Digital Surface Representation
and the Constructibility of Gehry’s Architecture

by

Dennis R. Shelden
Director of Computing, Gehry Partners, LLP.
MS Civil and Environmental Engineering, MIT, 1997

Submitted to the Department of Architecture
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY IN THE FIELD OF ARCHITECTURE:
DESIGN AND COMPUTATION
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Signature of Author: __________________________________________________________

Department of Architecture
August 9, 2002

Certified by: ________________________________________________________________

William J. Mitchell
Dean of the School of Architecture and Planning
Professor of Architecture and Media Arts and Sciences
Thesis Supervisor

Certified by: ________________________________________________________________

Stanford Anderson
Professor of History and Architecture
Chair, Department Committee on Graduate Students
READERS

William J. Mitchell
Dean of the School of Architecture and Planning,
Professor of Architecture and Media Arts and Sciences, MIT
Thesis Supervisor

John R. Williams
Associate Professor of Civil and Environmental Engineering,
Associate Engineering Systems, MIT

George Stiny
Professor of Design and Computation, MIT
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ABSTRACT

This thesis presents work in the development of computational descriptions of Gehry’s architectural forms. In Gehry’s process for realizing buildings, computation serves as an intermediary agent for the integration of design intent with the geometric logics of fabrication and construction. This agenda for digital representation of both formal and operational intentions, in the context of an ongoing exploration of challenging geometries, has provided new roles for computation in architectural practice.

The work described in this thesis focuses on the digital representation of surface geometry and its capacity for describing the constructibility of building enclosure systems. A particular class of paper surface forms – curved surfaces with minimal in plane deformation of the surface material – provide the specific object of inquiry for exploring the relationships between form, geometry and constructibility.

An analysis and framework for the description of Gehry’s geometry is developed through existing theory of differential geometry and topology. Geometric rules of constructibility associated with several enclosure system strategies are presented in this framework. With this theoretical framework in place, the discussion turns to efforts to develop generative strategies for the rationalization of surface forms into constructible configurations.

Thesis Supervisor: William J. Mitchell
Title: Dean of the School of Architecture and Planning,
Professor of Architecture and Media Arts and Sciences, MIT
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A work of this nature owes a heavy debt of gratitude to many persons. During the time that this thesis has been prepared, it has been my rare privilege to work closely with a number of enormously talented individuals, both members of Gehry's firm as well as those of associated engineering, construction and fabrication organizations. The products of their efforts are often referenced in this work, and the inspiration for this inquiry would not have occurred without their influence. In the interest of brevity, I can unfortunately only mention a few of their names.

The first and foremost debt of gratitude is owed to Frank Gehry himself. His design vision and exploratory energy have fostered the community of talent and ideas in which the work described in this document has occurred. The efforts to realize his design ambitions have resulted in a context of architectural and building practice for which there is perhaps no equivalent at this point of writing. Furthermore, his commitment to the achievement of these design intentions have translated into a support of computational efforts beyond that of his contemporaries, and have provided the environment for computational inquiry in which the work described in this document has taken place.

Jim Gymph has served as a mentor and inspiration on all matters architectural and computational during my time with the firm. The description of a reconstructed architectural practice presented in Part 1 of this document is largely attributable to many hours of formal and informal discussions with this visionary practitioner.

The opportunity to apply this research to the firm's projects has occurred through close collaboration with the senior designers and project architects on these projects. I gratefully acknowledge Partner Randy Jefferson, Project Designers Craig Webb and Edwin Chan, and Project Architects Terry Bell (Disney Concert Hall), Marc Salette (MIT Stata Center), George Metzger and Larry Tighe (Experience Music Project), Gerhard Mayer (Weatherhead) and Michal Sedlacek (Museum of Tolerance), for their support and willingness to accommodate these research efforts on their projects.

The firm’s computational methodologies are similarly the product of many persons' efforts. The work of Rick Smith of C-Cubed, Kristin Woehl, Henry Brawner and Kurt Komraus on
projects is extensively referenced in this document, while the efforts of Reg Prentice and Cristiano Ceccato in the computing group have profoundly contributed to the development of the firm’s computational practice. David Bonner of Dassault Systèmes Research and Development and John Weatherwax from Department of Mathematics at MIT assisted substantially in the formulation of the material simulation model described in Chapter VII.

On the academic front, I would like to thank the members of my Doctoral Committee, for their guidance and support of what has become a circuitous path to the completion of this thesis.

Finally, I thank the Reader, for taking the time and interest to review the thoughts contained herein.
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### TABLE OF SYMBOLS

**Topologies and manifolds**
- \( \mathbb{R} \): the set of real numbers, the real number line, the real number topology
- \( \mathbb{R}^n \): \( n \)–dimensional Euclidean space, a Cartesian product of \( n \) real numbers
- \( n, m, \) etc.: the ordinality or degree of a Cartesian product space (e.g. \( \mathbb{R}^n \))
- \( \mathbb{I} \): the set of integers, the integer topology
- \( \mathbb{Z} \): a set of discrete values, the discrete topology
- \( \alpha, \beta, \phi, \) etc.: a mapping function of the form \( \mathbb{R}^n \rightarrow \mathbb{R}^m \), e.g. curves and surfaces.
- \( N, M, \) etc.: a bounded region of space in \( \mathbb{R}^n, \mathbb{R}^m, \) etc.
- \( a, b, c, \) etc.: a (typically scalar, real valued) variable
- \( p, q, \) etc.: a vector or vector field
- \( i, j, \) etc.: the index of a vector component (e.g. \( p_i \))

**Curves and surfaces**
- \( t \): a scalar parameter in the curve function \( \alpha : t \rightarrow \mathbf{x} \)
- \( \alpha', \alpha'' \), etc.: differentiation with respect to \( t \)
- \( s \): the unit arc length parameterization of a curve
- \( \dot{\alpha}, \ddot{\alpha} \), etc.: differentiation with respect to \( s \)
- \( \mathbf{u} \): a 2-dimensional position vector in \( \mathbb{R}^2 \) "parametric space"
- \( u, v \): the scalar components of \( \mathbf{u} \)
- \( \mathbf{x} \): a 3-dimensional position vector in \( \mathbb{R}^3 \) "world space"
- \( x, y, z \): the scalar components of \( \mathbf{x} \)

**Physical modeling**
- \( m \): particle mass
- \( M \): the \( 3n \times 3n \) particle mass matrix
- \( t \): time
- \( h \): time step (\( \Delta t \))
- \( n \): vertex count
- \( \mathbf{x} \): the \( 3n \) vector of particle locations
- \( \mathbf{v} \): particle velocity
- \( \mathbf{a} \): particle acceleration
\( f \) ................. force on a particle
\( \mathbf{x}_i \) .................. \( \mathbb{R}^3 \) location of particle \( i \)
\( \mathbf{x}^1, \mathbf{x}^2, \mathbf{x}^3 \) ........ the individual \((x,y,z)\) coordinates
\( \phi \) ....................... the \( \mathbb{R}^2 \rightarrow \mathbb{R}^3 \) material mapping function
\( \omega \) ....................... the linear approximation of \( \phi \) on a triangle
\( C \) ......................... the behavior function
\( E \) ......................... the system energy
\( K \) ......................... a stiffness constant
REFERENCED PROJECTS AND ABBREVIATIONS

Santa Monica Place, Santa Monica, CA 1973-80
Gehry Residence, Santa Monica, California 1977-78; 1991-92
Winston Guest House, Wayzata, Minnesota 1983-87
Edgemar Development, Venice, California 1984-88
Chiat Day Building, Venice, CA 1985-91
Lewis Residence, Lyndhurst, Ohio, 1989-95 (unbuilt)
Team Disneyland Administration Building, Anaheim, California 1987-96

_DCH_ Walt Disney Concert Hall, Los Angeles, CA 1987-
_Barcelona_ Vila Olimpica, Barcelona, Spain 1989-92
_Weissman_ Frederick R. Weissman Art Museum, Minneapolis, Minnesota 1990-93
_Bilbao_ Guggenheim Museum Bilbao, Bilbao, Spain 1991-97
_Prague_ Nationale-Nederlanden Building, Prague, Czech Republic 1992-96
_Dusseldorf_ Der Neue Zollhof, Dusseldorf, Germany 1994-99
_Berlin_ DG Bank Building, Berlin, Germany 1995-2001
_Weatherhead_ Peter B. Lewis Building, Weatherhead School of Management, Case Western Reserve University Cleveland, Ohio 1997-
_MIT_ Ray and Maria Stata Center, Cambridge, Massachusetts 1998-
_OHR_ Ohr-O’Keefe Museum, Biloxi, Mississippi 1999-
_MOT_ Winnick Institute Museum of Tolerance, Jerusalem, Israel 2000-
FOREWORD

Over the past decade, Gehry’s firm has developed a unique and innovative approach to the process of delivering complex building projects. Computer based project information plays a vital and integral role in enabling this process. The concepts and strategies that have emerged though the development of the firm’s methodologies offer profound lessons for the design community, not simply in the ways that computing may be applied to architectural practice, but in the ways by which computing methods can change the process of building. It is with an eye to providing further insight into this important example of computing and practice that this thesis has been prepared.

This thesis offers a view into Gehry Partner’s computer aided design methodologies, based on the author’s experiences with the firm over the past half decade. Rather than attempting to tell this story in a historical or encyclopedic fashion, this thesis takes as its object of inquiry a specific set of building intentions, and associated computational strategies, playing a fundamental role in the firm’s work: the design, engineering and fabrication of surface forms on Gehry’s projects. This set of issues is explored as a topic of substantial interest in its own right, while serving as an example of the larger sets of intentions exhibited by the firm’s practice.

The qualities of materials and the role of craftsmanship as guiding intentions of Gehry’s work have received considerable discussion. These intentions have critical counterparts in project documentation and construction activities, and in associated computational constructs. The goal of adequately representing intentions of materiality and craft in digital form is perhaps the most important and complex aspect of the firm’s computing efforts. These intentions are fundamental motivations of the firm’s approach to digital representation of the geometry of project forms, and of the fabrication processes responsible for their realization. These are central themes of this thesis.

This body of this text is organized into three parts. Part 1 offers an introduction to the role of computing in Gehry’s design and building delivery process. Computing is explored in its relationship to key project design, analysis and construction intentions. Important concepts guiding the development of the firm’s computing efforts are presented, including the nature of geometric representations employed by the firm, and the role of analytically driven operations.
on project geometry. A set of materially guided intentions fundamental to the generation of Gehry’s surface forms are introduced. Examples and case studies are provided that demonstrate the application of these tenets on recent projects. This introductory section establishes the framework for the inquiry developed in the remainder of the text.

Part 2 focuses on developing a formal representation of materially guided surface forms. This section describes the firm’s efforts to develop digital counterparts to the behavior of surface materials in modeling and fabrication. A review of the theory of topology and manifolds underlying representations of curved spatial objects is presented in Chapter V, followed by a rigorous formal exploration of the geometric structures employed by the firm and their applications to specific constructibility problems. A promising new approach to the representation of surfaces through physical modeling of material behaviors is presented in detail in Chapter VII. This Part establishes a unified geometric framework for the modeling, simulation and analysis of the elementary shape elements employed in the firm’s designs.

Part 3 expands on this geometrical framework, in developing a formal methodology for considering assemblies of these basic surface elements. This extended framework has implications for the digital representation of project scale gestures, as well as utility for addressing localized surfacing system fabrication and assembly requirements. With a formal framework for the representation of surface organizations established, the discussion turns to operations on these assemblies. The potential is demonstrated for automaton of key processes addressing constructibility requirements of building systems. Several examples of these generative approaches to the design of surface systems are documented. The thesis concludes by presenting a computational framework for the generation of materially guided surface assemblies.
PART 1: DIGITAL REPRESENTATION AND CONSTRUCTIBILITY
I. INTRODUCTION

It seems that Gehry’s practice has become synonymous with cutting edge computing technology and CAD / CAM manufacturing processes. But the path to the firm’s prominence in architectural computing applications has not been easy or straight forward. Gehry himself remains skeptical of computing as a tool for design. He speaks with a certain degree of pride in his inability to operate a computer, and suggests that the quality of the digital image is dangerous and subversive to the designer’s eye.

Gehry’s design process is perhaps best characterized by its emphasis on physical objects as the principal artifacts on which design takes place. The firm places a unique emphasis on the development of designs through physical models, full scale mockups and other physical artifacts as the means for understanding and developing design intentions. These artifacts of include numerous sketch models, some undergoing active transformation while others wait on shelves or in storage, documented in photos, serving as records of design intentions at significant points in the process. These models are often deliberately developed to a rough, unfinished state, in order to allow suggestion of new directions of development as the designers contemplate the objects. The power of this design process springs in part from the ambiguity presented by this multiplicity of physical design representations.

These evocative qualities of the firm’s designs persist in the further development of projects as they enter documentation and construction phases. Project engineering and detailing strategies are often developed that accommodate the real world indeterminacy of on-site construction events. Many building system strategies have involved in-situ fabrication and placement of system elements as a means for responding to on-site conditions. This reliance on the efforts of craftsmen, operating in the field, again reflects the profound concern for physical artifacts and events as driving elements of the design process and the aesthetic that results.

The role of computer-based methodologies in this fundamentally tactile, evocative process presents a dilemma. Contemporary CAD modeling capabilities seem to stand in marked contrast to these design intentions. CAD modeling strips away ambiguity, producing definitive geometric forms that “leave little to the imagination”. These digital, logically founded
constructs stand in curious contrast to the indeterminacy of physical based activities and artifacts.

The physical / digital interactions, and the tension between these realms of the process have become fundamental to the success of the firm’s design process. At the heart of the process is an ongoing affinity between a disparate set of design intentions, embodied in multiple physical representations, and a coherent set of computer based representations. The process utilizes the definitiveness computer representations at points in the process where it is appropriate, and draws these digital descriptions into the assemblage of representations. The computer based description represents the glue that ties the physical design representations together, and ultimately document their convergence. Computer representations allow the intentions embodied in multiple physical representations to be resolved, translations of scale to be performed, and incursion of system fabrication decisions to be resolved into the design intent.

