dECOi atelier was created by Mark Goulthorpe in 1991 as a forward-looking architectural practice, whose design calibre was quickly established by winning entries in several international competitions, and with awards from various cultural institutions around the world. This has been reinforced by numerous publications, international lectures and conferences, and frequent guest-professorships, including a design unit at the renowned Architectural Association in London and the Ecole Speciale in Paris.

dECOi's portfolio ranges from pure design and artwork through interior design to architecture and urbanism, and at every scale their work has received acclaim for its sensual contemporary aesthetic. Based in Paris and London, dECOi has developed a supple working practice to be able to bring its design skill to bear effectively in an international arena. This has resulted in a high level of technical expertise, a fully computerized working practice and an extensive network of affiliations with engineering support groups in Europe and Asia, such as Ove Arup (London) and Rice Francis Ritchie (Paris). This has extended to a recent collaboration with Foster and Partners to offer creative technical input to various projects of theirs.

dECOi has received awards from the Royal Academy in London, the French Ministry of Culture and the Architectural League of New York, and has represented France at the Venice Biennale and the United Nations. They were selected by the *Architects Design Journal* in its international survey of 30 'Emerging Voices' at the RIBA in London, and were awarded second place in the BD 'Young Architect of the Year' Competition, 1999. Most recently, they were invited as international representatives at the Venice Biennale 2000, and to exhibit ten years of work at the FRAC Centre in Orleans, France.

http://www.hyposurface.com/

SULAN KOLATAN
Principal
Kolatan/Mac Donald Studio
New York, USA

Sulan Kolatan was born in Istanbul, Turkey. She received a Diplom-Ingenieur degree from Rheinisch-Westfalische Technische Hochschule Aachen, Germany, and a Master of Science in Architecture and Building Design from Columbia University. She divided her time equally between Istanbul and Koln until 1982. After finishing her graduate studies at Columbia, she settled in New York. In addition to their practice, she has taught architecture at Barnard College, Ohio State University, and at the University of Pennsylvania. Since 1990, she has been teaching at Columbia University's Graduate School of Architecture, Planning and Preservation.

In 1988 Sulan Kolatan and Bill Mac Donald founded Kolatan/Mac Donald Studio. The firm has received the 48th Annual Progressive Architecture Award, the 1999 AIA Projects Award, the 44th Annual Progressive Architecture Citation Award, the Forty under Forty Award, the Emerging Voices Award, the Fifth Young Architects Award, and the New York Foundation for the Arts Grant and Fellowship.

The work produced by Kolatan/Mac Donald Studio is in the permanent collections of the Museum of Modern Art in New York, the San Francisco Museum of Modern Art, the FRAC Centre in Orleans, France, and the Avery Library Collection. In addition, the Kolatan/Mac Donald Studio has been exhibited in a number of distinguished venues, such as the Deutsches Architektur Museum in Frankfurt, Germany, the Museum of Modern Art in New York, the Cooper Hewitt Smithsonian Institute, Artists Space in New York, MACBA Barcelona, MAC Vienna, and the Carnegie Museum Pittsburgh. Their recent work has been featured in numerous publications.

http://www.kolatanmacdonaldstudio.com/

CHRIS LUEBKEMAN
Director
Arup Research + Development
London, UK

Dr. Chris Luebkeman is a bridge builder of many kinds. He has been formally educated as a geologist, structural engineer and architect. He is a *cum laude* Bachelor of Engineering (Honors) graduate of Vanderbilt University and a Master of Science (Civil Engineering) graduate of Cornell University. In 1992, he completed a doctorate in architecture at the ETH (Swiss Federal Institute of Technology) in Zurich, Switzerland. In 1987, he joined the design office of Santiago Calatrava where he introduced structural computer modeling. Since leaving Switzerland, he has since been a faculty member of the Departments of Architecture at the University of Oregon, the Chinese University of Hong Kong and the Massachusetts Institute of Technology (MIT). His architectural practice focused on low-impact zero-energy homes, his engineering practice focused on mobile and deployable structures, and his teaching practice on the integration of building systems. His research program at MIT, which continues today, is titled "house_n: MIT's intelligent home of the future."

