Applications of CAD/CAM Technology to

Avant-Garde Structural Engineering

By

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ABSTRACT

Over the last decade improvements in design technology has taken grand steps in changing the way we build the structures of tomorrow. Conventional drafting software like AutoCAD and Microstation are being challenged by tools that go beyond the two dimensional representational abilities of paper documentation and replacing it with complex three dimensional virtual construction files that are more comprehensible and offer more flexibility with respect to design and also in terms of inter-professional communication. My interest's lie in the new dialectic emerging between architects and fabricators, who ironically sit at opposite ends of the construction spectrum yet are now collaborating with the help of modern-day software. I envision these new tools as being pivotal in both reassigning the roles of design and creating a more seamless construction process. It is this modified construction process that I intend to explore through this thesis.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

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TABLE OF CONTENTS

LISTS OF FIGURES

LISTS OF TABLES

LISTS OF ACRONYMS

2-D	Two Dimensional
3-D	Three Dimensional
AutoCAD	Automated Computer Aided Drawing
CAD/CAM	Computer Aided Drawing/Computer Aided Manufacturing
CATIA	Computer Aided Three Dimensional Integrated Application
FPs	Foster and Partners
GPs	Gehry Partners
GTs	Gehry Technologies
SAP2000	Structural Analysis Program 2000

1. INTRODUCTION

The advent of computer-aided drafting and manufacturing (CAD/CAM) has opened the door to a multitude of possibilities across the entire construction industry. Interactive design software has revolutionized the way we design things … it means that engineering has become more of an art, architecture more of a science, and all design more intuitive. (Wise 2000) Definitely a bold statement to make, still it is obvious that a lofty progressive step has been taken with regards to the overall shape and forms of contemporary avant-garde buildings. Architects tend to draw what they can build, and build what they can draw. New technology is taking this a step further and as result radical curves and free-flowing surfaces are beginning to trace abstract silhouettes across our 21st century skylines, figure 1. Further, not only what we design is radically changing but also how we conceptually design is being equally adjusted. Architects can request more elaborate product definitions that imply higher qualitative measures. These requests can then be clearly translated to fabricators who specialize in product specification. CAD/CAM technology allows the architect's design detailers to communicate directly with fabricators essentially assimilating the members from opposite ends of the spectrum within the conventional hierarchy of a construction assembly line. With this new direct channel of communication between designers and fabricators, a proactive control over the final product is potentially achievable by the original designer.

The dialectic between the visual talents of the architect and the technical talents of the structural engineer are becoming increasingly intertwined. Today's avant-garde

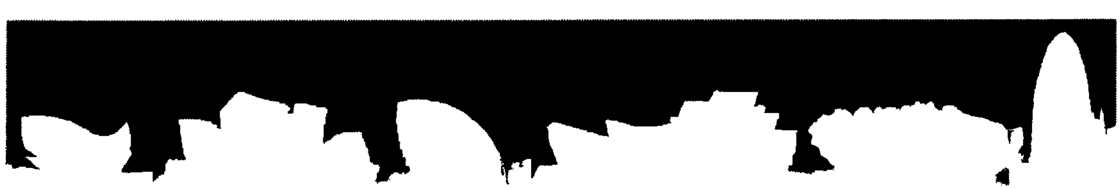

Figure 1: Silhouette traced over contemporary avant-garde designs

structures go beyond the Euclidean imagination of blue-print buildings to include complex three dimensional forms emanating from either sculpted works of art or visual models conceived in virtual space. These complicated building forms require innovative structural systems in order to simply make them stand, let alone remain aesthetically appealing.

The objective of this thesis is to explore the impact of CAD/CAM technology on the construction industry by taking a snap-shot of current avant-garde architecture. The paper is divided into three separate sections; first, clarification of terminology is necessary to have a better overview of the objective at hand. Second, a hand full of examples will be discussed to summarize some of the most recent and most progressive buildings built. Included with these buildings and designers will be architect and mason Antonio Gaudí (1852-1926). Although moderately outdated, his unrivaled originality and profound understanding of structure and detail will clearly define the meaning of avant-garde and appropriately introduce the designers of today. Finally, the third section will explore the financial and economic implications of this new technology on the construction industry.

Design has taken a radical step within the last ten years and it is imperative that we recognize this change and attempt to connect it to its origins and then predict the direction it will take. For the first time the construction industry is exploring into other industries in an attempt to promote and expand the potentials of construction. Although each person may develop their own opinion of these designs, they are definitely becoming more pedestrian and we need to recognize this and be prepared for the future.

2. TERMINOLOGY

2.1 Avant-garde

> Having abandoned the discourse of style, the architecture of modern times is characterized by its capacity to take advantage of the specific achievements of that same modernity: the innovations offered it by present-day science and technology. The relationship between new technology and new architecture even comprises a fundamental datum of what are referred to as avant-garde architectures, so fundamental as to constitute a dominant albeit diffuse motif in the figuration of new architectures. (Kolarevic 2000)

For the purpose of this thesis the term avant-garde will suggest a snapshot of the current position of structural design as it is evolving currently, 2004 A.D. Most of the contemporary projects will have been built within the last decade and future impacts will be predicted along these lines.

2.2 Parametric Design

Parametric design is an automated design feature that goes beyond the fundamental drafting abilities of 2-D programs like AutoCAD and Microstation. Advanced design software achieves higher productivity through macros and scripting languages. "Parametric language is predicated on the design being so well understood that the derivation of its constituent parameters can be recorded historically along with relationships between geometric entities." (Burry 1999) The ramifications of a single alternations will automatically influence all those directly dependant of that property. The model will therefore self adjust accordingly. Still unlike purely creative design, parametric design requires a well-defined model of the intended product. Familiarity and understanding of local components therefore provide better optimization of the final product.

2.3 Rationalization

Rationalization with respect to design refers to the ordering system that can be associated with buildings that facilitates the definition of the overall shape and structure. This order usually acts as a bridge between the architect and the structural engineer by simultaneously characterizing the form of the building and also the geometrical system that defines the structure. Geometry is often the commonality to describe rationalization. Typical buildings are based on a series of vertical columns which prop floor plates and form a relatively simple rectilinear framing system. Some contemporary architects have toyed with more complex geometrical shapes to create equivalent order except to a higher complexity. Foster and Partners are often seen using a toroid to define the surface of large atriums. Figure 2 associates the roof over the Botanic Garden in Whales with the strict geometry of a toroid. In this case both architect and structural engineer can profit from the shape of the design.