Three dimensional computer aided design applications provide a critical characteristic relative to traditional building documentation, in the ability to translate design intentions from physical design artifacts to constructed objects without recourse to two-dimensional representations. On more “conventional” building projects, this direct translation is unnecessary and perhaps inefficient. Conventional two dimensional architectural documents, comprised of plans, sections, elevations and details, compress the full spatial and dimensional scope of a design into a set of inter-related representations. The regularity of an object whose dimensions may vary little or not at all from floor to floor can be efficiently described by a single floor plan background, repeated for each floor. Variations in fit out can be overlaid on this normalizing representation. Typical details may be specified as a single detailed drawing. Its application across the project is specified by annotation on floor plans or sections, or in specifications. For buildings with repetitive components, and regular floor plans, the necessity for individually describing each element as a three dimensional model correctly positioned in space would require substantial additional labor. The ability to mentally resolve multiple two-dimensional representations of a design into a coherent understanding of the three dimensional object and its methods of construction is a core part of traditional architectural training and heritage. Architects take a professional pride in the development of this mental ability.
The relationships between tools, process of making enabled by tools, and the objects produced by operating tools are subtle and deep. The operations enabled by a chosen tool guide the operator to make specific types of objects or products that the tool affords. The parallel rule and triangle, blue print and tracing paper overlay of conventional document production facilitated the design of orthogonally organized building designs. The compass allows circular arcs to be included in these compositions. When two-dimensional plans are extruded perpendicularly to the plane of the paper in a uniform fashion, a single drawing presents a slice through the designed objects whose applicability is invariant of where the cut is taken. The two dimensional drawing construction provides tremendous expressive power in describing this geometric regularity. In turn, the designer is subtly guided toward the development of designs for which the utility of this geometric construct holds. More elaborate geometries than simple extruded form are of course possible, by combining multiple sections either in parallel or orthogonally, but the “trace” of the tool is inevitably felt in the resulting designs.

The adoption of the tools of two-dimensional representation has provided a basis for the development of descriptive conventions unifying the building industries. This shared language has Euclidean geometric forms and their sectional representations as an underlying construct. Straight lines stand in for wall and floor planes, arcs represent cylindrical forms. Parallel bold lines represent vertical walls, dashed lines represent overhead elements, usually aligned with elements on a floor plan cut at a higher elevation. This common understanding among participants in a building project is so deeply shared that it eludes dissection. An architect and contractor can discuss the layout and construction of a building on the basis of a two dimensional floor plan without any discussion of what the elements in the drawing mean. In parallel with the development of this common language of Euclidean elements, numerous interwoven industries and industrial processes have been developed around the making of Euclidean objects and building components. Saw mills turn trees into straight lumber of square profile and flat, rectangular sheets of plywood, steel mills extrude molten steel into linear members with invariant profiles. Carpenters use plumb bobs, string, levels and 3:4:5 triangle measurements to produce straight, vertical walls and their perpendiculars. So pervasive has the “tyranny” of Euclidean geometry become in the building industries that any building designed without strict accordance to its rules is subject to characterization as impossible to build.
In Gehry’s design process, physical model making is the principal design tool. This primacy of the construction of physical objects as the vehicle for design explorations in itself propels the firm’s work beyond the constraints of the Euclidean rationale. In its place, a new set of guiding rules have been developed, directly related to the materials and operations available to the processes of object making. Viewed in isolation, the operations of physical modeling are insufficient to guarantee the constructibility of the full scale products that models are intended to represent. However, in Gehry’s process, models serve not simply to describe the object in scale. Rather, the processes and materials of model making are brought into alignment with, and stand in for, those of craftsmen and fabricators on the resulting building construction. Materials and construction strategies are selected to emulate aspects of their full scale counterparts. This approach binds the operations of design directly to those of building, bypassing the filter of a common language of Euclidean geometry.

Prior to the firm’s adoption of computing based practices, the firm’s process suffered a key limitation in its methods of project documentation. While the firm could reasonably guarantee that the designs could be fabricated, the designs still required rendition into conventional two-dimensional description to support steps of the conventional construction process, including building permit submissions, bidding and on-site project layout. In order to bring the design back into the language of building industry convention, two dimensional plans, sections and elevations needed to be developed. Often, the forms of the models would require re-interpretation into conventional Euclidean forms of planes, cylinders and cones, simply to be consistently described through plans and sections.

Even with this painstaking development of project documentation, the geometry was still beyond the norms of conventional construction description. While fabricators could build the shapes, the process of bidding and coordinating the projects presented difficulty to construction managers. Accuracy of quantity takeoffs could not be guaranteed using conventional methods of measuring off of plans. Shop drawings – necessary for describing the detailed fabrication geometry – were difficult to render into orthogonal views. Spatial coordination of building elements became unmanageable as component details were developed. The limitations of understanding the project geometry through the lens of two dimensional views exacerbated perceptions of project complexity.
The history of the development of computer-assisted building delivery by the firm in response to these limitations has been well documented. Jim Glymph joined Gehry’s firm in 1989. Glymph had substantial experience in the role of Executive Architect on several substantially complex building projects, including the San Diego and Los Angeles Convention Centers. At the time, 3D CAD was beginning to have application to architectural visualization, movie animation and automotive and aerospace design. Glymph realized that these technologies could be applied to the processes of architectural documentation, independent of the contemporary interest in the technology as a means for project visualization.

Initial forays into the technology were tentatively undertaken. The firm selected the Barcelona Fish sculpture – part of the Vila Olimpica project as an initial test of the approach. The fish sculpture – a 50-meter-long sculpture of woven stainless steel mesh on a structural steel frame – provided a relatively safe test case for the use of digital representation as a vehicle for construction documentation. As a sculpture, with minimal life safety or building system issues, only the geometry of the project and the elements of fabrication needed to be represented digitally. Code compliance documentation requirements were minimal compared to that required for an inhabitable structure.

The development of the surface mesh geometry presented substantial concern for the design team. The mesh was understood to have a resistance to forming in an arbitrarily curved fashion, and would buckle undesirably if certain constraints on the surface form were adhered to. Additionally, templates for cutting the shape of the mesh elements needed to be provided.
Glymph contacted William J. Mitchell, then Professor of Architecture at the Harvard Graduate School of Design, who produced an initial model of the design in the Alias software package with graduate student Evan Smythe. While the results of the study demonstrated the possibility of representing construction documentation in digital form, a critical limitation emerged in the Alias software’s underlying representation of surfaces. Alias represented the surface of the sculpture through a tessellation of triangular faces. While this representation was sufficient to provide visual fidelity to Gehry’s initial physical model, geometric operations on the surface required to produce the structural steel model were problematic. The sculpture’s skeleton is constructed as a set of planar, vaulted truss “ribs”, offset from the surface, and connected to a cross braced structural steel skeleton. Intersections of the rib planes with the tessellated surface resulted in segmented polylines. It was difficult to control the segmentation of the mesh surface produced by Alias to correctly produce the required segmentation of the steel trusses. Offsetting of curves to produce the bottom chord of the trusses and other geometric operations produced similar undesirable linearization of the geometry.

Realizing that this segmentation of smooth surfaces would be a critical limitation to its digital construction documentation process, the firm began to search for more advanced representational capabilities in other software packages. At the time, the CATIA software package was one of the few CAD platforms offering true smooth surface representations. CATIA – initially developed by Dassault Aviation as an in house CAD application for the development of the Mirage fighter plane – had recently been released as a commercial application through IBM and was gaining acceptance by the automotive and aerospace industries. At the time CATIA Version 3 had achieved a commercially viable CAD application based on Bézier curve and surface algorithms.

As an engineering tool, CATIA also offered capabilities for surface analysis not provided by Alias. While unable to provide a detailed assessment of the mesh behavior, capabilities for analyzing surface curvature were supported. Additionally, CATIA allowed curved surfaces to be flattened into shapes allowing a reasonable approximation of the mesh profiles required to cover the surface. These utilities, while representing quite loose approximations of the true mesh behavior, were sufficiently powerful to support the design and detailing of the mesh surface.
Rick Smith – proprietor of the consulting company C-Cubed - was at the time an independent IBM business partner, providing CATIA services to the southern California aerospace industries. Smith revisited the digital modeling of the fish, demonstrating the possibility of accurately creating the curved geometry of the surface and the construction of the structural steel geometry as offsets and intersections derived from the curved surface model. Construction of the sculpture was awarded to Permasteelisa, an Italian curtain wall fabrication company, for what would be the first of many successful collaborations between the two firms. Smith brought his model and CATIA station to Italy and worked directly with the Permasteelisa's engineers and fabricators to produce the shop drawings for the steel and layouts for the mesh elements.

Glymph characterizes the experiences of the Barcelona Fish project as a breakthrough in many ways. The fact that the project, with its admitted geometric complexity, was completed on time and on budget, while the conventional steel construction of the rest of the Pavilion complex was suffering construction delays and on site reworking of steel elements “showed that [the firm] was onto something” in identifying a new process for project documentation. Furthermore, the direct collaboration with Permasteelisa on the development of shop drawings - with the endorsement of the project owner - circumvented the conventional disassociation between architect and fabricator.

At the same time as initial experiments in digital project description were being conducted by the firm, Dassault Systèmes, the developers of CATIA, were developing a comprehensive methodology to support the design of Boeing’s 777 aircraft line. Dassault termed this methodology Digital Mockup (DMU), with the intent to support design, detailing and CNC fabrication of the 777 aircraft and all components in an integrated, paperless fashion. This development effort resulted in software functionality within the CATIA product line beyond the limited functionality of curved surface description that Gehry’s firm had initially sought. The story of these developments in the digital design of manufactured products presents a parallel history to Gehry Partners’ efforts in developing similar methodologies for the support of building projects, and served as an important example closely observed by the firm. The parallel development of these manufacturing methodologies has also disclosed important differences in economies and supply chain organization between “vertically integrated” industries such as the aerospace industry, with opportunities afforded by economies of scale,
and the constraints of process imposed by construction industry. Comparisons between the methodologies of these industries are discussed below.

Applications to building projects followed shortly. The Nationale-Nederland Building in Prague and Team Disneyland Building drew on elements of the process proven on the Barcelona Fish. The development of the firm’s process culminated with the opening of the Guggenheim Bilbao museum in 1997. While refinements of the process continue, the essential elements of the process and its applications were defined in the early successes of these projects.

It would seem, from the success of these projects, that digital representation is poised to free architecture from the constraints imposed by historically developed project description. Complexity of geometric representation and methods of constructibility are apparent in the design and construction of Gehry’s projects, but digital technology seems to have proven up to the task of resolving this complexity. Digital modeling now allows free form, non-Euclidean shapes to be represented with exacting tolerances. Digital CNC fabrication technologies, developed to serve the automotive, aerospace, and Hollywood animation industries stand ready for application to building, faithfully rendering building components to similar exactness. The Boeing 777 project and other manufacturing processes have proven the viability of a fully digital design development process. To the delight of some critics and the dismay of others, digital technology seems poised to cast off the last relics of a historically developed building context, translating the designer’s gesture effortlessly into final form through Hollywood animation software coupled to robotic production devices. As post modern historicism freed design from contextual constraints, digital representation seems poised to remove the remaining constraints imposed by historically developed conventions of building description and production.

It would be unfortunate to draw so simple a lesson from Gehry’s work. The firm’s ability to successfully realize innovative forms springs partly from its ability to bring these projects within the context of conventional construction documentation and building process. A view of the development of Gehry’s body of work shows a formal language that originates in the forms and materials of conventional construction, and an ongoing experimentation to press these materials and methods to their limits. The succession of Gehry’s built projects shows a gradual, continual coaxing of the conventions of fabrication and building, each work drawing
on the lessons learned from previous successes to push building method in new directions and to further limits. The power of Gehry’s architecture springs partly from a struggle, negotiation and ultimate reconciliation with existing context and conventions.

Part of the role of digital technology in the firm’s process has been to disclose simplicity within the geometric complexity, and to bring the description of building elements and processes within the conventional language of contemporary construction practice. This discipline is key to the success the firm has enjoyed in successfully completing projects. Perhaps surprisingly, much of the detailing of building components relies on extensions to conventional processes of building, and seldom relies on aerospace or Hollywood methods of object making. Rather, the firm strives to work with the existing processes of craftsmen and fabricators, and attempts to produce detailing and documentation strategies that reflect a deep understanding of the methods and constraints of existing fabrication processes. Two dimensional documentation, flat patterns, Euclidean cut edges and profiles are the norm in these fabrication methods. Digital technology is drawn on to render Gehry’s forms within these conventions; is it not seen as an opportunity to discard the capabilities of traditional craftsmanship. Part of the reason for this approach is of course necessity. Even where fully digital fabrication technologies are available, the costs of these methods are frequently prohibitive. But part of this methodology seems to be drawn from Gehry’s embracing of material qualities and craftsmanship, and an aesthetic that pushes conventions to their limits, rather than creating a design language from scratch.

Viewed from a geometric perspective, the methods drawn on in the digital description and documentation of projects are enabled by capabilities for developing project descriptions in full three dimensional, digital form, using non-Euclidean geometric constructs. However, the reliance on non-Euclidean geometric constructs in no way means that these structures are constraint free. Non-Euclidean, digital representations bring their own constraints and artifacts to description processes, in the forms that can be represented, the geometric operations that can be performed, and the fabrication processes that are enabled. This structuring of non-Euclidean geometry on surface representation and associated constructibility will be a central theme of this thesis. It will be shown that the non-Euclidean representational constructs at the heart of the firm’s digital process can in fact be positioned as extensions of Euclidean constructs into a more general framework, in which Euclidean and a variety of non-Euclidean descriptive elements coexist on equal footing.
II. THE DEVELOPMENT OF GEHRY’S BUILDING PROCESS

In order to realize the innovations of Gehry’s forms on built projects, corresponding innovations of design development and building process have been required. The firm’s computational innovations have been developed parallel to, and as part of, these building process innovations. To understand the context in which the firm’s digital process has evolved, it is appropriate to review some of the guiding intentions of the firm’s building delivery methodologies that these digital representations serve.