   Chris Luebkeman joined Arup in 1999 to become joint Director of Research and Development. He is jointly responsible for developing the role of the group with a focus on design research and has particular responsibility for future projects. Since joining the firm he has facilitated the creation of an eCommerce strategy, has initiated research projects on the designer's desktop of the future, and has encouraged thinking about the evolution of the firm's skills networks into a knowledge network. He is a member of Arup's Design and Technical Executive which promotes the highest standards of design and technical skill to ensure that Arup is one of the world's leading practitioners in its chosen fields.

   http://www.arup.com/

BRENDAN MACFARLANE
Principal
Jakob + MacFarlane
Paris, France

Brendan MacFarlane received his Bachelor of Architecture degree at the Southern California Institute of Architecture (1984) and his Master of Architecture degree at the Harvard Graduate School of Design (1990). He has taught at the Bartlett School of Architecture in London (1996–98) and at the Ecole Spéciale d'Architecture in Paris (1998–99).

Dominique Jakob, his partner, received her degree in art history at the Université de Paris 1 (1990) before obtaining her degree in architecture at the Ecole d'Architecture Paris-Villemin (1991). She has taught at the Ecole Spéciale d'Architecture (1998–99) and the Ecole d'architecture Paris-Villemin and Paris-Malaquais since 1994.

Their main projects include the *T House,* La Garenne Colombes, France (1998), the restaurant *Georges* at the Centre Georges Pompidou, Paris (2000), the reconstruction of the *Theatre of Pont-Audemer,* France (2000) and the *Florence Loewy Books by Artists* bookshop, Paris (2001). They have been invited to participate in the International Competition for *Musée Branly* and extension of *Jussieu Université* campus in Paris. Currently they are working on the project for a *Communication Center* for Renault in Paris and *House H* in Corsica.

WILLIAM J.MITCHELL

Professor of Architecture and Media Arts and Sciences Dean of the School of Architecture and Planning, MIT Cambridge, USA

William J.Mitchell is Professor of Architecture and Media Arts and Sciences and Dean of the School of Architecture and Planning at MIT. He also serves as Architectural Adviser to the President of MIT. Among his publications are *E-Topia: Urban Life Jim—But Not As We Know It* (MIT Press, 1999), *High Technology and Low-Income Communities,* with Donald A.Schon and Bish Sanyal (MIT Press, 1999), *City of Bits: Space, Place, and the Infobahn* (MIT Press, 1995), *The Reconfigured Eye: Visual Truth in the Post-Photographic Era* (MIT Press, 1992), *The Logic of Architecture: Design, Computation, and Cognition* (MIT Press, 1990), *The Poetics of Gardens,* with Charles W.Moore and William Turnbull Jr. (MIT Press, 1988), and *Computer-Aided Architectural Design (Van* Nostrand Reinhold, 1977).

Before coming to MIT, he was the G. Ware and Edythe M. Travelstead Professor of Architecture and Director of the Master in Design Studies Program at the Harvard Graduate School of Design. He previously served as Head of the Architecture/Urban Design Program at UCLA's Graduate School of Architecture and Urban Planning, and he has also taught at Yale, Carnegie-Mellon and Cambridge Universities. In spring 1999, he was the visiting Thomas Jefferson Professor at the University of Virginia.

He holds a Bachelor of Architecture degree from the University of Melbourne, Master of Environmental Design from Yale University and Master of Arts from Cambridge. He is a Fellow of the Royal Australian Institute of Architects, a Fellow of the American Academy of Arts and Sciences, and a recipient of honorary doctorates from the University of Melbourne and the New Jersey Institute of Technology. In 1997, he was awarded the annual Appreciation Prize of the Architectural Institute of Japan for his "achievements in the development of architectural design theory in the information age as well as worldwide promotion of CAD education."

http://architecture.mit.edu/people/profiles/prmitche.html

JON H.PITTMAN, AIA
Vice President, Building Construction and Management Solutions
Building Solutions Division, Autodesk, Inc.
San Rafael, USA

Jon Pittman is Vice President of Building Construction and Management Solutions for Autodesk's Building Solutions Division, the world's leading design software company. He and his team are responsible for defining and driving solutions for builders and building owners.

With over 20 years of experience in computer-aided design, computer graphics, and Internet industries, Jon Pittman has held a variety of corporate venture, business development, product development, product management, and strategy positions at Autodesk, SDRC, Alias| Wavefront and Hellmuth, Obata, and Kassabaum (HOK) Architects. In addition to the work in the corporate world, Jon Pittman has been an Assistant Professor at Cornell University's Program of Computer Graphics and an instructor in user-interface design at the Art Center College of Design.