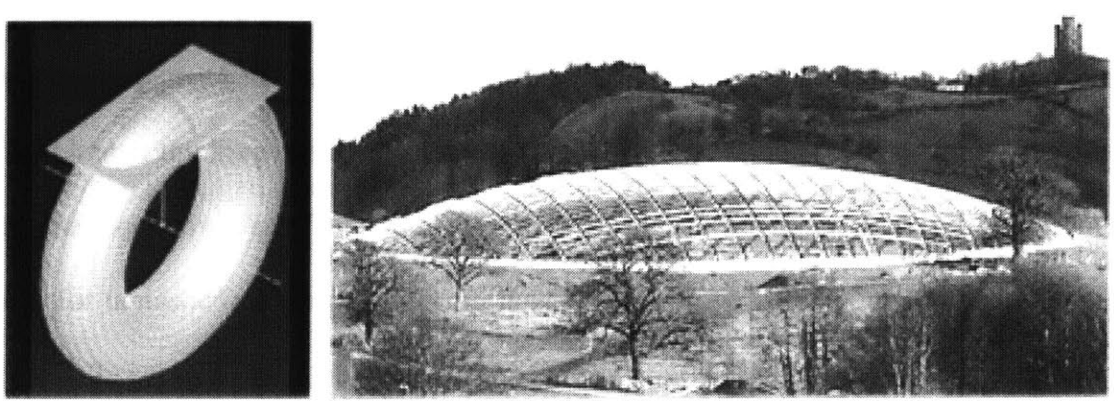

Figure 2: Botanic Gardens in Wales

2.3.1 Pre-Rational

A pre-rational system is one in which the construction system is defined before the design process happens. The previously mentioned FPs example is a clear representation of pre-rational design. Still, pre-rational design is constrained within the limits of what is constructible under the adopted system, in the case mentioned before, the geometrical shape. Although many benefits exist by using a controlled geometrical system it can equally impose conceptual limitations. Even though a defined system can be adjusted and revisited it is eternally limited to what the internal structure allows. "Developing assumptions about the limitations of a construction system too early can lead to an underdeveloped design."(Loukissas 2003)

2.3.2 Post-Rational

Approaching design from the other end of the spectrum can equally have its benefits and its repercussions. The formal design is conceived from a process that is for the most part divorced from considerations about construction systems. A geometrical system is then retroactively imposed on the design. Certain compromises inevitably have to happen in order for the design to conform to any systematic means of construction. Very often this creates a disparity between the shape and the structural system. The most obvious example of this line of thinking can be associated to Frank Gehry. Although his buildings are built with the innovative use of structural steel to form advanced structural latticed grids that allow for fantastic free structural forms, the cohesion of the visual complexity does not necessarily coincide with the complexity of the structure. Figure 3 shows a comparison of

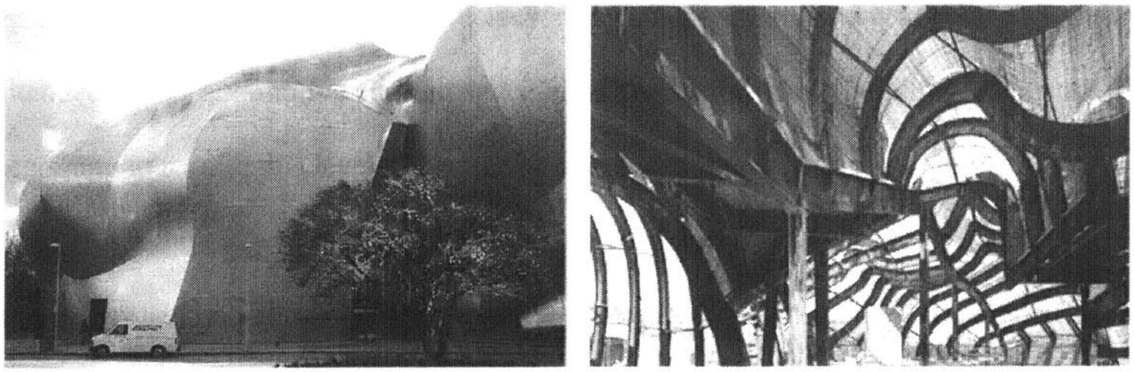

Figure 3: Experience Music Project in Seattle

the exterior surface of the Seattle Experience Music Project next to its complex internal structural system.

2.4 CAD/CAM and CATIA

Computers are increasingly playing a more proactive role in the product representation part of the construction process, specifically in the design-detailing phase. Designers still use CAD systems as drafting tools, mimicking manual drafting to a large extent. Taking these 2-D documents a step further by allowing automatic extraction of construction-related data is the inherent definition of CAM. These complex 3-D design files contain explicit data that is understood by multiple professionals in the construction industry. CAD/CAM technology, essentially, can be understood as an integrated software platform shared by designers and fabricators. It becomes a common channel of communication between three key professionals; the architect, the structural engineer and the fabricators.

Software like CATIA, Bentley, and a few others, create virtual 3-D design models with complex numerical control to define intricate surfaces by utilizing descriptive geometric mathematical formulas. This calculated level of detail permits the fabricators to query a CAD/CAM model for the precise location of any point on any surface. Originally intended for the automotive and aerospace industries, avant-garde building designs are beginning to require this level of complexity more and more.

Unfortunately, a powerful tool like CATIA obviously comes at a price. The complexity and power associated with the software requires a high level of competency by both the designer and the fabricator. Only specialists with extensive training and experience have the capacity to take full advantage of the software. Price is another key issue, because the target industry of the software manufactures is not the construction industry, small private offices rarely have the resources to invest in this technology. License costs and technical labor come at a premium price. Still with the rapidly changing attitude and increasing popularity of the software, license costs are dropping considerably and technical skill is being integrated through educational systems.

When compared to conventional 2-D drafting software CAD/CAM immediately appears to be overkill especially with standard relatively simple designs. Rightfully so, the relative primitiveness of the construction industry rarely requires the depth and complexity attributed to 3-D CAD/CAM software. It is a tool for fabrication and for design, but not for producing traditional 2-D drawings of standard Euclidean architecture. Still, the 2-D drawings that describe the abstract avant-garde structures of tomorrow tend to conversely complicate the actual design. Having a virtual 3-D design model provides clarity with respect to detail, and also with respect to overall shape and form. To optimize the potential of CAD/CAM software it is most beneficial to only apply it where its complexity is required and can be effectively implemented.

3. CONTEMPORARY AVANT-GARDE DESIGNS

3.1 Antonio Gaudí:

On first impression avant-garde would appear to represent a contemporary frozen moment in time. Still, an avant-garde snapshot could successively occur at periodic occasions, each fulfilling their role of progressive thinking and an aptitude for the future. For the purpose of this paper, if we could imagine that each decade represent an avant-garde snapshot, it is valuable to compare the progressive steps of the past with the innovative steps of today, especially when their connection is still very strong.

The first example of avant-garde design will date back nearly a century, to Antonio Gaudí who was a designer well ahead of his time. Renown for his eclectic designs yet often accused of proposing designs inspired by the devil, two major advancements were achieved including an inter-professional language based on ruled surface geometry and a hanging catenary system that described his structural designs. Obviously many other attributes also contribute to his success but these two are the most relevant with regards to this research. Many parallels can be drawn to the advancements in architecture being made today.

3.1.1 Ruled Surface Geometry

Gaudí's architectural designs drew inspiration from his professional training as a mason. His awareness of the physical properties of his materials and how to manipulate them in order to form successful architecture was a powerful and useful talent. He developed a pragmatic approach to the construction process and its relationship to programme. By being versed as both a masonry-craftsman and an architect he generated an automatic dialectic between both professions. This clear channel of communication was most effective when complex geometries were needed to convey his sculptural surface-forms to his craftsmen in a familiar and comprehensive manner.