A. PROJECT COST CONTROL

It may not be overstatement to say that project budget control – and the reconciliation of design intent with project financial requirements – are the most important driving forces behind the firm’s design development phase decisions. Certainly, project cost control has been the most important factor in the development of the firm’s digital building delivery process. This position may surprise readers. It is sometimes assumed that Gehry’s practice engages predominately or exclusively in “budget less” projects, with clients for whom money is no object. This is far from the truth. The firm has achieved its successful track record of completed projects by providing buildings within clients’ budgets, and within the rough per square foot costs of more conventional projects of similar building usage types.

Project costs can be broken down in a number of different ways. First, the distinction is often made between the “soft costs” of a project, including the design services of architects and engineers, versus the “hard” costs attributed to actual construction materials and labor. Second, there is an important distinction to be made between costs identified prior to commencement of construction, roughly up the GMP (Guaranteed Maximum Price) bid phase, and cost overruns that can crop up during construction. Both of these distinctions are subject to further inspection in light of the new forms and processes championed by Gehry’s firm.

It is often assumed by owners that the hard costs of a building are a fixed factor in building construction, while soft costs are an area for flexibility. This reasoning seems at a preliminary glance to be valid. In theory, a 2x4 stud is a 2x4, a cubic foot of concrete is a known quantity. The unit prices of these materials seem relatively fixed. Buildings of a certain size require
certain amounts of material. Metrics for these material quantities relative to square footages of given construction types are available in the industry. Quantity estimating on conventional construction is a fairly straight forward process. The estimator adds up linear wall lengths from the 2D drawings, multiplies this length by the height of the walls to determine square footages, throws in a percentage for material waste, and multiplies these quantities by established local costs for the building materials and per quantity estimates of hours and rates of construction labor, to arrive at a cost for the construction of a given building system. If the client is interested in higher quality materials or construction, these decisions can increase the cost of construction, but in theory the client “gets what he or she asks for” in terms of a higher quality product. In turn, it is perceived that the soft costs of the architectural and engineering services have some flexibility. If the architect spends less time in schematic design, the number of billed hours can be reduced, beneficially impacting the bottom line of the building construction budget. On many conventional building projects, the design services are seen as an area to squeeze some cost reduction.

The above distinctions between soft and hard costs of construction may be valid for conventional construction, where quantities and associated costs are relatively well established. On unconventional construction, where established industry costs for the type of construction are not available, the rules of the game are thrown wide open. Even the straight forward activity of quantity estimating can be difficult to accurately perform if these quantities can not be easily determined from conventional 2D documentation. Material waste factors can be difficult to estimate, since atypically shaped building elements can be more difficult to fit on industry standard sheets of material. The labor associated with unit quantities of unconventional construction systems can be difficult to anticipate.

Even on conventional construction, construction budgeting is less of a science than it first appears. For conventional construction, rough per unit cost rules of thumb are available in the industry, and are known to architects and construction managers. These unit costs vary widely from region to region, and are substantially impacted by short term localized economic factors. Factors contributing to the cost of a given system include local availability of materials and equipment, availability of skilled vs. unskilled labor and the influence of trade unions, and competition among projects in a given locale for certain elements of construction. A “hot” building market will drive up costs for most basic construction systems, as demand for sub-contractors is driven up. The history of Gehry’s projects is rife with
anecdotes of these local and temporary economic considerations. The economic feasibility of titanium for the Guggenheim Bilbao project is traced to a temporary glut of available titanium in the world market after the fall of the Soviet Union. The Big Dig project in Boston reduced the available concrete contractors in the local market during the construction of the Stata Center. Low demand for skilled carpenters in the Czech Republic after the fall of communism contributed to the development of a hybrid digital / manual fabrication process for concrete panels of the Nationale – Nederland project.

The premium on direct hard costs associated with unconventional project geometry is an important factor in preliminary project budgeting. This premium is acknowledged by clients as a cost associated with the acquiring one of the firm’s designs. The rationale of cost associated with receiving a superior product is applicable to Gehry’s buildings. Many budgetary tradeoffs are made throughout schematic design phase decision making. For example, Gehry’s design aesthetic suggests more economical, conventional materials used in unconventional forms, in lieu of more expensive finishes applied to conventional geometry. Mixing project geometry to include conventional construction and geometry along with more highly shaped elements is an important element of the design process. These tradeoffs can be managed in schematic design in order to meet client budget requirements.

A more problematic aspect of project budgeting can be identified, in terms of risk management. In North America, construction sub contracts are typically awarded based on guaranteed price bids. Typically, construction sub contracts are awarded through a competitive bidding process, with the low bidder being awarded the contract. The recipient of the contract is obligated to perform the agreed upon services – specified through project documentation - for a contractually committed price. On conventional construction, sub contract estimators have a good understanding of their internal unit price costs for conducting work, and can make trade offs between competitive pricing and profit margin. On unconventional construction, where prior experience and industry established price points do not exist, cost estimation is difficult to conduct with any guarantee of successful completion of the project. The level of risk associated with contracting to perform the work at any specific price can be substantial. The result can be sub contractor bids containing large factors of safety, which ultimately represent premiums on the price of construction. Many sub contractors will simply elect not to consider taking on the work, reducing the competitive pool of providers and resulting in higher cost bids being accepted. The premiums cannot be
construed to be costs associated with a superior product, but simply represent higher costs for the same quality of construction. This price of risk can dwarf the premiums that can be expected due purely to additional labor or materials.

While the pre-construction pricing exercises can jeopardize the commencement of a project, lack of project and associated cost control during construction present even greater jeopardy to the project and participating organizations. The major risks in terms of cost overruns during construction can be traced to lack of dimensional coordination, and errors and omissions in construction documentation or their interpretation. Errors in dimensional coordination can result from mis-communication between trades, misunderstanding of dimensions of components, and complexities of routing equipment through tight spaces, such as duct runs of mechanical systems. Obvious errors of miscalculating dimensions on traditional 2D documents or not updating dimensions on plans when updates and changes are made occur all too frequently on conventionally documented construction drawings. When such errors escape notice until they are discovered in the field, at best re-work is necessary. More significantly, this rework can cause delays impacting many of the trades on the job. If these delays are significant enough, they can cause a “ripple affect” where subsequent trades are impacted. For example, the mis-sizing of a single primary steel beam, discovered in the field can delay the placement of adjoining members while the erroneous member is rebuilt and shipped. In turn, placement of any system to be attached to the primary steel system may be held up. If delays are significant, they can put in jeopardy guaranteed contracts with sub contractors, who may have other work scheduled in anticipation of completing their portion of the job by a certain date. The costs of running a large construction site per day can be substantial even without the subcontractor labor costs.

Improved project information provided by 3D CAD documentation has the potential to address many of these issues, allowing control of, and dramatically reducing, the so called “hard costs” of project construction. Much of the cost saving opportunities offered by information technology can be traced to reduction of risk. By facilitating improved unit quantity estimates early in schematic design, budget tradeoffs can be played out before detailed design has begun. Improved dimensional coordination can be a direct outcome of “virtually” constructing the building and its components to some level of detail prior to generating contract documents. Tricky or idiosyncratic conditions for typical system details – at corners or atypical interfaces with other systems – can be identified prior to committing
work contractually. Admittedly, this added information may give prospective bidders better insight into the complexity of the project, resulting in higher initial bids. However, if this complexity were to be discovered after the fact, disputes about the completeness of construction documents would need to be resolved, likely resulting in remediation.

Part of the successful design development practices of Gehry’s firm results from the frequent use of conventional system detailing, applied to unconventional geometry. The firm is continually cognizant of the availability of locally available talented craftsmanship, and seeks to take advantage of the materials and practices of their local construction practices. This is part of the contextual aesthetic of Gehry’s designs, and an aspect of the respect of craftsmanship for which the firm is known. One strategy for reducing project costs is to be able to provide construction information in a format familiar to these local trades. The 3 dimensional project database allows information to be “sliced and diced” to extract information supporting construction practices familiar to these local trades. If the description of complex geometry can be provided in a format that supports practices familiar to these trades, the risk factor can be reduced or eliminated. Complex geometry may still carry a premium in labor and material, but these factors can be understood in terms of real impact on the costs of construction, not buried in excessive cost contingencies to protect the contractor from unknown risks.

B. BUILDING TEAM ORGANIZATION AND INFORMATION FLOW

The conventions of contractual relationships among organizations participating in a construction project vary widely in different parts of the world. In many ways, the North American construction environment is among the most difficult for supporting unconventional building practices. It is partly for this reason that many of the early successes of the firm’s digital building delivery process were achieved on projects outside North America. Much of the development of the divisions between design and construction teams can be traced to the increase in construction litigation that has occurred in America since the 1950s. To protect the various partners from litigation, strict boundaries have been defined for the scope of responsibility each party takes on, and the flow of information between parties.
Figure II-1 diagrams the contractual relationship between organizations on a standard North American design – bid - build project. The contractual relationships are organized as a tree. The major contractual relationships are defined between the owner and architect, and owner and contractor. The architect is “prime contractor” for the design team, which specifies the scope of construction through construction drawings and specifications. The general contractor is responsible for the construction of the project per the construction documentation provided by the design team. All contractual relationships at the top of the hierarchy are with the owner; no contractual relationship exists between the architect and general contractor.

The architect sub-contracts for engineering services to structural, mechanical, acoustical, lighting and other consulting engineers. Various specialist engineers may be enlisted to perform peer review on the work of the engineering team. The design team completes the
specification of the project to demonstrate conformance with local building codes, and to
sufficient level of detail to guarantee in theory that the project can be built without errors or
conflicts between the activities of building trades.

The general contractor in turn apportions work, at their discretion, to internal resources or to
subcontractors. These contracts need only to guarantee that the specifications of the design
team are met; beyond these base line requirements the contractor is free to select any
contracting organizations that can reasonably be expected to perform the work. The
contractor will generally award sub contracts on the basis of lowest bid.

Sub contracting organizations “fill in the details” of the project specification through shop
drawings that describe building systems and components to a level of detail necessary for
actual construction. The sub contracting organizations have their own engineering teams that
conduct detailed engineering of system components to verify that proposed fabrication meets
the standards specified by the design team. Again in theory, the contract documents
provided by the design team have anticipated all the geometric and coordination conditions
that will occur as a consequence of the systems that have been selected for the project. In
practice, the level of detail performed by the design team to define the resolution of typical
conditions may not anticipate all the actual localized conditions generated by the specified
systems. The level of detail provided by the shop drawing detailing may be necessary to
disclose the full range of implications of a selected building system strategy. Any
discrepancies between general and actual localized conditions can be a source of dispute
between the design and construction teams. These shop drawings are submitted to the
design team for review, comment or exception. The design team is usually responsible for
guaranteeing that the details specified in the shop drawings can be dimensionally
coordinated between trades. Note that dimensional conflicts between the work of different
trades may not be apparent in any single trade’s shop drawing submissions. Coordination
through integrating information contained on numerous shop drawings may be required for
the design team’s review. Problems can be difficult to detect when this information is
contained on disparate two dimensional documents.

When a condition is detected by the sub contractor that is beyond the scope of the details
specified by the bid package, requests for information (RFIs) are generated by the sub
contractor and sent through the contractual hierarchy to the architect - as head of the design
team - for clarification of design intent. Depending on the severity of the condition, the design team may issue a supplemental information document (SI), indicating that the design team believes the condition is within the original intent of the contract documents. If the condition is determined to be outside the scope of the details specified in the contract documents, change orders may need to be generated. The generation of change orders indicate that resolution of the condition is in fact beyond the scope of the original construction documents and contract, and will frequently generate additional fees for the construction team. This change of contractual scope will necessarily require the approval of the owner.

Information flow between organizations is strictly controlled along the paths of contractual relationships (Figure II-2). The parties higher up in the contractual tree are typically leery of allowing their sub contractor organizations to communicate or make decisions directly with other organizations, since they are ultimately responsible for the work of the subordinate organizations. Worse, the fear is, subcontracting organizations may “leak” information about internal decision making between contracting and sub contracting organizations to
organizations “on the other side of the fence”, who may use this information to their advantage if disputes arise.

When construction proceeds smoothly (which it seldom does, even on conventional construction!) this strict control of information generation and dissemination protects all parties from erroneous decision making that would jeopardize the intent of the project specifications that form the basis of the contractual relationships. For conventional construction, where the work of each party is fairly well defined by standard details and other conventions of practice, the process of design and construction decision making can be accommodated by this tightly contractually controlled process.

For innovative, complex or unconventional construction, the disaggregation of information and limitations imposed on communications between decision makers can virtually guarantee that problems will occur in project coordination. When they do occur during construction, resolution of problems can be difficult. Problems which could be quickly fixed on the spot - if the construction team had sufficient authority - require a chain of events and decisions, above all a determination of the party responsible for the condition. While the resolution of decisions are winding their way through the chain of command, construction delays can ensue, further aggravating the impact the condition has on the project schedule and cost. Communication technologies have been drawn on to assist in the speed of resolution of on site conditions, including simple technologies (such as emailed digital photos) and more elaborate technologies including information tracking Web sites.

More problematic for innovation of construction is that the true sources of fabrication innovation – and the parties ultimately responsible for execution of this innovation – are the fabricators themselves. These are the organizations that will ultimately be required to develop innovations of process necessary to efficiently construct innovative project geometries. This expertise is best included in the design process during design development decision making, before the contract documents have been completed. In the contractual scheme defined above, these entities are excluded from the decision making process. Worse, sophisticated fabricators may be better informed of the actual effort and cost required to perform sophisticated construction work. This knowledge may work to their detriment, since the bids they submit may reflect the actual cost required to complete the project. Their bids may be turned down by the general contractor in favor of less qualified fabricators, who
may turn out be unable to execute the work to which they have committed themselves. The specification and bidding process also can fail to turn the award of contracts in favor of fabricators who perform higher quality work.