Jon Pittman holds a Bachelor of Architecture and a Master of Business Administration in Marketing and Finance from the University of Cincinnati. He also holds a Master of Science in Computer Graphics from Cornell University. He is a licensed architect and an instrument-rated private pilot.

http://www.autodesk.com/

ALI RAHIM
Assistant Professor of Architecture
University of Pennsylvania
Philadelphia, USA

Ali Rahim is director of the Contemporary Architecture Practice in New York City and an Assistant Professor of Architecture at the University of Pennsylvania. His books include *Contemporary Techniques in Architecture* (Academy Editions/Wiley, February 2002) and *Contemporary Processes in Architecture* (Academy Editions/Wiley, August 2000). He has won competitions for a shopping mall and steel museum, as well as a one-acre naval memorial. He is the recipient of the Honor Award for Excellence in Design from Columbia University, where he received his Master of Architecture. His projects have been published in several journals and in forthcoming books and journals published by Actar Press, Barcelona, Columbia University Press, Lusitania Press, New York, and Academy Editions/Wiley, London.

http://www.c-a-p.net/

ANTONINO SAGGIO
Professor of Architectural Design
University La Sapienza
Rome, Italy

Antonino Saggio is the founder and editor of the book series *IT Revolution in Architecture* published in English by Birkhäuser, in Italian by Testo&Immagine and in Chinese by Prominence Publishing. His most recent books are: *Giuseppe Terragni Life and Works* (Laterza, 1995), *Peter Eisenman* (Testo&Immagine, 1996) and *Frank O.Gehry* (Testo&Immagine,

1997). He is the co-founder of the magazine il *Progetto,* and his essays have appeared in several international catalogues, books and magazines.

Antonino Saggio won awards in design competitions early in his career, and received academic research grants from institutions such as the Fulbright Commission, the Graham Foundation and the Council of Italian Research. He holds a professional degree in architecture (1979), a diploma of planning from the University of Rome, a Master of Science degree from Carnegie-Mellon, and a PhD from the Italian Ministry of Research. He has been lecturing at several universities in Europe, Africa and the United States. He is currently Professor of Architectural Design at La Sapienza, Rome.

http://www.citicord.uniromal.it/saggio/

HUGH WHITEHEAD
Director, Specialist Modelling Group
Foster and Partners
London, UK

Hugh Whitehead graduated from Liverpool University in 1973 where he was awarded a First Class Honors Degree for research on optimization applied in an architectural context. The thesis explored the potential for using mathematical optimization techniques as an aid to design, but also researched the problems of how to construct a solution space, which can then be explored programmatically. Hugh Whitehead then spent eight years as an architect working on large planning projects in the Middle East and Africa, before joining YRM in London when they had just bought their first computer-aided design (CAD) system. During the next 12 years he became an Associate and CAD Applications Manager. He also specialized in model building for design and visualization, which led to the formation of a successful consultancy. During the next two years Hugh Whitehead worked on six winning entries for millennium competitions and had four animations broadcast on national television, including the award winning *Stadium Australia* for the Sydney Olympics.

In 1998 Hugh Whitehead was invited to join Foster and Partners to set up a new Specialist Modelling Group (SMG), whose brief is to carry out research and development in an environment that is intensely project driven. The SMG specializes in helping to solve geometry problems, from concept design stage through to fabrication and construction.

http://www.fosterandpartners.com/

CHRIS I.YESSIOS
CEO and President
auto•des•sys, Inc.
Columbus, USA

Chris I.Yessios holds a PhD in Computer Aided Design from Carnegie-Mellon University (1973) and his formal education includes a Bachelor of Architecture (1967) and a Diploma in Law (1962), both from the Aristotelian University in Greece. He taught and researched at the Ohio State University from 1973 to 1995, where he was a Professor of Computer Aided Design and Director of the Graduate Program in Computer Aided Architectural Design. During his tenure he wrote and published more than 100 research papers and chapters, and conducted research worth millions of dollars that resulted in a number of prototypical computer-aided design (CAD) and three-dimensional modeling systems. In 1990, with an ex-student, he founded auto•des•sys, acompany that produces three-dimensional modeling software, such as form•Z. He has been the CEO and President of the company since its inception.