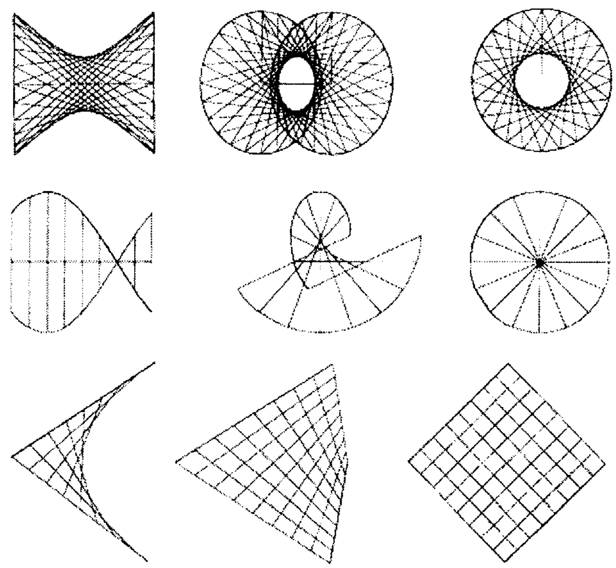

Figure 4: Typical ruled surfaces

The universal language he created is ruled surface geometry, where "curved surfaces are generated through straight lines geometrically ordered so as not to lie on a plane and coincidentally are the basis for the structural forms of most plants and organisms."(Nonell 1992) Figure 4 illustrates three relatively simple ruled surfaces. The amount of complexity is only limited to the creativity of the designer. Almost any form can be created through the combination of multiple ruled surfaces. The implication of ruled surface geometry on construction communication is that his masons could interpret the system through a series of straight lines and easily translate them into the cutting of modular stones, figure 5. This pre-rational design tool formed a series of conventions based on which Gaudí's designs were derived.

Figure 5: Cut stone

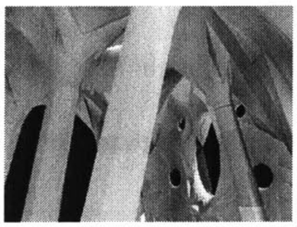

Figure 6: Maquette

To take this ruled surface geometry system a step further, Gaudí was able to correlate his structures together so that even after his passing, the construction of Sagrada Familia could continue according to his original visions. Gaudí built a scaled replica of his design, figure 6, from which builders could follow the exact proportions. Compared to conventional paper documents this physical modeling technique was an innovative means of describing the surface of a building. Ironically scaled 3-D model would give hint to future virtual potentials.

3.1.2 Catenary Equilibrium

The equations governing the equilibrium of inextensible and infinitely long flexible threads can be used to analyze thin masonry elements such as arches, vaults, and domes, all elements often applied to the design of grand cathedrals. Gaudí's Sagrada Familia, figure 7, was a prize cathedral to be built in Barcelona towards the end of his career, early 1900's. He applied this principle of handing models as a method of design to help explain the physical principles that occur within masonry architecture. "Hanging models enable one to determine the optimal form of structures carrying loads purely in compression, particularly those consisting mainly of vaults."(Tomlow) Because the opposite of tension is compression, the catenary, when inverted, constitutes the optimal structural form for purely compression loaded constructions. This simplified analytical technique allowed nature to dictate the structure of his building. By building an inverted catenary hanging model, the lines of force could be traced through positions aligned naturally by gravity, figure 8.

Gaudí's primary motivations for applying this unique structural solution were the simplified benefits associated with catenary design. The geometry described by a funicular curve produces a statically determinate shape and eliminates the need to support lateral thrust lines. This could be seen a very useful in cathedral architecture where traditionally flying buttresses are used to compensate for the dissipation of lateral loads. Gaudí viewed flying buttresses as crutches eclipsing the entrance of light into the cathedral's nave. Although his ultimate design of the Sagrada Familia may appear to be a radical departure from conventional cathedrals, his motivations were both found in purity and honesty of design.

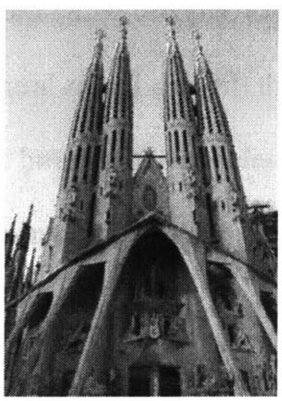

Figure 7: Sagrada Familia

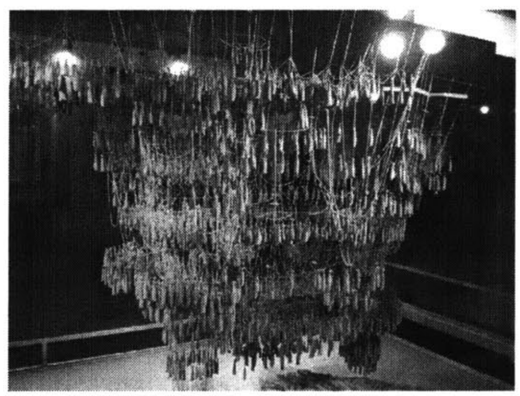

Figure 8: Catenary hanging model

3.1.3 Parallels to Modern Day Avant-Garde

The title of master-builder has been eluded for the last two or three centuries. The divergence between professionals can be attributed to the increased complexity that is evolving in the construction industry. The bridging of construction professionals holds valuable clout in the progressive of designs to come. By balancing the talents of different professionals a more complete and comprehensive design solution is attainable. Gaudí profited from this communication by maximizing the skills of a mason with those of an architect. The language he developed can be seen in the avant-garde design of today. Ruled surfaces are being reintroduced to explain complicated surface geometries and are useful is generating constructible designs. Likewise, catenary principles are both valuable and effective structural solutions. Still the flexibility of catenaries to accommodate to abstract design is rather limited. Nevertheless, the creativity involved in applying this original structural solution deserves credit in and of itself.

Nearly 100 years later, CAD/CAM technology is being applied to the completion of Sagrada Familia. The parametric design capabilities associated with CATIA can effectively be applied to the designs prescribed originally by Gaudí. Modern stone cutting machines are producing the blocks to build the cathedral based on inputs incorporated into the software. Gaudí did not have the luxury of powerful digital tools yet his fundamental logic and techniques are predicated on the same principles that software designers use today.

3.2 Foster and Partners- Buro Happold- Ove Arup

In the last decade, the United Kingdom has a seen a variety of avant-garde structures built that are testaments to the collaborative skills of architects and structural engineers. CAD/CAM technology has played a significant role in these collaborations by creating a common language between professionals. Sir Norman Foster is an established architect with enormous international acclaim. His forward thinking in terms of design is changing the image of urban architecture and redefining the process of construction. Two highly reputable engineering offices that often work with FPs are Buro Happold and Ove Arup. Between the three offices boundaries are being extended every day through collaborative efforts and progressive thinking. Design engineers are participating at earlier stages of conceptual design and are influencing the overall design solution.