Gehry’s design aesthetic has always tended to favored innovation of fabrication and craft over that of engineering. These intentions would conspire to flip the standard contractual process around. Theoretically, the fabricators would work directly with the architect and engineers of the design team to provide the specification of the work to be performed. Unfortunately, this tight relationship between design team and craftsmen violates many of the contractual conventions of North American construction.

To address this issue, GP has occasionally – with the consent of owner and general contractor - entered into unconventional contractual relations with fabricators in the design development phase. These design assist contracts are forged between the architect and skilled fabricators. The fabricator serves as a quasi consulting engineer for the specification of a building system, and is compensated for this service. There is no commitment by the general contractor to ultimately award the contract to the particular fabricator; it may be awarded to the fabricator’s competition, if the fabricator’s bid is unreasonable. In practice, this is however seldom the case.

A second issue of potential impact on contractual relations is the availability of computing capabilities by the fabrication organizations. The accurate performance of shop drawing work requires the fabricator to dig into the master model database. Until recently, the skills necessary to operate CATIA, and familiarity with a 3D centric approach to detailing were unavailable outside of Gehry Partners. While the ability to fabricate the components existed in skilled fabrication shops, the necessary CAD expertise was not part of these organizations’ services. When CAD expertise existed, data would still need to be translated into formats appropriate for the fabricator’s work. This lack of availability of computational expertise has often required Gehry Partners to perform services as part of construction administration phase activities, well beyond those conventionally within the architect’s scope. In order to address the contractual ambiguity of these services, C-Cubed – Rick Smith’s CATIA consulting organization – has often been recommended as a sub contractor to general contractors and fabricators. C-Cubed provides both CATIA operator expertise, as well as familiarity with the firm’s digital methodologies. C-Cubed has contracted directly to contractor
and sub contractor organizations to perform digital shop drawing services, removing Gehry Partners from any direct work and contractual relationship with these organizations.

On recent projects, 3D CAD capabilities have become more prevalent in fabricating organizations. Often these organizations have developed sophisticated digital methods of their own, or have acquired 3rd party applications whose development targets the specific activities of their trade. CAD activities to support these relationships have turned more toward translation of data between the CATIA master model and these proprietary formats. Often, Gehry Partners will engage in development of translation processes to serve particular contracting organizations. These capabilities are officially provided “for reference only”; the CATIA database remains the official format for 3D data on the firm’s projects. When appropriate, GP has provided these translation technologies to the general contractor, who becomes responsible for data coordination with their subcontractors.

C. FABRICATION ECONOMIES

Building projects are predominately singular endeavors. Site conditions, local building practices and codes, client specific requirements, and the need to work with locally based construction firms and their heavy equipment, all are conditions that contribute to the necessity for treating each project as a unique undertaking.

This characteristic is perhaps the single most important distinction between building construction and product manufacturing industries. The products of manufacturing industries vary widely in scale, complexity and cost. Airplanes are enormously complex design and engineering endeavors, and carry very high unit costs. Only a few hundred or thousand units may be produced over the lifetime of an aircraft product line. A toy is a relatively simple object to engineer and produce. Hundreds of thousands or even millions of identical toys may be produced in the lifetime of the product line.

Economies of scale unify the production these different manufactured products. There are many implications of mass production on the economics and opportunities afforded by product lines. With economies of scale, the up front cost of engineering and tooling design required to develop the product line is distributed over the cost of each unit. Even if these costs are high relative to the unit cost, substantial design and engineering activity can be
undertaken with limited impact on this unit cost. These implications impact the fabrication methods available to mass production, and in turn have consequences on the shapes that be manufactured. The tooling of dies for extrusion molding or stamping fabrication technologies often represent a high fixed cost of product manufacturing. Metal stamping requires the fabrication of a positive and negative dies. The manufacturing of these dies in manufacturing is often a multi-step process. A wax positive form may be constructed, or highly finished CNC routed positive is developed in foam. Then, a high strength negative form is cast from the sculpted positive form. Depending on the stamping process, a second positive in high strength material may be developed from the negative form, and a high strength steel die formed from this element. This elaborate process can be easily justified for large scale runs of identical parts. It is fairly obvious that application of such a process to one of a kind component runs would be drastically expensive. Yet, for fully free form surface forms, elements of a stamping or molding process are still required.

A more subtle implication of economies of scale – or lack thereof – is found in the cost of information required to develop a given component. This cost of information can be identified in the design, engineering, and modeling or drafting associated with the development of the component. With large product runs, the cost of engineering and modeling a component is again a small component of the cost of fabricating the individual unit. In the development of singular products and components, the relative cost of engineering to that of materials or fabrication labor can be high. It may be more economical to over design the specification for all units, adding more material and hence strength into the objects’ designs, than to engineer each unit to a more optimal configuration. Similarly, it may be more cost effective to use additional fabrication effort - allowing the craftsman working on the component to figure out aspects of the component’s configuration – than it would be to fully detail an individual component through computer based or traditional drafting.

Issues of mass production have been a topic for architecture since the industrial revolution. While a full treatment of this topic is well beyond the scope of this thesis, some observations may be made on the geometric organization of building projects and its affordance of mass production. The regularized, Euclidean organizations of building layout strategies have historically provided the basis for incorporating mass produced elements. Modular systems based on grid layouts - repetition of rectangular dimensions in the organization of building designs – allow components of identical proportions to be mass produced and deployed
across the project. Countless examples of such designs exist, we note in passing much of the work of Mies van der Rohe and fellow high modernists. These strategies rely on dimensional repetition as a means for achieving geometric symmetries supporting the incorporation of identical elements. Rotational symmetries afford similar dimensional repetition. Variations in localized performance requirements may exist across elements of identical dimensions. The wind forces on the glazing modules of high rise buildings are greater at the top than at the bottom. This localized performance variation may be trivially satisfied by over designing the unit to satisfy the worst case design conditions; the inefficiency of deploying materials in a less than optimal fashion may be vastly outweighed by the informational economy of engineering the unit a single time.

There is perhaps an even greater body of built work drawing on regularities of Euclidean geometry to support systems founded on mass produced raw materials. The conventional American 2x4 system is a key such example. This system does not require modular dimensions, but rather relies on easily formed raw materials with certain assumed constraints on the building geometry to which they will be applied. The obvious constraints of the 2x4 system are planar wall, floor and roof geometries. Straight, rectangular edges and perpendicular wall organizations are suggested by this system; however, the system can accommodate angles between planar elements and non-perpendicular edges with minor customization. Gehry’s early work (Section IV.A) explored the limits of these building systems and materials.

The non-repetitive geometries that characterize Gehry’s recent work afford neither modular dimensional regularities nor other regularities afforded by Euclidean systems. However, in order to satisfy budgetary and schedule requirements on the firm’s projects, systematic building strategies are still required. This imperative has caused design development strategies and geometric modeling efforts to pursue the identification of geometric regularities that do exist in the design geometry, or can be imposed on the geometry with minimal impact on the design intent. The term rationalization (Section III.F, below) is used within the firm to describe this process of pursuing and incorporating geometric regularities in the building form. The disclosure and constructibility implications of geometric regularities in non-Euclidean geometry are a central topic of this thesis. Considerable discussion of different geometric forms present in Gehry’s designs, the regularities inherent to these
geometries, and constructibility strategies that take advantage of these regularities will be provided in Parts 2 and 3 of this thesis.

D. MANUFACTURING TECHNOLOGIES AND METHODS

CNC (Computer Numerically Controlled) production methods hold promise to alleviate some of the geometric constraints on mass production strategies. CNC fabrication equipment can dramatically reduce the labor associated with controlled fabrication of custom components. CNC technologies include a variety of different technologies, including laser or plasma cutting of flat sheet materials, automated hole punching used in structural steel fabrication, 3 and 5 axis routing, automatic lathing, and full fledged robotic manufacturing. However, there are economic and formal considerations in applying these technologies. The cost of this equipment is substantial relative to more conventional fabrication equipment. This up front cost must be amortized over the life of the machine, which can in it self result in significant costs per cutting operation. Certain combinations of materials, sizes of elements and shapes have no current CNC solutions. For example, re-configurable mold technologies are currently being researched, but to date these technologies are unavailable in commercial applications for high quality fabrication of steel plate or other high strength materials. The cost of generating and processing the information necessary to drive the equipment must be considered as well. Long machine run times on expensive equipment (such as 5 axis milling) can make applications of these technologies prohibitively expensive. Computer based modeling requires highly skilled operators, frequently working on high priced workstations and software. The amount of information necessary to generate shop drawing information for CNC fabrication may be more than that necessary to generate equivalent shop drawings for manual fabrication. To date, few building fabrication shops have invested in these technologies. The limited competition among firms for this type of work has to date resulted in premiums for full CNC enabled approaches to building component generation. Certainly, we can expect to see continual reductions in the cost of these technologies over time. The automation of shop drawing production combined with the ongoing reduction in cost of computer hardware promises to beneficially impact the cost of generating building components with unique configurations.

Gehry’s firm has promoted the use of CNC manufacturing technologies in these production processes. CNC technologies are utilized in the manufacturing process to produce the
custom geometry of individual components at exact tolerances. Manufacturing tool paths may be exported directly from the CATIA master model to the CNC production equipment, resulting in building components that conform to the local geometric requirements of the project. The building systems that result from this method offer tremendous flexibility in addressing programmatic or aesthetic considerations. Using CNC production methods tied directly to the definitive 3D project information additionally results in improved coordination of connection geometries throughout the project, fewer dimensional conflicts between building system components, and fewer costly modifications of components at the construction site.

In other situations, the more traditional methods associated with manual construction techniques have proven to be more cost effective. When traditional construction methods are adopted, the resulting systems are subjected to similar requirements of dimensional coordination with the three dimensional computer master model. To fulfill this requirement, manual fabrication is directed through the use of loft drawings - full scale construction templates. With the full three dimensional model in place, information may be extracted in forms appropriate for the support of traditional trade practices.

The processes that have been developed by the firm provide interfaces to both traditional manual construction practices, and to technical innovations associated with CNC manufacturing. For each building system, a manufacturing process is developed through close collaboration between Gehry’s firm and partnering fabricators. The resulting process is rigorously substantiated through full scale mockups in conjunction with computer modeling and analysis, and subjected to value engineering assessment. The approach which is ultimately pursued can combine traditional, manual construction techniques with advanced computer based manufacturing methods, to arrive at an optimal solution both from the perspective of cost as well as the quality of the resulting system.

E. DIMENSIONAL TOLERANCES

Building construction neither provides nor requires the tight fabrication tolerances of aircraft and automotive manufacturing. The tightest tolerances that can be achieved through typical fabrication and construction techniques are on the order of 1/8” to 1/16”. In practice many building fabrication systems have far lower tolerances. Primary structural steel fabrication in North America can be expected to have tolerances of no better than 1 inch. These tolerances
differ greatly from those expected in manufacturing industries, where tolerances tighter than 1 mil may be expected. CNC fabrication methods can offer higher tolerances of components to their corresponding digital description. However, CNC developed components often still require assembly through traditional manual methods, and the typical construction tolerances are often re-introduced into these systems during manual assembly. As a general rule, one can anticipate a premium for fabrication with tighter construction tolerances, and lower tolerances for one of a kind objects relative to those produced through machine automated mass production methods.

Construction tolerances are closely related to the issue of dimensional control of the project. The exacting numerical specificity of contemporary CAD modeling applications are of little utility if building components can not reasonably be expected to be accurately positioned in space in conformance with the digital model. On site digital surveying capabilities allow components to be positioned in space in tight conformance with the digital model. However, the labor involved with positioning building components through digital surveying is significant. Building system strategies that rely on sampling vast quantities of surveyed points can be expected to have associated project cost and schedule implications. Even if such exacting positioning of certain building system elements is presumed, the relative fabrication tolerances of adjoining building components can require adjustable connection strategies for resolving dimensional discrepancies.

An alternative strategy for positioning building components is to rely on one building system to serve as the positioning device or dimensional control mechanism for adjoining elements. The benefits of such a strategy are readily apparent. The dimensional control element serves simultaneously as building component, jig for the positioning of other elements, and structural support for the elements that join it. This requires, however, that the dimensional control element be fabricated to the construction tolerances required of the adjoining elements, with associated costs of a potentially high tolerance fabrication. Typically, the dimensional control component will be a more primary element than the elements that frame in. The costs for fabricating primary structural elements to tight tolerance may be far greater than that of fabricating secondary systems to similar tolerances. For example, primary steel can be used as the dimensional control for a stud framed wall system that it supports. The construction tolerances of the stud wall system are dictated by the requirements of the cladding system, while primary steel would normally be subject to more generous tolerances.
than that required for the wall system. This generates a higher unit cost for the primary steel. On the other hand, only relative system conformance to the dimensions specified in the CAD model may be required. The positioning of framing members in the above example may need to tightly correspond to the edge geometry of the primary steel and to one another, but where this assemblage winds up relative to other elements of the project may be of little consequence. If so, then the tolerance requirements of the dimensional control system can be relaxed.

CNC fabrication technologies can often support the development of registration information as part of the fabrication process. Laser or plasma cutting tools, operated at lower power levels than required to burn through material, can allow dimensionally accurate registration marks and even textual annotation as part of the cutting process\textsuperscript{66}.

Issues of tolerance and dimensional control have profound implications for project cost and quality. Tolerance decisions can not be isolated from the system design and modeling strategies. These decisions will have implications for manufacturability, erection and project cost which can impact the design, coordination and site logistics with implications beyond the actual system on which these decisions are made. A judicious use of tolerance and flexibility in the dimensional control of project geometries has been an important part of the firm’s success in realizing projects within reasonable construction budgets.
III. THE MASTER MODEL METHODOLOGY

A. INTRODUCTION

The master model methodology represents the technological core of Gehry Partner's digitally assisted building delivery process. Broadly stated, the project master model is an integrated repository for three dimensional CAD based descriptions of all aspects of project construction. The geometric nature of these descriptions, and the utilities it serves in guiding the development of the built project and the coordination of building processes will be considered in some detail.