http://www.formz.com/

NORBERT W.YOUNG, JR., FAIA
President, Construction Information Group
McGraw-Hill
New York, USA

Norbert W.Young, Jr. is President of the McGraw-Hill Construction Information Group, the leading source of project news, product information, industry analysis and editorial coverage for design and construction professionals. Norbert Young joined the McGraw-

Hill companies in December 1997 as Vice-President, Editorial, for F.W. Dodge. Prior to joining Dodge, Norbert Young spent eight years with the Bovis Construction Group, a global leader in the management of high-profile construction projects. In 1994, he was appointed President for the newly created Bovis Management Systems (BMS), which was established to serve the construction and project management needs for both private and public sector clients on a national, as well as a global basis. During the 1980s, Norbert Young was a partner at Toombs Development Company, New Canaan, CT. He started his career in Philadelphia as an architect, where he gained 12 years of experience covering a wide range of building types and projects. He holds a Master of Architecture degree from the University of Pennsylvania and a Bachelor of Arts degree from Bowdoin College, Brunswick, Maine.

A registered architect, his professional affiliations include membership of the Urban Land Institute, the American Institute of Architects and the International Alliance for Interoperability (IAI), where he serves as Chairman of the IAI North-American Board of Directors. In addition, he serves as a trustee of the National Building Museum, as well as a regent of the American Architectural Foundation. In February 2000, the American Institute of Architects elevated him to its prestigious College of Fellows, an honor awarded to members who have made contributions of national significance to the profession.

http://www.construction.com/

PROJECT CREDITS

CHAPTER 12
MARK GOULTHORPE
dECOi ARCHITECTS

IN THE SHADOW OF LEDOUX

CNAC Le Magasin, Grenoble, France, 1993

Design Team: Mark Goulthorpe, Zainie Zainul Construction Team: Students of the Ecole d'architecture, Grenoble, France

ETHER/I

United Nations 50th Anniversary Exhibition, Geneva, Switzerland, 1995

Design Team: Mark Goulthorpe, Zainie Zainul, Wilf Sinclair, Rachel Doherty, Matthieu le Savre Comp. Modeling: Michel Saup, Laurence Stern Dancers: Joni & Jacopo, The Frankfurt Ballet Engineering: David Glover of Group IV, Ove Arup & Partners, London, UK Fabrication: Optikinetics, UK Sponsors: Yayasan Seni, Guthries, Malaysia

HYSTERA PROTERA

Graphics commission for the Public Art Commisions Agency, London, UK, 1996

Design Team: Mark Goulthorpe, Arnaud Descombes with Max Mosscrop (artist)

PALLAS HOUSE

Bukit Tunku, Malaysia, 1997

Design Team: Mark Goulthorpe, Matthieu le Savre, Karine Chartier, Nadir Tazdait, Arnaud Descombes, with Objectile (Bernard Cache, Patrick Beaucé) Engineers: David Glover, Sean Billings and Andy Sedgwick of Group IV, Ove Arup & Partners, London, UK Client: VXL Holdings, Sdn Bhd, Malaysia

FOSTER/FORM I: SWISS RE

Formal study for Foster and Partners, London, UK, 1998

Design Team: Mark Goulthorpe, Prof. Mark Burry (Deakin University, Australia), Prof. Keith Ball (University College London, UK), Peter Wood (University of Wellington, New Zealand), Arnaud Descombes

FOSTER/FORM II: GATESHEAD REGIONAL MUSIC CENTRE

Formal study for Foster and Partners, London, UK, 1998

Design Team: Mark Goulthorpe, Prof. Mark Burry (Deakin University, Australia), Gaspard Giroud, Arnaud Descombes

Mathematical Studies: Dr. Alex Scott (University College London, UK)

AEGIS HYPOSURFACE© (Patent pending)

Birmingham Hippodrome Foyer Art-Work Competition, UK, 1999 First Prize (commissioned)

Design Team: Mark Goulthorpe, Mark Burry, Oliver Dering, Arnaud Descombes, with Prof. Mark Burry (Deakin University, Australia) and Grant Dunlop Programming: Peter Wood (University of Wellington, New Zealand), Xavier Robitaille (University of Montreal, Canada) Mechatronics: Prof. Saeid Navahandra, Dr. Abbas Kouzani (Deakin University, Australia)