3.2.1 London's Great Hall (FPs & Ove Arup)

"City Hall was designed as a model of democracy, accessibility and sustainability."(GA Document 2003) Completed in 2002, this tilted egg sits opposite the London Tower and houses the assembly chamber for the 25 elected members of the London Assembly, figure 9. The concept of the building was based on discovering a shape that would provide the most energy-efficient design. The geometrically modified sphere offered the greatest volume with the least surface area and the 17-degree angle to the south was devised to minimize the surface area exposed to direct

Figure 9: Great Hall, London

sunlight while still admitting daylight. The southern overhangs allow each floor to shade the one beneath it. The structural system applied was also an original innovation; raked columns would support a grid/diaphragm floor system that would transfer loads to a central concrete core. Figure 10 describes the construction sequence of the major structural elements and clearly describes the internal structural system.

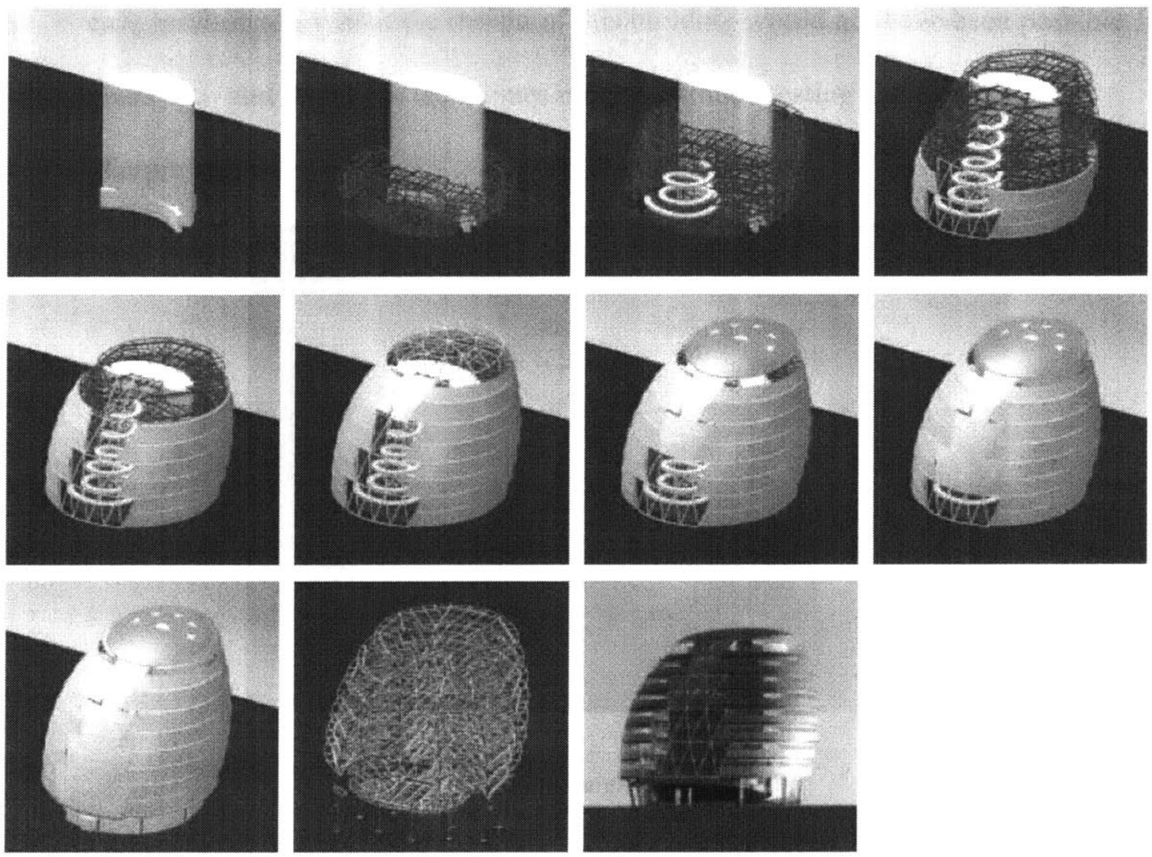

Figure 10: Construction sequence for the Great Hall

The building's irregular form exerted a major influence on the size and distribution of the forces to be resisted. The inclined columns were necessary to accommodate the shape of the building and optimize the floor area. Since the lateral loads were five times that required by wind loading, the floor plates needed to carry the horizontal forces directly to the core. Thirty to forty computer driven iterations were made between FPs and Arup to determine the critical column positions which could reduce the greatest horizontal loads, figure 11. Each iteration took two days and was achieved through by exchange of information through electronic data.

> City Hall stands as a unique testament to cutting-edge building design that tested the unexplored potential of three dimensional computer-aided drawing and the transfer of large amounts of technical information electronically. It is no exaggeration to say that the design of this building would not have been possible 10 years ago- and that these techniques merit continued testing and exploration. (Turpin 2003)

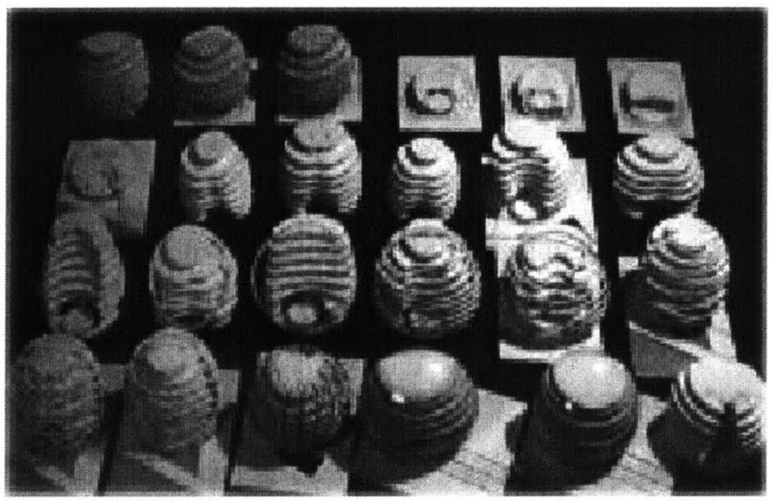

Figure 11: Conceptual design iterations

3.2.2 The British Museum's New Roof (FPs & Buro Happold)

The roof over the Great Court in the British Museum is a triumph in both aesthetic and engineering terms, figure 12. Originally planned by Foster and Partners the design was resolved by Buro Happold Engineers. The complex aperture between the square court and the circular library is glazed by a triangular lattice, which conforms to both frames with remarkable subtlety, and does not exert lateral thrust on the existing masonry walls. The entire span has a tolerance of just three millimeters forcing every connection to be made with finite precision. Also, all 3,312 panes of glass needed to be cut to a different shape to accommodate the intricate geometry. Obviously, computer-determined geometry accounted for the demanding precision involved with this structure. Every connection was CAD/CAM fabricated according to the details prescribed by the structural engineers.