The master model methodology grew out of early experiments in paperless shop drawing development discussed in the introduction provided in Chapter I. However, substantial development of both digital technologies and the building development methodologies that these technologies support has taken place, from the early, relatively simple applications on Gehry’s sculptural projects to current iterations serving full design, engineering and construction activities on the firm’s current major projects.

Although the master model approach has been developed on a specific technology platform – Dassault Systèmes CATIA software product line – and is informed by technologically driven methodologies developed by Dassault to serve large scale complex manufacturing projects, the firm’s technological methodology is wider in reach than reliance on any specific software product would allow. Nor is the methodology exclusively 3D centric, since support of conventional two dimensional documentation remains a requirement for successful operation in current construction practice. Ultimately, the master model methodology is exactly that, a methodology and an associated set of practices oriented toward the integration of project data through digital representation. Some of the goals of this methodology are to:

- Provide an common, integrating framework for all geometric project data, regardless of source;
- Support the extraction of geometry necessary for completion of all engineering and construction activities, in geometric forms and data formats appropriate to these activities;
- Allow the extraction and re-integration of “traditional” two dimensional project documentation;
- Support high resolution description of continuously curved surface and curve representations, and operations on these geometries;
- Support a design methodology centered around the creation of physically based design artifacts;
- Support a design development process requiring the incremental geometric development of building systems descriptions and intentions, corresponding to the incremental development of project information associated with project phasing;
- Support information control mechanisms appropriate for the development of building projects in light of industry standard project control and contractual practices.

It is important to recognize that the innovative use of three dimensional digital models represents only one component of the firm's process. The firm's success in realizing its projects is due in no small part to the development of methodologies that integrate three dimensional digital models with two dimensional drawings and other conventional project information. The master model technologies represent an extension – not abandonment - of conventional project descriptions and processes. The rationale behind the development of this hybrid process are partly related to cost control. In the current construction environment, fully digitally capable construction and fabrication partners do not always exist. Where they do, the costs of advanced CNC fabricated components may be much higher than that of traditional processes. The hybrid process allows these economic and quality tradeoffs to be made on a case by case basis, even within the scope of a single project. More importantly, Gehry’s building occurs within the context of traditionally based construction environment. Substantial existing conventions of practice have been developed around two dimensional construction documentation. On large scale projects, disregarding these conventions in favor of a wholly unprecedented approach would be both impractical and dangerous.
The ambitious agenda for digital project data raises questions of appropriate geometric representational formats, and the level of data development appropriate for each party's function in the building process. The full rendition of building components in 3-dimensional solid form would represent a level of effort well beyond that supportable even with generous
architectural fees. This is not simply a question of the firm’s economics, but also a question of the level of project development and associated project responsibility allocated to the design team. As with conventional documentation, the architect developed project geometry to a certain level of detail, sufficient for other parties to build on and refine. The result is that project geometry provided as part of the architectural contract documents is surprisingly reduced and representational in terms of its level of geometric detail. However, the geometry that is shown provides the correct nominal dimensional control geometry for the indicated components.

An illustrative example is shown in Figure III-2. This model shows the 3D CAD component of the contract documents for the Experience Music Project’s structural rib system. The model shows the location and positioning of the structural ribs and cross bracing, and the supporting concrete foundation. Each system is represented with a different geometric abstraction, reflecting the scope of detail provided as part of the design team’s package. These abstractions provide the geometric information necessary to position the element in space and for the steel contractor to further develop the structural detailing. The structural concrete foundation is provided in full solid form, and correctly reflects the nominal surface of construction necessary for the development of concrete formwork. However, the structural ribs are for the most part shown only as a face cast between top and bottom curves. This representation provides only the dimensional information necessary for the structural fabricator to understand material quantities involved, and to geometrically guide the further development of the full rib geometry. The rest of the information necessary to satisfy the performance criteria of the ribs are found in conventional two-dimensional detail drawings and text based specifications. Text based rib numbering is
provided in the model to allow cross referencing with schedules and other information in the conventional documentation. The cross bracing between ribs is provided in even simpler form, as single line elements cast between the top and bottom chords of the ribs.

Each of these geometric descriptions represent substantially impoverished abstractions relative to what one might imagine as a full geometric description of the structural elements. Much more information is needed to fully develop these systems in shop drawings: bolt holes, splices, weld specifications, etc. But this information is not typically considered to be part of either the architect or structural engineer's scope of work. The design team would not receive compensation for the effort or responsibility associated with providing this detailed information in the contract model. The level of geometric detail also reflects project phasing considerations, and the level project geometry known at the point in time of construction documentation. Providing additional geometry would likely be extraneous, since the structural detailer would likely request modifications of the geometry based on their more extensive knowledge of their fabrication process. These changes would then need to be carried forward by updating the master model geometry. More importantly, provision of excessive information by the design team would blur the boundaries of scope between the design and construction teams. If substantially detailed geometry were provided in contract documents, and then modifications of this geometry were required during shop drawing phase, these modifications would reflect changes relative to the construction documentation and hence to the contract itself. These changes could result in change orders or possibly invalidation of the contract. This re-opening of contractual agreements could ultimately result in additional fees to the construction team, even if the geometry and fabrication were simpler than that specified in the model.

This example serves to illustrate a critical point in the development of the master model methodology: the selections of geometric representation in the digital documents reflect the nature of the processes and relationships between parties of the project. These decisions are of enormous significance to the control of the construction process. Such implications are not new to a digital centric process; conventions in divisions of labor and associated project description exist in paper driven construction projects with conventional geometries and fabrication systems. However, in more traditional projects these conventions are well defined in the nature of existing practice. The scope of project development associated with each participating organization, and the descriptive conventions associated with performing this
work, are largely pre-determined. Legally binding standards for level of professional practice are defined relative to the information contained in conventional documentation.

The re-development of these practices in light of digital technology requires all of the conventions embedded in traditional documentation to be reviewed. The nature of each participant's scope of work in developing project definition is subject to reconsideration. Agreements between the parties regarding the type of information needed to perform allocated work, and the scope of responsibility assumed by parties in providing this information, need to be defined. Specifications need to be created to establish what these geometric abstractions represent, and the ways in which this information is to be used or not used. These decisions and agreements need to be revisited each time a new partnering organization is brought into the process, and each time a new building system is designed.

As a general rule in the firm's process, three dimensional models are provided as part of the legally binding project construction documentation. The 3D models specify the minimal dimensional information needed to develop spatially coordinated system components. Information necessary for quantity takeoffs is provided in these models, to some level of detail and abstraction. The specifications of component performance and connection detailing are provided through conventional two-dimensional documentation. The conventions established for these project descriptions are expressed in the (textually based) project specifications, including what each form of documentation provides, how the information is to be used, and which documentation governs in case of conflicts.

As the firm's digital process has matured, the level of detail represented in the jointly developed project database has dramatically expanded, and the amount of information provided solely in two dimensional form has diminished. Geometric abstractions have become less abstract; more geometric detail is provided as part of the design documentation. This expansion of geometric detail parallels an expansion of the firm’s services from that of a design architect to full architectural services on many projects. Substantial experience with certain types of building systems often used on its projects has led the firm to provide increasingly detailed geometric specifications of these systems. Nonetheless, the mantra developed early in the firm’s process development still applies as a guiding principal:

“Draw all - and only - the information necessary.”
B. PROJECT CONTROL

Beginning in design development phase, responsibility for development of portions of the project description begins to be turned over to partnering organizations – engineers, construction managers and fabricators. Elements of the 3D models are turned over to these partnering entities, who begin to develop the project information required for their roles in the process. The information developed by these organizations needs to be coordinated. Project coordination is within the traditional scope of the architect’s role on a building project. Conventionally, this role is conducted by reviewing 2D drawing documentation provided by each partnering organization in format founded on conventions of their discipline. Coordination of the assembled body of documentation from these numerous partners in their native physical drawing formats is an extraordinarily difficult undertaking, and a major source of errors and omissions on construction projects.

The comprehensive 3D model that resides at the center of the firm’s process provides an enormous aid for coordination. Even when two dimensional documentation is employed by a partner, this 2D documentation can be translated back into three dimensions, and oriented appropriately in 3D space relative to the other information on the project. When partners employ 3D documentation – as is increasingly becoming the case – this information may be directly imported and overlaid on the architectural models. The result is a comprehensive repository for all geometric data generated by the partners in the design process. By assembling and filtering this information, the process of system coordination is radically improved. System interferences may be detected, either via visual inspection or through tools that automate checking for spatial clashes or violations of system envelopes by other systems.
Time based visualization of construction sequencing has become a useful coordination tool on the firm’s larger projects, including the Experience Music Project, the Disney Concert Hall, and the Stata Center at MIT. This detailed coordination of on site activities is part of the general contractor’s responsibility. The enabling technology – developed by Disney Imagineering in collaboration with Stanford University’s Center for Integrated Facilities Management (CIFE) – allows 3D project geometry to be associated with information from project scheduling software such as Primavera. Project managers and personnel responsible for on-site coordination can simulate the progression of activities on the construction site.

C. PERFORMANCE ANALYSIS

The ease by which specific engineering and other analytical models may be supported is a core benefit of the 3D project master model. The transfer of project information to and from formats satisfying the requirements of engineering and fabrication partners is a critical component of design development activities.

Numerous computational engineering analysis techniques have become available over the past two decades. Examples of such techniques include structural analysis, energy simulation and computation fluid dynamics based air flow studies, equipment performance simulation, as well as lighting and acoustic simulation. Much of this development has been through the use of finite element and finite difference techniques. These techniques approximate complicated geometric forms into assemblies of simplified elements. The global solution for the form is achieved by simultaneous solution of the individual elements’ performances. These techniques are well suited to the analysis of the geometry on Gehry’s projects. The feasibility of Gehry’s recent projects is due in no small measure to the availability of these analytical approaches.
In conventional architectural processes, if such simulations are required, a special 3D model must be constructed, on the basis of 2D plans or other conventional documentation, and for the sole purpose of the particular analysis. Re-use of these models for other purposes in conventional architectural processes is generally not practical.

With the availability of a comprehensive, three dimensional project description, the level of effort required to provide specific analytical models becomes greatly reduced. In the firm’s process, some representation of the system under inquiry is often available in the master model by the time that the analysis is required. Many of these techniques are undertaken relative to 3D geometric models in proprietary formats. However, software packages are continuing to improve their ability to import elements of these proprietary descriptions from neutral geometry formats.

Finite element structural analyses (FEA) have been conducted on virtually all recent Gehry projects, and are a critical part of project structural engineering activities. Often, the finite element models can be developed directly from the structural system wire frame from the master model. Typically, the project wireframe provides only the geometric definition of the positioning of elements. Additional information including materials, sectional properties and nodal degrees of freedom must be added to the engineering model. Currently, finite element structural software typically can not accept curved elements, a direct consequence of the geometries of finite elements that serve as the basis for these solution techniques. The project geometry must be rationalized (Section III.F) into segmented linear members and triangulated plate sections prior to import into the FEA solver.

FEA structural analysis results in additional information pertinent to subsequent phases of structural system development, including the specification of member sections and load information at the connections. The firm’s pursuit of comprehensive digitally based processes suggests that this information be translated directly back into the master model and on to
steel detailing and fabrication applications. To date, the full re-integration of FEA model information has been only partly successful. This is partly due to the “degradation” of project geometry that occurs in approximating curved project geometry into linearized elements, described above. The geometric approximations required for fabrication can involve different geometric abstractions than those required for FEA analysis. Translating critical, non-geometric performance information between applications and across the division between the design and construction teams has to date been deemed to involve too great a risk to undertake without human oversight. Finally, the project geometry is typically not refined to the level required for structural detailing at the point in time of structural analysis. Structural analysis requires only fairly loose geometric tolerance relative to that required for fabrication. Dimensional approximations of frame elements of several inches have negligible effects on project loads, member sizing and modal analysis. This level of construction tolerance would obviously be unacceptable for final detailing. Nonetheless, many of these limitations are procedural more than any technical limitation of digital translation. Currently, geometry and sectional information are translated directly from the master model to both FEA and detailing applications. It can be anticipated that this digital integration of analytical and fabrication processes will continue to be expanded.

Computational Fluid Dynamics (CFD) techniques are becoming widely used in building energy and life safety applications. CFD can be used to model air, energy and particulate flows through spaces with complex shapes. In energy studies, these techniques are often combined with radiant analysis of solar gains to assess building heating and cooling strategies. Advanced building energy strategies such as displacement ventilation or natural heating and cooling can require this detailed analysis of air and energy flows in their design.

CFD is also used to simulate smoke and heat migration through atria and other interior spaces.
These applications are critical to the feasibility of Gehry’s projects, since existing life safety codes are difficult to interpret in the context of Gehry projects. Codes typically allow variances in conditions where minimum safety conditions can be proven. Typically, the driving condition for fire safety is the time between the beginning of a fire event and the incursion of a specified density of smoke into occupied regions of the building. CFD applications allow specific fire events to be simulated. The dispersion of smoke through atria can be simulated, along with the behavior of fire doors, smoke dispersion fans and other fire safety equipment.

These simulation techniques require the generation of a negative space model delineating the boundaries of spaces enclosed by the building surfaces, which are readily extracted from the building geometry model (Figure III-6). Typically, adjoining walls, roof and floor surfaces must be extracted from the master model, then trimmed to each other to form a closed solid. The negative space model must then be tessellated into triangular facets to conform to the geometric requirements of the simulation technique.

Historically, the computational requirements of such techniques, and the necessity for trained engineering operators to run and interpret results, has relegated advanced performance simulation techniques to confirmation or final engineering assessment, conducted late in design development. The increasing speed of personal computing and availability of performance simulation software for personal computers has raised the possibility of drawing engineering simulation techniques into the set of tools available for schematic design iterations. The possibility of using performance analysis iteratively as part of the design process has been explored in many areas. Often, the level of accuracy required during early design development is at a much more qualitative level than would be required for the final, detailed engineering. These limitations on the required level of analytical detail can translate into corresponding reductions of computing complexity, fostering more interactive applications of these analytical techniques.