Mathematics: Dr. Alex Scott, Prof. Keith Ball (University College London, UK)

Engineering: David Glover of Group IV, Ove Arup & Partners, London, UK

Facade Consultant: Sean Billings of Billings Design Associates, Ireland

PARAMORPH

Gateway to the South Bank Competition, London, UK, 1999

Short listed to final four, awarded People's Choice

Design Team: Mark Goulthorpe, Gabriele Evangelisti, Gaspard Giroud, Felix Robbins Parametric Design: Prof. Mark Burry (Deakin University, Australia) with Grant Dunlop and Andrew Maher

Mathematical Studies: Dr. Alex Scott (University College London, UK) Engineers: David Glover of Group IV Ove Arup & Partners, London, UK Model: Grant Dunlop (Deakin University, Australia)

BLUE GALLERY

London, UK, 1999

Design Team: Mark Goulthorpe, Gabriele Evangelisti, Greg More, Felix Robbins, Gaspard Giroud

Engineers: Ed Clark of Group IV, Ove Arup & Partners, London Fabrication: Optikinetics (aluminum), Peter Goodman (fiberglass)

Model: Julien Lomessey, Adrian Raoul (formwork), Greg Ryan (bronze)

Video: Simon Topliss, Tollen Adkins, Greg More Photos: Mark Goulthorpe

DIETRICH HOUSE

London, UK, 2000

Design Team: Mark Goulthorpe, Gabriele Evangelisti, Greg More

Engineers: David Glover and Ed Clark of Group IV, Ove Arup & Partners, London

EXCIDEUIL FOLIE

Excideuil, Perigord, France, 2001–2

Client: Design for the association EXCIT'ŒIL in Excideuil as part of their "Nouveaux Commanditaires" program, sponsored by the Fondation de France

Design Team: Julian Lomessey, Mark Goulthorpe, Maruan Halabi

Plastic Model: Spatial Information Architecture Laboratory, Faculty of the Constructed Environment, RMIT University, Melbourne,

Australia: Prof. Mark Burry, Jane Burry, Gregory More, Julian Canterbury, Grant Dunlop Thermojet Modeling: Affonso Orciuoli with Maruan Halabi (ESARQ, Barcelona)

Engineering: Ed Clark and David Glover of Group IV, Ove Arup & Partners, London Fiberglass Prototypes: Peter Goodman, Goodman Glass Fibre

HANDLESMAN APARTMENT

London, UK, 2002

Client: Harry Handlesman, Manhattan Loft

Design Team: Mark Goulthorpe, Matteo Grimaldi, Julian Lomessey

Engineering: David Glover and Ed Clark of Group IV, Ove Arup & Partners, London

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11.11. Sagrada Família archive
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13.1–46b. Jakob + MacFarlane, except:
13.1. N.Borel
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13.24a-b. RFR Consulting Engineers
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13.37a-b. N.Borel
14.1–22. Ali Rahim/Contemporary Architecture Practice
15.1–25. Sulan Kolatan/Kolatan and Mac Donald, except:
15.1. Universal Studios
15.4. American Phytopathological Society
15.5. Dr. Gary Anderson, University of Califonia at Davis
15.7. Nancy Burson
15.8. Thomas Grunfeld
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15.10. Thomas Grunfeld
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15.13. Patagonia
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15.17. Young Hyun, CAIDA
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15.21. University of Illinois at Urbana-Champaign
15.22. National Science Foundation/ Felice Frankel

15.23. NASA Langley Research Center
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16.19. Margaret Wozniak
16.20. Benoit Sokal
17.1–4d. Kevin Rotheroe/FreeForm Design + Manufacturing Studio
19.1a-d. Sam Jacoby, Architectural Association
19.2a-b. Rok Oman and Spela Videcnik, Architectural Association
19.3a-b. Abbey Chung and Robb Walker, SCI-Arc
19.4. Stan Arnett, University of Colorado, Denver
19.5a-c. Kostas Terzidis, UCLA
21.1–17. Arup, except:
21.1. U.S. Navy
21.2. Norman Bel Geddes
21.3. University of Toronto Institute for Aerospace Studies

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