The break through came in the actual manufacturing of the individual pieces. To optimize the efficiency of material use, the six-prong nodes were water jet cut from single pieces of solid steel. Because the cuts could only be made orthogonal to the surface of the sheet, the member struts would need to be tapered in order accommodate the curvature prescribed by the geometry. Flexible machining equipment could cut each member to precise accuracy to bring the entire surface to with 3 millimeters of accuracy. Also, because the surface is composed solely of triangulated sections, no additional structure is necessary to add stability to the shell. Although the concept for the roof was envisioned by the architect it was the structural engineer is bridged the gap with the manufacturer to resolve the design. "The overall aesthetic success comes from the simplicity and deceptive impression of weightlessness the roof engenders." (Pearman 2000)

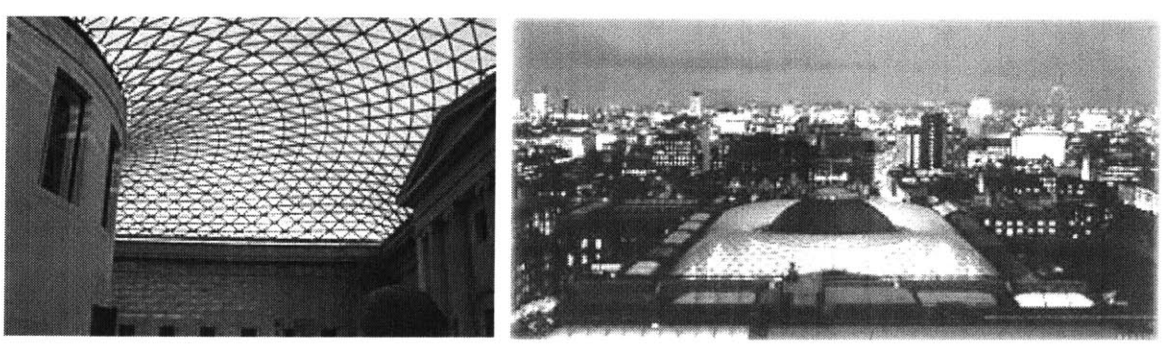

Figure 12: Roof over the British Museum, London

3.3 Frank O. Gehry

CAD/CAM technology made its first appearance at a monumental scale in the Guggenheim Museum in Bilbao, figure 13, designed by Gerhy Partners architectural office. Since then GPs has grown exponentially both in terms of office size and also industry popularity. Gehry-style buildings are "inspired by movement and the notion of an environment that is constantly evolving." (DeSimone 2002) His structural sculptures are emerging around the world, and almost single-handedly he is changing the way design is understood. North America has seen over a dozen new GPs buildings erect themselves over the past ten years. Their complex surface patterns and unpredictable geometry has forced structural engineers to reconsider conventional design techniques to resolve their structural systems. Gehry's breakthrough into manufacturing software has also opened the door to a multitude of new opportunities. Relative to more advanced industries like the aerospace and automotive, the construction industry is still quite fragmented, where smaller firms hold a majority within the industry. By introducing powerful aerospace software like CATIA into a simple industry may appear overkill. Still, perhaps the construction industry should emerge from its primitive position and capitalize on such existing opportunities.

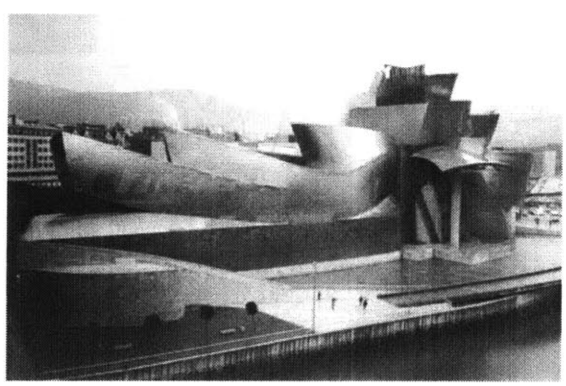

Figure 13: Guggenheim Museum, Bilbao

3.3.1 Surface Analysis

GPs creativity comes form an unconventional style of design. The shape and forms of his building are originally conceived by constructing scaled maquettes that are then digitized with laser scanning hardware to input the designs into the computer. These digitized models are then viewed in rendering software like Rhino V3.0 to get a better computational understanding of the shapes. Multiple iterations are made of this procedure by constantly reverting to the maquatte and making physical adjustments until a design concept is decided and approved. Then the digital model is transferred into CATIA where the complex analysis begins. Figure 14 illustrates the iterative process applied by GPs. In this cycle CATIA is not used to design the actually building concept, but rather "create, portray, render and manipulate objects in three dimensions." (Roordra 2002) GPs have developed a flavor for curved surfaces that evoke ideas of nature and movement. CATIA has the translation tool which can take a surface and convert it into a 'developable surface'.

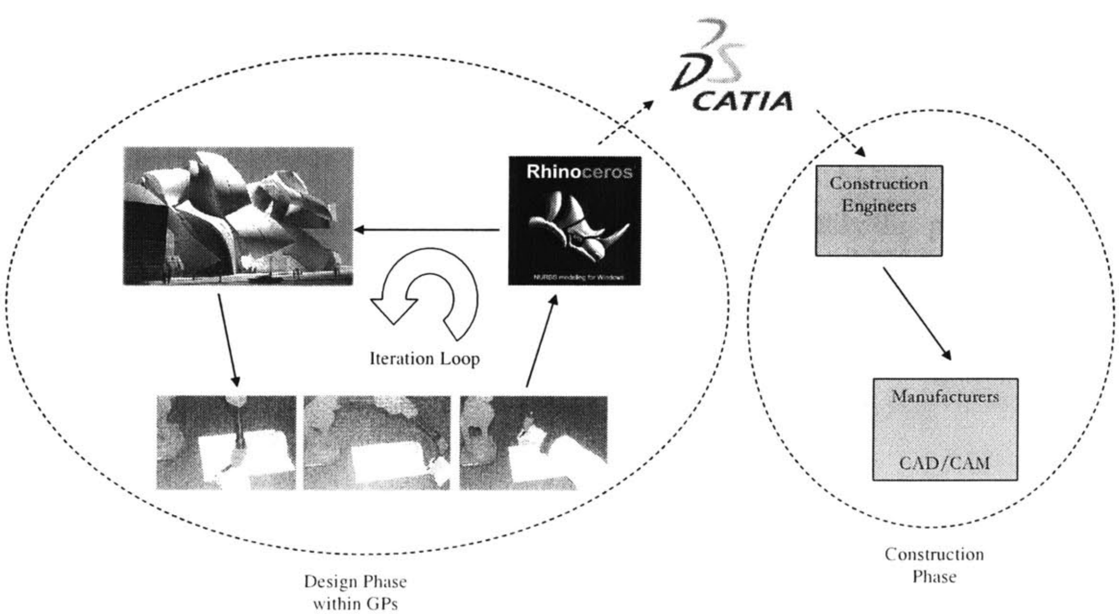

Figure 14: Gehry Partners design cycle

What this feature does is alter the input slightly to generate a ruled surface.