A variety of applications of such schematic performance simulations have found use on Gehry’s projects. The use of CFD as an iterative tool to assess wind flow and associated pedestrian comfort was applied to massing studies on the MIT Stata Center Project\(^2\) (Figure III-7). Visualization software is frequently used for shadow studies to assess natural lighting and energy performance (Figure III-8).
Figure III-7: CFD wind studies (MIT)

Figure III-8: Solar shadow studies (MIT)
The use of materials simulation techniques, described in Chapter VII, is a further example of the interactive performance applications that become available through tradeoffs between simulation accuracy and speed. This migration of performance analysis techniques from engineering to design applications is an important opportunity for the development of project design activities, and is again enabled through the existence of the building master model.

D. 3D – 2D INTEGRATION

The need to carry both three dimensional and two dimensional descriptions of the project through the many design iterations and document submissions over the lifetime of a construction project has been one of the most difficult aspects of the firm’s digital process. There are many reasons why two dimensional representations remain a necessary component of project descriptions for the foreseeable future:

- Interaction needs to occur with many organizations using traditional processes. Increasingly, technologically sophisticated partners are available who can provide favorable prices for services through efficiencies generated by technological advancement. However partners may, for regional cultural or economic reasons, provide the best price for services through traditional methods, or there may simply be no technologically enabled alternatives.

It is largely the building agencies that remain most firmly entrenched in conventional documentation processes. These are the local governmental authorities that approve building permits, and review code compliance. These agencies need approval processes that serve the “lowest common denominator” for building projects within their jurisdiction. They also have neither direct financial incentives nor economic resources to justify technological advancements of process. Most building agencies will not accept even two dimensional CAD documentation.

- Building information is often symbolic in nature at points in the design process. Elements such as door swings, tile patterns and bathroom fixtures either do not merit full 3D geometric description, or the full geometric nature may not be known at a given point in time. The building description is facilitated by treating these elements as symbols on plans, rather than developing such abstract or trivial information into detailed three dimensional representations. As technology continues to be adopted industry wide, and
efficient standards for including and reviewing this information become available, this symbolic information may eventually be migrated to a three dimensional form.

- Many building components have important two dimensional qualities. Many of the efficiencies in building systems used on Gehry projects are derived from building components that are essentially two dimensional. CNC cut plate elements, flattenable surface elements, floor finishes, all have geometric natures efficiently expressed through appropriately oriented two dimensional views.

For these reasons, two dimensional project descriptions are likely to be an important element of design and construction processes for some time to come. The technical and procedural integration of 3D and 2D information is a substantial focus of technological development by the firm. At times, the process has had the flavor of maintaining a dual database: one database of three dimensional data, and the other embodied in two dimensional drawings. The process of integrating between these two representations, distanced by technological and representational conventions, is not yet ideal.

A number of technological approaches support this integration between 2D and 3D project representations. However, not all are applicable to complex non-Euclidean geometry. Until recently, brute force geometric operations were required to extract drawings from 3D models. Section cuts could be easily generated by intersecting the model geometry with a plane at the location of the cut. Utilities also existed for performing isometric or perspective projections. However, hidden line removal utilities did function correctly for all geometric objects. Laborious geometric operations were needed to remove hidden geometry such as pattern curves on surfaces. Creation of section / projection views required manually splitting the master model at the cut plane, and erasing geometry prior to drawing extraction! This two dimensional geometry was then exported to AutoCAD and cleaned up. Finally, annotation, text, and hatching, line weight correction and other two dimensional “dress up” were manually applied in 2D.

Even minor changes to the project geometry required redoing the entire process. Existing two dimensional annotations could be manually repositioned, rather than re-drawing. Any drawings unaffected by changes in geometry would of course not be re-processed. The whole process took enormous amounts of time for each revision. In times of project
deadlines, shorts would be taken. The 2D drawings might be manually changed, rather than modifying the 3D geometry and repeating the process. The result has been difficulty in maintaining the integrity of the dual database. This difficulty was exacerbated as the detail in project models has grown.

This dual 2D / 3D nature of project geometry, and the necessity for its integration has been known to software developers for some time. Various approaches to the 2D / 3D integration, and the integration of symbolic expressions of project information with geometric representations, have been proposed by researchers and vendors. The support of automatic 3D to 2D geometric extractions has improved. Other approaches involving the “intelligent” re-writing of the building objects in various contexts have been proposed as well. For example, AutoDesk’s Architectural Desktop software allows walls, and other project objects to be drawn in 2D, while retaining knowledge of their behavior and representation in 3D. This approach works satisfactorily for conventional, Euclidean project geometry, but is ill suited to Gehry’s geometry, where the 3D behavior of building geometry can not easily be predicted from simple two dimensional views. The firm’s strategy has been to find ways to easily embed necessary project information in 3D representations, then draw on more powerful geometric and symbolic extraction mechanisms to produce 2D representations.

Recent enhancements in the CATIA modeling platform promise to streamline this process. The software allows parametric definitions of geometric drawing extractions to be defined in a persistent manner. Section cuts can be defined in the 3D model space. When project geometry is modified, drawing extraction is achieved through a simple (though slow in terms of computer time) update request. These improvements have allowed an approximately 90% increase in operator efficiency for generating backgrounds for two dimensional documentation from the 3D model. Opportunities for automated extraction to 2D of annotation from non geometric attributes defined on 3D objects are also being pursued. Figure III-9 provides views of this drawing extraction process. These developments promise an eventual integration of two- and three- dimensional information into a single, comprehensive project database.
Figure III-9: Drawing extraction from the CATIA master model (MOT)
Once these two dimensional extractions and annotations have been developed, it is of great benefit to be able to integrate this data back into the master project geometry, to allow review and coordination. This is easily achieved by importing the 2D CAD documents into the 3D environment, then moving and rotating the geometry back into alignment with the plane of the original cut. CATIA now allows AutoCAD files – exported through IGES format – to be permanently fixed to a location and orientation in space. Changes in the 2D drawing are thus automatically updated in the master model. Figure III-10 shows this overlaid 2D geometry – including projections of the geometry below – oriented with the project master model, which in turn has been cut at the level of the 2D drawing.

Many other applications of two dimensional extractions need to be supported in addition to the comprehensive documentation required for architectural documentation. The generation of shop drawings for certain systems can require numerous two dimensional extractions. For
example, concrete detailing requires many simple plan and section cuts of small areas of the project for detailed layout of re-bar. The utility of simple sketch drawings is preferable to the detailed generation of 3 dimensional layouts in this case. These simple cuts are easily achieved by planar intersections with the project geometry. Usually, these operations are performed either by the fabricator or by the general contractor as a service to the fabricator.

**E. THE PHYSICAL / DIGITAL INTERFACE**

The role of physical objects in Gehry’s design process has had a profound role in the development of the firm’s digital process. In any architectural or product design process, this relationship exists, since the products of the process are ultimately physical objects. Other firms do on occasion generate presentation models using CAD / CAM prototyping. The unique aspects of the physical / digital interaction in Gehry’s process stem from the authority bestowed on physical objects and processes of making. Physical models are the primary elements of the process where the project design is developed. These physical objects define and embody the formal design intent as it is developed over the course of the project. Digital representations serve to capture this intent and allow for its processing and communication.

On more conventional project geometry, this division between physical and digital representation might not be so problematic. There are perfectly adequate ways of digitally and physically modeling orthogonally configured planar objects, and great geometric affinity between these digital and physical forms. Digitizing such conventional geometries is straightforward. A few dimensions can be measured, and then orthogonal planes can be positioned in digital space and intersected to form boundaries of surfaces. It is even arguable that the digital representation of such assemblies is a “better” representation of the design intent. Physical modeling necessarily introduces fabrication errors relative to pure Euclidean geometry. Materials warp, elements are cut too short or too long, edges are not perfectly straight, corners are not completely tight. While these imperfections might be imperceptible on well constructed scale models, when fully scaled these imperfections would likely be outside of construction tolerances. A gap at a corner of $\frac{1}{32}$” on an $\frac{1}{8}$” scale model represents a 3” hole at the corner of the construction! CAD modeling allows these imperfections to be cleaned up to within machine tolerances, well below the tolerances of construction. It is thus arguable that, if the design intent of a project is concerned with Euclidean geometry, digital
modeling can provide a more exact representation for the description of this intent than any scale physical representation. 3D CAD can even be a more efficient interface for generating this geometry, as the digital tools for performing cutting, positioning, moving, and editing of planar geometries can be easier than corresponding operations on physical modeling materials.

Gehry’s process introduces a number of problematic issues into this clean relationship between physical and digital representations. Gehry’s design models also contain imperfections of construction. However, unlike Euclidean geometries, established reference formalisms that serve to define the “true” geometry behind the shape do not necessarily exist. The geometry of the physical model provides the only definitive reference of design intent that digital representations must strive to emulate.

Highly accurate digitizing technologies exist that can sample points in tight conformance with physical objects. However, these representations still need to be cleaned up, to remove imperfections in the physical object and to simplify digital geometry to a form that can be manipulated. These operations introduce artifacts of the geometric representation underlying the CAD system – representational constructs whose characteristics may be radically different than those of the modeling materials. Distinctions between features of the physical object that are desired and those that are model imperfections or noise are qualitative, and must be undertaken through the filter of the CAD system’s geometric representation.

A closely related issue emerges in comparing the “user interfaces” afforded by physical and digital modeling operations. Physical materials afford the development of certain forms, guided by the behavior of materials and operations that are facilitated by these materials. In the development of non-Euclidean geometries, these behaviors can be subtle and complex, as materials are driven to deformation at the limits of their material behavior. These effects generate formal qualities in the physical models important to the designers. The natural and intuitive operations of designers operating on these physical objects can be difficult to even approximately reproduce in digital form. As a result, either digital operations can result in subtly but critically different geometries, or the development of shapes with similar qualities can take substantial skill, time and attention by operators.
In Gehry’s architecture, the physical models do not simply represent the geometry of the project. Modeling materials and operations on these materials have a certain representational relationship to qualities of the full scale materials and fabrication processes. Digital modeling substitutes mathematically founded constructs for physically based processes. In the process of taking a form from physical model to physical construction through the filter of digital representation, elements of the physical correspondence that binds model making to fabrication can be lost. The development of digital constructs that emulate and can retain these important physical qualities are a core part of the firm’s computing research, and are explored in depth for specific materials and associated processes in the latter parts of this thesis.

Despite the complexity of these issues, relatively simple technology is at the heart of the firms’ digitizing process. The firm has relied on a FARO digitizing arm for the past eight years. This device allows points to be individually selected by the operator from the model. Segmented polylines can be generated by stringing sequences of these sampled points together. The arm is calibrated for each digitizing session so that samples from physical models can be registered with existing digital representations in “full scale” digital space. Many more elaborate digitizing technologies have been assessed over the years, such as cloud of points digitizing capabilities used by the automotive and animation industries. These technologies have until now been rejected due to practical
limitations, including cost, speed, visual occlusion issues and problems with the capturing of specific materials used in the firms’ physical models.

The geometry sampled from the physical models is relatively sparse (Figure III-11A). This geometry captures critical features of the form to be observed in the digital reconstruction of the geometry, rather than a comprehensive sampling of the physical form. Critical features of the geometry vary depending on the material of the physical model. The edges between intersecting surfaces are often the most important manifestations of the designers’ formal intentions. These edges include both those representing breaks in the surface form between surfaces of the model (shown in red in Figure III-11A), as well as the pattern of edges between sheets forming a single surface shape. Intermediate curves representing the flow of surfaces inside their boundaries are also captured to serve as guides for surface modeling efforts. On surfaces constructed from paper and other sheet materials, straight lines of ruling can be approximated from the surface material, shown in green in Figure III-11A. The geometric existence and implications of these features are discussed at length in Section VI.B below.

On the basis of these digitized features, a CAD surface model is developed using conventional NURBS modeling techniques (Figure III-11B). The result of this digitizing and re-construction process represents a “sketch” of the project geometry. It is far from a final representation, but rather serves as a background to the rest of the modeling process, providing the medium for production activities that resolve the shape into constructible form. Basic geometric operations such as closure of the surface into a “water tight” configuration can only be performed in the idealized geometric environment afforded by computer modeling.

The completed sketch model still represents a rudimentary representation of the building. It mirrors the level of detail of the physical sketch models, and may represent only the exterior envelope of the building. This digital sketch model will be in acceptable dimensional conformance with the physical model, such that preliminary architectural development exercises may be conducted relative to this digital artifact.

Verification models will be constructed from the CAD model so that designers can confirm that digital project representation does not deviate significantly from the form of the physical
models. Typically, “low tech” prototyping techniques are used by the firm to produce these models. In early versions of the process, “pancake models” were the preferred method for generating confirmation models. These models are made from layers of foam core, manually cut from the digital surface model. Planar intersections of the geometry generate profiles for these layers. The layers are manually cut from foam core, then re-assembled and glued together, and finally sanded and finished. These solid representations of the surface form can be physically modified by cutting into the foam core or layering on additional material. These modifications are then re-digitized, and the digital surfaces modified to reflect the changes.

As the process has developed and more intensive modeling operations are conducted earlier in design, more detailed and accurate verification model generation processes have become the norm. Frequently, verification models are now developed from intersecting sections of the surface geometry, organized as a “jig saw” puzzle of parts representing orthogonal sections though the surface geometry. These parts are developed in 3D as sections through the exterior and interior surfaces of the project geometry. Cut outs are inserted to allow elements to be connected together at their intersections. These parts are then flattened into 2D and cut out using flat bed laser cutting. The parts are re-assembled into a spatial framework, then covered with modeling materials (Figure III-11C). This process both allows a tighter conformance to the project geometry than the pancake method, and provides a model supporting the definition of both exterior and interior surfaces.