> A ruled surface is one comprising adjacent straight lines. The simplest ruled surfaces are a cylinder, where the ruled lines are parallel, and a cone, where the lines converge to a single point. By joining parts of these basic forms, one can create more complicated ruled surfaces. Achieving a ruled surface is essential to ensure that it can be covered with pieces of flat material (drywall, plywood, sheet metal, waterproofing membrane, etc.) without kinking. If a non ruled surface, such as a sphere, is covered with a flat piece of material, large unsightly wrinkles are formed." (Roorda 2002)

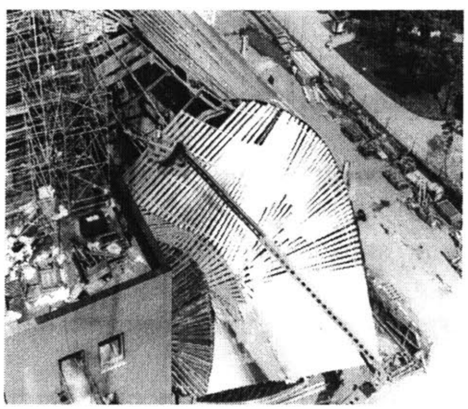

Figure 15: Peter B. Lewis Building, Cleveland

Figure 15 is the roof system for the Peter B. Lewis Building in Cleveland, Ohio. The steel rafters that describe the curved roof surface illustrate the application of this ruled surface analysis.

Still it is obvious that this system of analysis is unconventionally post-rational. First a shape is created, and then from that form a system is derived to accommodate the constructability of the shape. Although logically this procedure may appear counter intuitive, the results are a dramatic step forward from the buildings designed a decade ago.

3.3.2 Structural Adaptation

A key element associated with Gehry architecture is the lack of legibility from an objective point of view. Most large buildings have a geometrical order which serves as a platform for a structural system. This order is usually based of linear vectors that connect orthogonally to each other to complete a closed structural system. Still, rarely is this type of organized geometry present is a Gehry building. Instead a second set of structural plans are created to convey the geometrical information. The entire building could be imagined to sit within a large 3-D cartesian space. Each column is described by an X, Y, and Z coordinate and a vector that passes through the center of the member. These values all corresponded to the master coordinate system defined by a CATIA model used to design and detail the structure. Advanced survey technology and global positioning systems can locate specific points on the construction site to describe the location of all the members.

Although legible 3-D wire-frame models allow structural engineers to input the information into structural analysis software, like SAP2000, and generate loads conditions for the given members, their understanding of the system is almost completely blind and fully dependant on the results provided by the software. Although values and dimensions can be obtained for members, very often, because of their irregular and inefficient position there support capacity needs to be uncontrollably large. Without a coherent rationalized order in the building bulky design is unavoidable. Also, placing such a high dependence on software analysis leaves structural designers in the dark to the actual organization of elements in the system. Conventional theories and formulas cannot be applied to unconventional systems. With liability being such a big issue, engineers are forced to take a giant leap of faith into very risky business.

3.3.3 Lessons Learned

It is without a doubt that the radical departures made by GPs in terms of design are the most drastic compared to conventional design. Right from the onset the notion of sculpture was part of their design. Gehry's profound familiarity with CAD/CAM technologies allows him to fabricate all the surfaces of the building with digitally controlled industrial equipment. He indirectly becomes both the architect and the builder of the building. Such innovative design reaches for the limits of fabrication and with it an enormous disparity opens up within the rest of the construction assembly line. This gap needs to be bridged by the structural engineers. What this demonstrates is that the aesthetic pinnacle Gehry strives for is achievable because of his ability to control the origins of the assembly chain. That being said though, at what price? Economics and efficiency in construction are the factors sacrificed for a visual masterpiece of a form, which is really a large scale sculpture and does not represent structural efficiency or the flow of forces at all.

4. ECONOMIC IMPLICATIOONS OF CAD/CAM TECHNOLOGY

The purpose of examining an economic perspective is to analyze what major reforms to the industry may come about as a result of this new wave of interactive technology. Then, to examine the strategic opportunities that are made available with its application to the construction market. The impact of CAD/CAM will be both technologically and contractually analyzed by its potential influence on the conventional construction supply chain. The methodology of this section will begin with a brief explanation of the conventional supply chain arrangement. It is important to understand where exactly the technology relates with respect to the industry and then which players can expect the largest impact.

This section will also map out the relationships of the relevant players and examine what profits and pitfalls can result from any new arrangement. Some hypothetical scenarios will be drawn out to envision what strategies and potentials a company can achieve with the application of CAD/CAM. Potential strategies can be evaluated based on this analysis and determine an effective use of the technology. Ultimately, this section aims to shed some light on the business aspects associated with the up-and-coming technology of CAD/CAM.

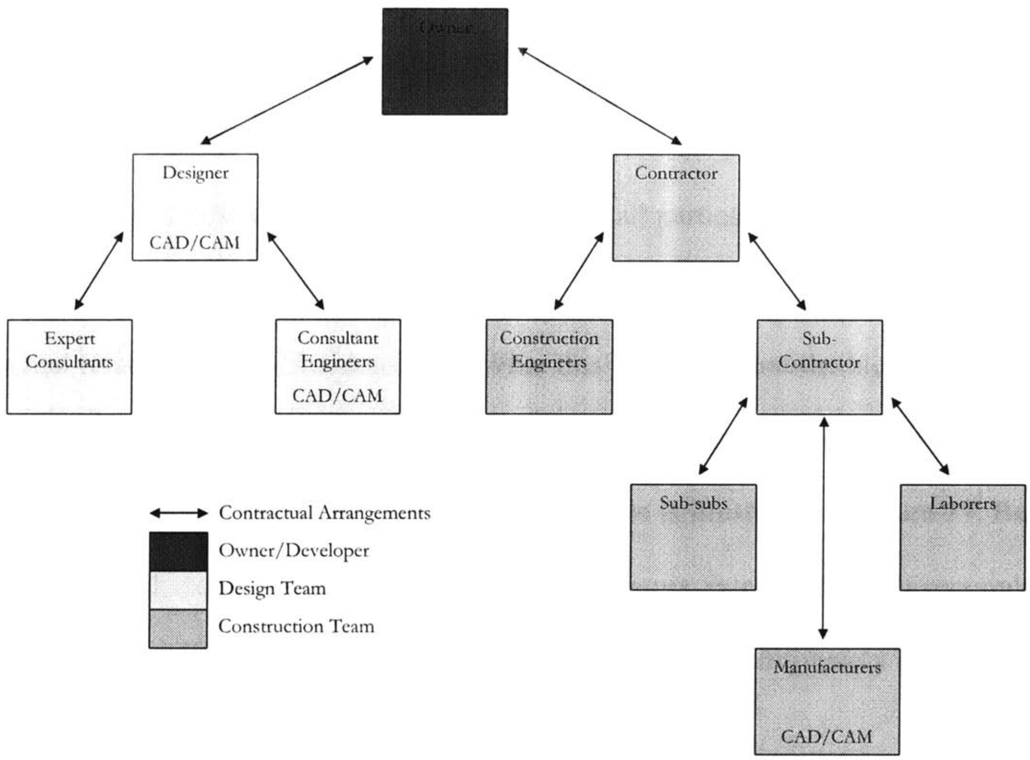

Figure 16: Design-bid-build construction setup

4.1 Integrated Supply Chain

Figure 16 illustrates the conventional arrangement for a design-bid-build construction setup. The major players in the construction industry thrive on their autonomy based on the manifestation of unique priorities and personal incentives. The owner usually desires to receive the best value and the highest quality for their money. The designer strives to achieve this for the owner and is under the constraints to operate a successful business. The contractor works in a very competitive industry where profit margins are low and risk is high.

The competitive nature of these participants may cause a breakdown of the teamwork crucial to a highly successful project. This breakdown causes; untimely information flow, distrust, excessive documentation, expensive delays, reduced quality, and ultimately impacts to the cost and schedule of a project. (Bender)

Segregation between professionals is fundamentally rational because "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 contractual relationships". (Sheldon 2003) What this implies is that the hierarchy of the construction assembly line controls the flow of information along the paths of contractual relations. Tracing these paths along the construction tree is illustrated in figure 17. Because no contractual link exists between designers and fabricators, intermediary players must filter the information associated with CAD/CAM, since they are ultimately responsible for the work of the subordinate professionals.

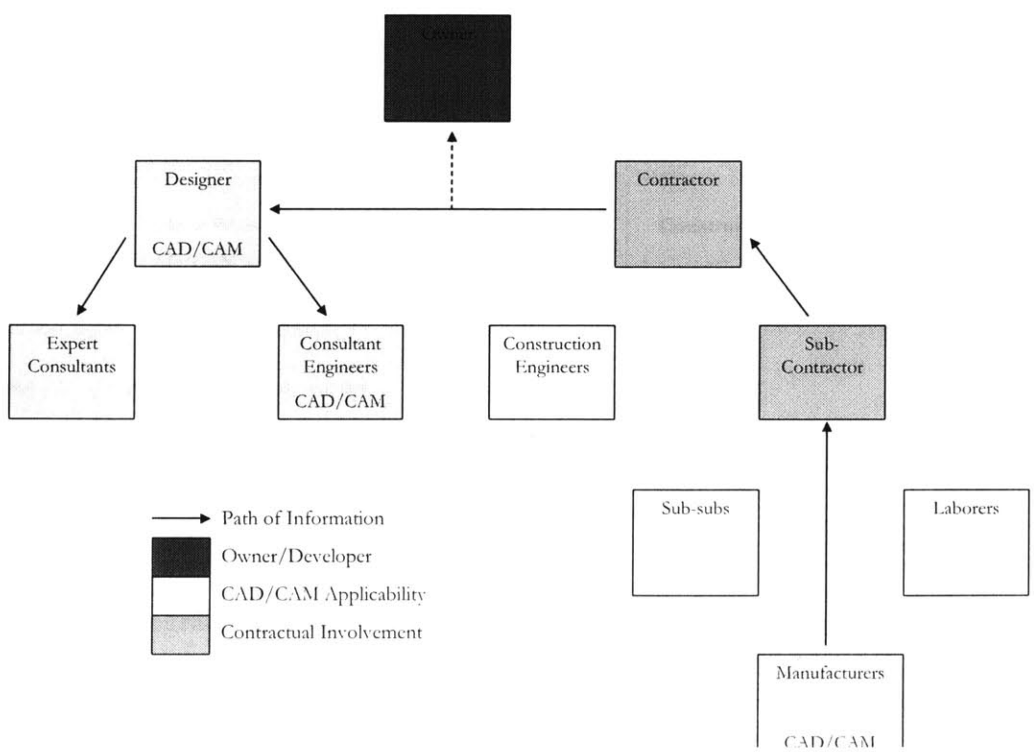

Figure 17: Contractual paths within a construction setup

The conventions of contractual relations among professionals vary widely in different parts of the world. In many ways, the North American construction market is the most difficult for supporting unconventional building practices. A determining factor that explains our fractured industry is "the increase in construction litigation that has occurred since the 1950's." (Navon 1995) Looking at more progressive alternatives may suggest an arrangement more appropriate to accommodate CAD/CAM technology.

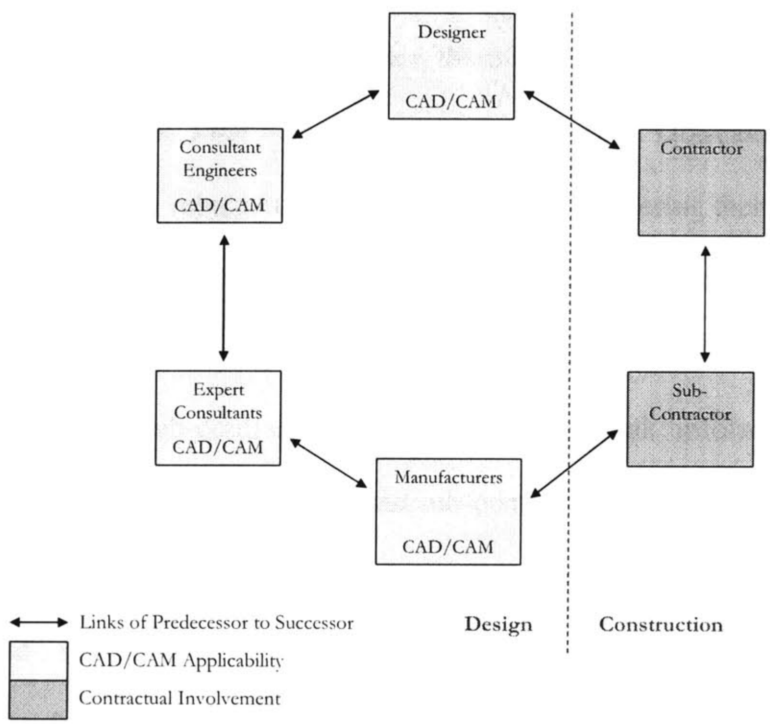

Figure 18: Circle integration setup

4.2 Re-Aligning the Supply Chain

Circle integration, figure 18, is an organization setup for integrating pre-construction activities that "link the professionals to a single predecessor and a successor. All applications form a single feedback loop." (Fischer 1995) These predecessors and successors refer to the individuals from who you either receive information or to whom you pass forward information. Although circle integration is intended to be based on a single software platform and to be restricted to the pre-construction planning stages, CAD/CAM technology can apply a similar setup to accommodate for preconceived conflicts. By closing the loop between the fabricator and the designer the fabricator serves as a quasi-consulting engineer for the specification of a building system. The important distinction develops depending on what side of the fence the fabricator stands? If the fabricator participates as a consultant to the designer, there is no commitment by the general contractor to ultimately award the contract to that particular fabricator. That being said, fabricators may prove reluctant to act as consultants considering their major profits come from product sales and installation. General contractors would equally be reluctant to enter into contractual agreement with fabricators who act as contracted consultants to designers due to "the fear that sub-contracting 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 should arise." (Sheldon 2003) This stalemate confirms that traditional design-bid-build organization does not effectively coincide with the challenges posed by avant-garde architecture.