Occasionally, more elaborate technologies are drawn on, both for digitizing and prototyping. Layered object manufacturing (LOM, Figure IV-5), stereo lithography and material deposition (Figure III-17) techniques have been used on various projects. However, these techniques have important implications on the qualities of the resulting models, both in the forms produced and the modeling materials compatible with these techniques. Although these techniques result in models that are highly accurate dimensional representations of the digital models, they remove aspects of fabrication process from the model generation process, and rely on materials that may not retain qualities of either the generating physical models or the final fabrication methods. These prototyping techniques have typically been reserved for project elements whose ultimate fabrication materials are either molded materials such as concrete, or relatively free form fabric materials such as fiberglass or other composites.
More elaborate digitizing techniques have been attempted when the physical model would prohibit use of the firm’s feature digitizing and reconstruction process. CAT scanning of physical models was used on the flower sculpture on the DCH project, where the form and complexity of the physical model would have prohibited feature sampling using a digitizing arm (Figure III-12).

Figure III-12: CAT scan and reconstruction of a complicated physical model (DCH)
The digital project models are developed in parallel with physical design modeling. At the end of design development, there exists a master physical model of the project and a corresponding digital model that are the in tight dimensional correspondence and together represent the master project geometric representations. The digital model is then carried forward through to construction. If there are changes to the geometry required to address construction issues, these changes will be made to both the physical and digital master models.

As the design progresses in its definition of constructibility intentions, the relationships between physical and digital elements take on new forms. The integration becomes less concerned with the capabilities of digital representation to capture form, and rather to come to an understanding of issues of constructibility. Gehry projects often adopt fabrication systems that have no exact precedent, and apply these systems to forms for which the full impact of geometry on fabrication can not easily be anticipated. Often building performance codes and analytical methods have been developed with the assumption of more conventional geometric conditions. Physical mockups of building systems provide valuable information for their development.
Schematic level studies of potential construction systems are conducted in both physical and digital form early in the design process. The level of detail of early systems exploration is intentionally limited. These studies may serve to test the feasibility of a system strategy, and provide a vehicle for communication with partnering organizations. Figure III-14 shows examples of schematic physical and digital structural studies.

Larger scale physical mockups may be constructed of portions of the project geometry, and clad using potential materials of the final construction. These early mockups identify qualities of construction materials that may impact the aesthetic qualities of the project. During early design development, these mockups are constructed by the firm’s internal modeling resources, and the actual correspondence to the final systems – in terms of fabrication or assembly components – is limited. Rather, the mock-ups at this point are utilized to explore the qualities of potential construction materials, and to expose some of the relationships between fabrication methodologies and the qualities of the shapes that are being considered. The full system detailing may not be employed; these mockups serve simply to test whether the assumptions about the relationship between project geometry and finish material qualities are valid. One main consideration to be tested is whether the finish system can actually assume the form specified in the digital model without warping, cracking or localized distortion around fasteners.

Later mockups become more elaborate. Fully detailed digital studies are conducted of small portions of the project, to fully test system detailing strategies in the CAD environment. These studies are conducted on selected portions of the project deemed representative of typical geometric conditions. These digital mockups are developed to a level of detail where
the organization of components – and special cases that may result from the deployment of a selected building system – can be understood. Issues identified in these selected portions of the facility will be extrapolated to the rest of the project. The level of detail undertaken will be up to that which would suggest that full completion of shop drawings could be undertaken. Figure III-15 shows design development phase digital mockups of several approaches to the construction of the “Kiva” element of the MIT Stata Center project. This element was considered to represent the geometry and construction of several areas of the project.

Ultimately, full scale performance mockups may be constructed to allow full engineering testing of proposed building systems. These mockups test the full digital – physical construction process of the design and construction teams, including hand offs of geometric information. These mockups are typically developed for cladding systems to allow full engineering testing. Tests may include structural and wind loading performance, water penetration, and response to frame racking that might occur as a result of seismic events. Figure III-16 shows an example from the Disney Concert Hall project, in which a performance mockup was developed using the actual geometry of a small corner of the project from the project master model. This geometry served as the basis for developing a mockup comprising three major cladding systems: the typical cladding system, skylights and vertical glazing. The mockup was subjected to testing under simulated wind and rain conditions, in initial state as well as after frame racking was imposed.
A. Digital shop drawing of mockup
B. Typical cladding system

D. Testing under simulated wind and rain conditions
C. Glazing system and knife edge, skylight beyond

Figure III-16: Performance mockup of DCH cladding systems
F. RATIONALIZATION

The concept of rationalization is at the heart of Gehry Partner’s computing and construction methodologies. Broadly stated, rationalization is *the resolution of rules of constructibility into project geometry*. The concept encompasses broad applications in the firm’s process. Many of these applications can have substantial impact on the formal qualities and design intent of the project architecture. Others can have dramatic effects on the cost and control of construction, and hence can determine the feasibility of building strategies.

This issue of problem description through mathematics and geometry, and the fitness of a mathematical / geometric model to a given solution approach is of course nothing new in engineering and physics applications. In Gehry’s building process, geometric representation and its role in providing the syntax for describing the project design intent, and supporting its translation into constructibility and building intentions deserves some inspection.

Mitchell makes reference to the role of rationalization on constructibility decisions in his comparison of the Sydney Opera House and Guggenheim Bilbao projects. The Sydney Opera House (1957-73) designed and constructed just before the advent of digital geometric modeling, required the designed form to be rationalized into spherical elements simply to be describable using contemporary drafting and engineering methods. With the advent of digital curved surface modeling, these limitations on designer’s descriptive capabilities seem to have largely been addressed. However, experience by the firm indicates issues of project description and geometric constraints are still very much in play.

Simply the operation of rendering a physical shape into digital form implies a structuring through the geometric representations of the CAD application. A broad palette geometric forms with various characteristics – one, two or three dimensional, Euclidean or other differentiable forms – are available to serve as representational bases for the surface geometry or any other element of the building. Selection of a set of geometric elements as a basis for the digital representation in itself imbues the digital description with certain characteristics. In the process of rendering the project design surface into digital form, variations between the shapes produced by physical modeling and that produced through digitizing occur. This is not so much due to any specific, substantial deviation in the sampling of geometry, but rather more subtly due to the qualities of the smoothing functions embodied
in NURBS representations, relative to that provided by physical materials. NURBS modeling tends to produce a more uniformly varying surface smoothness. Localized variations of the surface form generated through the forming of physical materials are lost in the process. Slight imperfections of the model geometry need to be “fixed” in order to close the project surface into a tight form. Loss of these nuances of form is apparent to the project designers, and the control of form as it passes between physical and digital representations is of substantial concern in design phase. While certainly digital modeling represents a vast improvement over traditional drafting methods in capturing non-Euclidean design forms, qualities of these digital geometric representations still have an impact on the description of forms.

The impact of geometric representation on project form is more apparent when representational constructs associated with fabrication are considered. The notion of congruence between a geometric representational form and the requirements of a system may seem unfamiliar on the basis of “conventional” construction. However, such decisions are made, even if standard conventions of project documentation make these decisions seem implicit. In conventional framing, a stud seems to be naturally described by one form: that of a line or linear extrusion. However, different views of the project (plans, sections, details) are based on other geometric constructs. Within these disparate representations, even a simple object such as a stud might assume a variety of geometric forms.

In the documentation of Gehry’s forms, the issues involved in selecting geometric representations for project elements is more readily apparent. Numerous mathematical forms are available for representing curved objects in space. Each of these approaches introduces a de facto set of constraints on the shapes that can be represented. The activity of selecting a digital representation for spatial system components – in congruence with the physical constraints on the fabrication of these components – is a core aspect of the rationalization process.
One motivation for rationalization efforts is ultimately project cost, reflected in the unit costs of available fabrication and construction systems. Fabrication efficiencies can pose substantial constraints on project geometry. Building systems come with rules or constraints that have direct bearing on the qualities of forms that can be accommodated. Low cost systems may highly constrain the forms that can be produced. Many contemporary fabrication processes rely on equipment geared toward the generation of Euclidean shapes: straight line break cutting and sawing, bending of extrusions to arc shapes on spindles. Alternatively, construction methodologies with great degrees of flexibility can represent prohibitive unit costs. Where competitive CNC enabled processes offering support of fully curved geometries exist, these processes often imply fabrication costs that would overwhelm reasonable construction budgets. Engineering and performance criteria can impose constraints on eccentricities in geometric positioning even if curved geometries can be fabricated.

In Gehry’s work, new construction systems are frequently developed to support specific project forms. However, these systems will necessarily bring formal and organizational requirements that can require some modification of the project forms. The project design development and associated systems engineering strategies must be able to accommodate these requirements individually, and negotiate between the geometric impacts of differing systems’ requirements as they interact. Computer modeling is the principal medium through which this geometric rationalization occurs. Digital project descriptions are the design artifacts in which detailed dimensional descriptions occur, where heuristics regarding the behavior of the design geometry can be made, where geometric rules organizing project elements can be represented, and where tools exist to perform operations that can bring project elements into conformance with these rules.

The identification of appropriate geometric constructs for a given system is fundamental to the development and deployment of building systems that support complex geometry. At best, if there is a tight conformance between the construction constraints of the system and the constraints of the geometric construct, simply generating shapes with this geometric construct guarantees constructibility of the shapes. Computational tools may be developed to support a rapid and intuitive generation of shapes based on the selected geometric form. The underlying logic presented by the geometric form – and its synergy with that of the construction system - may be drawn on to support automation of descriptive activities.
Consideration of these geometric and system decisions is ideally begun early in design, while the initial gestures of the project are still being developed. These rules, representing both formal and practical qualities of proposed systems, are developed in collaboration with engineers and fabricators. The development of system rules and operations occurs along a similar timeline to that of the project form. Initially, only general notions of the selected systems and their associated constraints may be understood. This initial understanding may influence the selection of materials to be used during physical model explorations. The design’s formal and system decisions are refined together as the project develops. A tighter level of understanding of the qualities of the design form the basis of more detailed system strategies, which in turn present more specific rules for the spatial organization of the project.

A simple example serves to illustrate the point. Many building systems used on Gehry’s projects involve components whose shapes are curves generated from planar intersections with the design surface or offsets of this surface. This curve will derive the structuring of its geometric description from the intersected surface, typically a NURBS curve from a NURBS surface (Section V.D.3). This curve is smoothly and continuously varying in shape and curvature.

For much of the project, the element may remain represented in the master model in this original geometric description as a simple planar curve in space, even as details of its performance, materials and fabrication are being defined. The structural frame may be carried in the master model through to construction documents simply as a wireframe. During shop drawing production and fabrication, the geometry of the elements’ descriptions will likely need to be refined. Economies of fabrication may dictate that performance criteria for the system can be satisfied most economically through systems which impose some constraints on the geometry of elements, relative to ideal curve generated from the model geometry.

Often, these smooth planar curves are ultimately rationalized into sequences of Euclidean sub-elements, either straight lines, constant curvature arc segments, or some combination of the two. Rationalization of curves into line segments is straightforward (Figure III-21B). A set of points on the curve is selected through some criteria; these points are joined together by line segments. This simple segmentation has obvious correlations to fabrication applications.
(Figure III-18), and fairly obvious impacts on the tolerance of the resulting system relative to the ideal geometry expressed by the input curve. Segmented members can be constructed out of extruded profiles, including I beams or custom channels. The selection of segmentation points can be dictated by a number of criteria, including connection relations to other project geometry, maximum or minimum efficient material lengths, angle criteria, maximum distance deviation from the ideal curve, etc. These fabrication efficiencies can be expressed as geometric rules and encoded in the segmentation strategy. Numerous systems on Gehry projects have employed this geometric rationalization strategy, driven by widely different fabrication criteria and corresponding geometric rules.

There are several limitations of a straight line segmentation approach from the perspective of constructibility. Segmentation produces angles between segments; which will cause kinks in the system that may disadvantageously affect the architectural form. The resulting angles may need to be resolved through complicated beveled connections. The deviation between the ideal curve and the linear segments can result in conflicts with other systems. Of course, the deviation can be controlled by increasing the number of segments, but this will also increase the number of parts and connections, which can drive up the cost of fabrication.

A second approach, used on several projects, rationalizes planar curves into sequences of arc segments, with tangency constraints imposed between the segments (Figure III-19). This can ameliorate some of the limitations of the linear segmentation strategy above. The connections between elements will be smooth, so no kinking of the system or the resulting connections results. The relationship between number of segments and deviation from the design curve is improved. Of course, bending material into an arc is likely to be more
expensive than leaving it straight, but the in reduction of the number of connections, and the resolution of connection geometry into straight connections can more than justify the expense of curving material.

Figure III-21C illustrates the geometry of this rationalization approach. Two points on the design curve – and the corresponding tangents to the curve at the points – are provided as input to the rationalization. These input location + tangent vector pairs can be joined through a biarc – two arcs joined in tangency. In fact, a given input point / tangent pair generates a one parameter family of biarcs. Within this family of biarcs, the arc pair closest to the input curve can be determined by optimization. If the deviation between this optimal biarc and the input curve is outside of the desired tolerance for the system, the approach can be recursively applied by selecting a point somewhere in the middle of the design curve. The biarc solution can be applied to each of these ranges, resulting in a total of four arc segments (Figure III-21D). The process can be repeated recursively until a satisfactory solution is achieved.

In pipe bending, fabrication requirements have sometimes suggested including a straight line connection of pre-determined length between adjoining arcs (Figure III-21E). The reason for this is that the bending equipment can not bend the material all the way to its ends; a "grip" section is required at the termination of the pipe bend. The rationalization strategy can be amended to accommodate this requirement by first casting a biarc over the curve as described above, then “backing off” the curve along lines of tangency at the ends and the biarc connection the required distance from both ends, and finally constructing arc segments from these new points.

Figure III-21F shows this approach on a study of the Weatherhead pipe system. The recursive biarc optimization algorithm, along with minimal straight line joining segments, was developed into a custom geometric modeling program. The program includes automation of dimensioning on arcs and straight segments of interest to the pipe bending fabricator.
A. Input planar curve
B. Linearized rationalization
C. Biarc rationalization
D. Recursive biarc rationalization
E. Biarcs with linear connections
F. Automated rationalization results

Figure III-21: Rationalization methods for planar curves
This example presents a quite simple application of rationalization methods to the fairly simple geometry of planar curves. Even in this context, it is apparent that differences in the designs of building systems can profoundly affect the strategy of geometric representation. The rationalization algorithms described above are substantially deterministic. Given a planar curve, a geometry rationalization algorithm embodying constructibility rules can be identified through which successful solution can usually be guaranteed.

Rationalization considerations can become substantially more complex when system organizations move “off the plane” to full three dimensional spatial organizations. Additional degrees of freedom imposed on problems of geometric elements in 3D space can quickly render such deterministic solution strategies unachievable, or at least introduce geometries with more complicated fabrication requirements. This is illustrated in the development of global structural strategies on Gehry projects. A variety of primary structural systems have been employed; we compare two relatively typical approaches on the Experience Music Project and the Walt Disney Concert Hall, both projects with a primary structural strategy developed around a steel frame (Figure III-22).

A basic difference can be detected in the geometry of the structural scheme employed on these two projects – a distinction that represents an extension of the rationalization operations discussed in the above example. DCH represents a more “conventional” braced steel frame constructed from straight stick steel extrusions. These extruded members are formed from conventional AISC steel sections$^1$ – predominately I beam and column sections.

AISC section steel is mass produced by commercial steel mills, and represent a quite economical “raw material” for construction. However, in order to approximate the curved surface geometry of the DCH surface, the structural frame presents a “tessellation” of the curved surface geometry. A relatively tightly framed grid of columns and beams – approximately 10’ on center – was required to accommodate the curved surface geometry to tight enough tolerances. This relatively fine grain tessellation of the frame geometry results in a relatively large number of connections between primary structural elements.
A. Frame geometry in the master model

B. Geometry of on site construction

Figure III-22: Comparison of DCH and EMP structural schemes
More importantly, the geometry of these connections is relatively complicated. Members do not frame together orthogonally, requiring difficult end bevels and complicated plate and clip assemblies (Figure III-23). The number and complexity of member connections has made the steel frame on DCH a difficult and expensive detailing job, offsetting the benefits of using straight, stock section members.

The frame design of the Experience Music Project takes a radically different approach. The structural strategy results from plate built ribs, essentially curved I beams built up from custom cut plate elements. The frame is initially laid out as intersections between the design surface and a pattern of parallel, vertically oriented planes, spaced 10’ on center. The resulting planar curves are offset inward 24” from the finish surface to accommodate the curtain wall system (described in detail in Section IX.A below). Finite element modeling by the engineer (Skilling, Ward, Magnussun, and Barkshire) determined the necessary stiffness for each rib. On the basis of these performance criteria, the depth of the I-beam profile was determined for each rib. These depths were reflected in the CAD model of the system by simply offsetting the external curve of the rib the calculated distance.

In some highly curved areas of the structure, exactly following the planar intersection curve of the surface form would have imposed excessively tight curvatures in the rib profile. These curved regions would have disrupted the load path through the curve, producing excessive bending forces. In these highly shaped areas, the rib geometry was rationalized further, bringing the rib geometry away from the surface. The deviation between the surface and the rib was accommodated through additional secondary steel.
In the EMP system, a fully curved edge representation was retained through to fabrication. The curves were brought into AutoCAD, re-oriented, and flattened in 2D for shop drawing detailing. Curves defining the boundary of each rib’s web were created, then sent to plasma cutting equipment (Figure III-24A). In a second step (Figure III-24B), the edge curves were passed to a custom built CNC plate rolling machine, which rolled plate steel for the top and bottom flanges of the ribs into shape.

Rationalization operations can be required simply as a consequence of the collaborative computational process. Translations from the NURBS surface based CATIA environment to other trade specific software applications can necessitate rationalization of the form described, just to achieve continuity of process. Currently, few of the steel analysis and detailing applications available accept curved elements. Finite element structural analysis programs still typically require linear elements for solution. While rationalized FEA models are not usually transferred directly to fabrication modeling, these linearized formats have
become the standard translation format for most steel translation. New additions to standards such as SDNF allow the translation of elements comprised of constant curvature arc segments (Figure III-19). This enhancement of translation format still dictates rationalization of curved geometry into arc segments.

It should not be surprising that the toughest rationalization problems on Gehry’s projects often derive from the fabrication of the surface envelope itself. The qualities of materials, and potential efficiencies in fabricating enclosure systems guided by material properties again present a wide range of geometric constructs, and constraints on the geometry and architectural intent determined by these constructs. The rationalization of surface forms adds another level of complexity to the digital process. Considerable attention will be paid to the geometric constructs underlying these systems’ development in latter parts of this thesis. Figure III-25 provides a cursory introduction to the topic, in the geometric variation of curved glass fabrication systems.

G. MODEL INTELLIGENCE, AUTOMATION, AND PARAMETRICS

Substantial operator effort is involved in developing detailed system geometry in 3D CAD form. Since the geometry of each system element is often unique on Gehry projects, substantial repetitive geometric operations are required to instantiate the description of system elements. This level of effort, coupled with the cost of relatively high priced CAD operator labor, can have a significant impact on design and detailing costs. Furthermore, the project geometry is often in flux well into design development. The product of modeling effort invested early in the process can need to be reworked as changes to project geometry occur. On the other hand, building system development often requires studies of system geometry
to be conducted to some level of detail early in design, to ensure that system strategies address varying local geometric conditions. These issues of modeling effort have been addressed in the firm’s process in several ways. Earlier in the development of the firm’s digital process, virtually all CAD modeling was deferred until late in the design process, when the project designers had “closed” or finalized the building form. Prior to that point, only digital sketch models – rough surface models corresponding to the basic form of the physical models – were developed, usually only to provide geometry for cut extraction associated with specific document packages.

A general decline in the cost of computer modeling hardware, software and labor has allowed greater application of digital modeling earlier in the design process. However, issues of labor associated with large scale instantiation of system component definitions persist. The costs associated with this effort are partly addressed by limiting the level of detail of component geometric representations, and by performing detailed system studies or “digital mockups” on only small portions of the project geometry.

The dual goals of increasing efficiency of 3D digital documentation efforts, and supporting re-use of this information as variations in the building form occur, have been topics of research and development efforts by the firm and its partners. Much of this work as been centered around the development of procedural CAD modeling scripts to automate repetitive geometry generation tasks. Often a simple geometric operation requires several intermediate constructions to produce the required geometry. These operations are typically performed relative to some existing geometry of the model. Scripting of these tasks can reduce the time required to generate geometric descriptions of building components. For example, commercially available steel detailing packages such as X-Steel and SDS-2 provide macros for the generation of categories of steel connections. These macros perform cut backs, fillets, bolt holes, and other difficult geometric operations on steel members in 3D form, in addition to placing plates, clip angles and other connection components. Unfortunately, these applications have often been shown to make orthogonality and other geometric assumptions that do not necessarily hold on Gehry project geometry. These macros have required re-coding to support the geometric conditions in the firm’s projects.

Sophisticated fabricators have developed their own programs to support the automation of repetitive geometric tasks during shop drawing generation. One example, A. Zahner
Company’s Automated Panel Layout Application (ZAPLA), is described in Section IX.A below.

While these examples of procedural or scripted automation provide an element of modeling efficiency, they can not address requirements for updating information in response to changes in project geometry. The geometric scripts and any associated manual interactions must be re-applied on any modified input geometry. Toward the goal of addressing this limitation of scripted approaches to automation, the firm has recently begun intensive efforts to incorporate parametric technology into its digital process.

Parametric technology allows relationships among geometric elements to be encoded in the model as part of operations on these elements. For example, when a curve is generated as the intersection of a surface and a plane in space, the nature of this curve as a geometric relationship between the surface and plane is retained in its digital description. Changes to the input geometry – by modifying the surface or moving the plane - will flag an update and regeneration of the curve. Variables may be included in the descriptions of geometries; changes to the values of these variables can also be used to trigger updates of geometry.

Parametric modeling capabilities have existed in commercial applications for more than a decade. The technology has been the focus of architectural computing research in describing design typologies. However, until recently, these applications were unmanageably slow for large scale geometric models. Furthermore, the user interface requirements for generating geometric associations between elements were unwieldy. The mathematical models underlying curved object representations add substantial computational requirements to the geometric description of objects, further slowing the updating of models.

Parametric technology has had substantial application in mechanical design applications, where changes to product definitions can be limited to dimensional variations of the product. Marc Burry’s efforts to develop parametrically based models of elements on the Sagrada Familia construction project over the last ten years provide a notable example of the application of parametrics in an architectural setting.

Recent improvements in the user interfaces to parametric modeling applications, and the inexorable advances in computational power, seem to have finally brought applications of
fully parametric modeling within the horizon of building construction applications. A pilot project to develop a fully parametric master model for the Museum of Tolerance (MOT) project was begun in January 2002, using Dassault Systèmes' most recent release of the CATIA product, Version 5. This initiative has produced promising results, although not without difficulties. One example from the project illustrates the potential of parametric approaches to constructibility issues.

Gehry Partners is currently collaborating with the engineering office of Schlaich Bergermann and Partner on the development of a free glass roof covering the atria of the Museum of Tolerance project. Several Gehry projects have included large curved surface elements comprised of triangular facets, including the DG Bank Headquarters skylight, a previous collaboration between the firms (Figure IV-2), and the entry façade of the Guggenheim Bilbao museum (Figure III-25).

A curved surface can be rationalized into an assembly of triangular facets with little difficulty. However, prior experience with large glazed roof structures by the engineer (Figure III-26) has suggested great economic advantage to constructing these structures from compositions of rectangular, as opposed to triangular, glazing elements. This requirement, while beneficial from a cost standpoint, imposes a substantial constraint on forms that can be constructed. While any surface can be tessellated into a closed composition of triangular faces, the surfaces that can be covered with a quadrilateral tessellation are highly constrained to configurations whose characteristics are not immediately obvious.

Independent study of the problem by both firms has identified the class of translation surfaces\(^\text{18}\), which adhere to the geometric constraints necessary to allow quadrilateral tessellation. These are surfaces generated by a curve (the \emph{generatrix} curve), swept in space without rotation along the path of a second curve (the \emph{directrix}). It can be demonstrated that points, invariantly positioned along the resulting family of curves, can be joined by facets that
are necessarily both quadrilateral and flat. Figure III-27 shows elements of this construction. The vectors \( \mathbf{A} \) (equivalently \( \mathbf{B} \)) can be shown to be uniformly parallel, guaranteeing that a face lofted between any successive pair of these vectors is necessarily planar. This class of translation surfaces can be further extended by allowing the generatrix curve to be scaled as it is translated along the directrix. While certainly not all forms can be generated as translation surfaces, there is considerable freedom to the set of surfaces that can be described or closely approximated by a surface of this construction.

The translation surface construction solves the problem of defining surfaces that can be approximated with quadrilateral tessellations. However, the generation of these surfaces requires a number of intermediate geometric constructions. Using conventional CAD approaches, the geometry must be re-constructed each time the generating curves are modified. This presents a substantial impediment to the interactive design of translation surfaces.

Parametric technologies allow these geometric operations to be encapsulated into a persistent, “intelligent” translation surface object that retains the structuring of its geometric construction. The inputs to, or handles on, this object are the generatrix and directrix curves, and a third curve that establishes the scaling of the generatrix as it is translated along the directrix. This dramatically simplifies the construction and modification of the surfaces, while still guaranteeing adherence to the constructibility constraints. Figure III-28 shows elements of this parametric construction, results of editing the surface by manipulating the input curves, and the resulting planar quadrilateral composition. It is anticipated that many of the firm’s constructibility problems can be attacked through similar definitions of parametric objects, which encapsulate the intelligence necessary to solve the given problem.
A. Controls and curve array

B. Clipping surface

C. Modification of generatrix curve

D. Modification of directrix curve

E. Modification of scaling law

F. Resulting quadrilateral glazing assembly

Figure III-28: Parametric modeling of MOT roof system.
More limited applications of associating intelligence with project geometry have been employed by the firm for some time. Various mechanisms exist for associating non-geometric or “semantic” information with geometry. Layering and coloring constructs ubiquitous in CAD applications provide a trivial example of such capabilities. The establishment of project layering and coloring standards is a simple but important element of the master model definition. These standards are included in the project specifications and annotated in schedules on the two dimensional project documents. Maintenance of this attribute information during translation between the various CAD applications on the project is an important and not necessarily trivial aspect of the firm’s computational process development in general, and an element of the collaborative computational process developed with any new project partner.

One limitation of layering schemes for supporting model semantic information is that layer information represents only one “axis” or field for such information. There are many non-geometric aspects of elements’ definition on a project that may be of interest, and that should be included in the project description along side geometry. These attributes may exist in many permutations. For example, on the Disney Concert Hall (Figure III-22B), attributes tracked in the structural steel wireframe model included primary vs. secondary steel, cardinal point (top of steel, center, etc.), steel grade, finish (galvanized, architectural finish quality), curved vs. straight elements, and provisional vs. released for construction. Each valid permutation of these attributes had to be tracked as a unique layer. While this scheme worked on this limited application, the strategy is not scalable as the number of systems and associated attributes in the master model are increased.

During the past three years, more advanced mechanisms for tracking of attributes have been attempted. CATIA V4 provides capabilities for developing attribute schema, named variables with defined values associated to the variable. The variables can be instantiated on any geometric object in the project master model. Queries can be run to identify elements of the project geometry with selected attribute combinations (Figure III-29A, B).

Similar capabilities provide support for associating attributes of structural steel elements with geometry. Attributes such as section profile, cardinal point, and material properties may be tied to a parametric description of structural elements’ position in space (Figure III-29C, D).
These developments promise to eventually achieve the firm’s vision for an intelligent, fully integrated digital database of all project information. To date, this integration has been achieved by a mix of automated integration with substantial amounts of operator effort and project manager diligence. The scale and variety of information to be tracked on a project through its development presents an enormous computational task. Project information is not completely coherent until well into design development or construction documentation phases. Often, known conflicts or omissions of design information are carried in the project until the information necessary for resolution of these gaps in the information are available. Project designers can accommodate an ambiguity of information that might be difficult for an integrated database to process. Nonetheless, the firm’s digital process and technologies offer elements of what can be imaged to be the future of digitally integrated project information.

Figure III-29: Attributes on enclosure system model (MIT), structural frame model (DCH)