4.3 Locating a Source of Profit

Determining what aspects of CAD/CAM can be opportunistic to the construction industry is vital to justifying software like CATIA's use. As mentioned before technical labor and licensing costs impose a premium price on the initial design costs and design

	Generalized Project Figures	
	Before CAD/CAM	After CAM/CAM
Design Time	10 Months	12 Months
Construction Costs	100 M$	90M$
Delivery Time	36 Months	30 Months
Relative Total	146	132

Table 1: Generalized project figures

time. Still, integrating the construction professionals under a universal software platform holds potential profits in construction time by accelerated communications lines and also more accurate material costs. Allocating less time to converting documents according to each professional's responsibilities facilitates the interaction between individuals. Applying generalized figures to this notion, table 1 illustrates the profits as viewed by the owner. Although idealized, this model still appropriately describes the potential profits available with the integration of CAD/CAM technology.

4.4 Introducing CAD/CAM into the Industry

The means by which a new technology is introduced into a foreign market depends very much on its source and also its initial consumer. The business strategy applied by the manufacturer usually depends on what outcome he is targeting. Dassault, the software manufacturer's of CATIA, primary patrons lie in the automotive and aerospace industries. Firms like Boeing and Ford who have the resources and also the requirements of complex software like CATIA absorb the major targeted market of manufacturers. For this reason, Daussault customize their user platforms for the design associated with planes and cars. Although the capital value of construction industry is much greater than both the automotive and the aerospace markets, its primitiveness causes companies like Dassault to easily over look this major target.

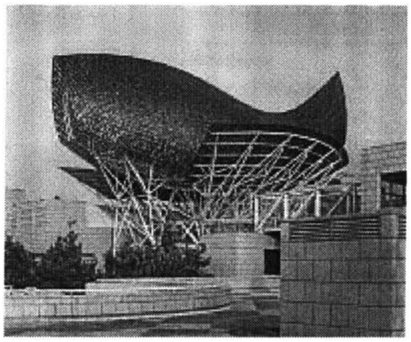

Figure 19: Barcelona Fish

In 1992, Gehry Partners was the first architectural design office to expand and incorporate CATIA into its design of the Barcelona Fish project, figure 19. Since then they have grown enormously both in company size and industry reputation. They are playing a pivotal role in pioneering the direction of modern day architecture. In 2002 GPs created a technology branch called Gehry Technologies who would collaborate with Dassault to create a user platform more comprehensible to the construction industry. The vision of GTs "is to bring the experience gained from fifteen years of technology and process development to the wider AEC community, by leveraging the very best in software tools and processes for architectural design and building construction projects." (GTs Vision) Essentially they are taking their experience and knowledge of this software and offering it to the industry, of course at a capital price though. Admirably, this generous offer by GTs to distribute this powerful technology into the AEC industry can be seen as a way of proactively cultivating collaborative relationships within the industry nurturing it to evolve and grow, but from a business stand point this act is both strategic and profitable.

4.5 The Pro-Active Role of Gehry Partners

This growth has offered them the opportunity to invest time and financial capital to develop the resources necessary to capitalize on the potentials of the technology. The resources developed over the past 12 years are essentially a profound understanding

	Generalized Gehry Partners Figures		
Firm Responsibilities	Before Integration of CAD/CAM	CAD/CAM CAM/CAM	After Integration of CAD/CAM
Time Period	Infinite	12 YRS	Infinite
Revenue	20 M$	20M$	40M$
Cost of Work	(16 M$)	(16 M$)	(30 M$)
Margin of Profit	4 M $	4 M$	10 M$
R & D	0 $	8 M$	0 $
Relative Net Total	4 M$	(4 M$)	10 M$

Table 2: Generalized Gehry Partners figures

through experience and the growth of detail libraries that can be reapplied to structural systems on future projects. These libraries hold significant clout exclusive to GPs and potentially serve and a possible high source of long term revenue. If you could imagine the hypothetical financial figures relating to this 12-year learning period they would likely reflect something similar to table 2. The first column represents a GPs design firm before the application of CATIA software. The integration column is the learning period that encompasses the past 12 years. The final column is the snap shot of GPs current profit margin in the design industry. Examining this idealized model illustrates the recent success currently being reaped by GPs.

Project libraries are also drastically changing; software like CATIA has parametric properties that allow for mass-customization in library details. One object can serve many functions based on the input variables that can be adjusted according to the detail constraint. These libraries will serve as major sources of revenue in the long run. Having a large library forces you to get integrity from elsewhere, namely from your inter-professional relationships, your credibility and your hard work. Having access to software should not be your source of revenue but rather expose the purity behind of your design concept. The aesthetic quality and design originality are the underlying factors attributed to GPs success.

4.6 Professional Impacts

Still, the impact CAD/CAM has on the industry depends very much from what perspective the ultimate user is applying the technology. It is important to observe the hypothetical opinions of buyer's, namely; the architects, the engineers, the contractors, the sub-contractors and the fabricators. To do this a market analysis technique will be taken from Competitive Advantage, by Michael Porter. To summarize the theory behind this analysis, any random industry can be influenced by five principle forces. These forces possess power through their leverage depending on their position in the industry. Figure 20 illustrates the typical organization of this theory. The industry itself occupies the central square and four of the five forces external forces while one is from within the market itself.

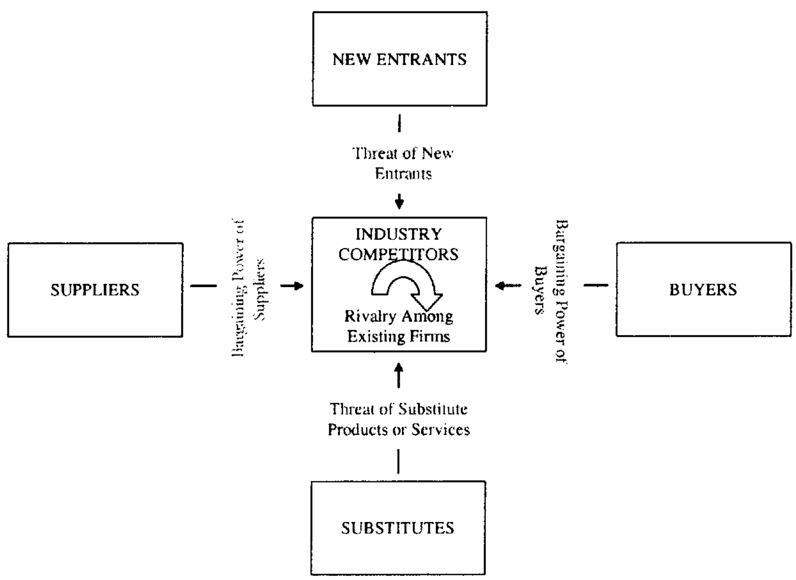

Figure 20: Model of Five Competitive Forces

4.6.1 Impact on the Architects

Architects who decide to follow in the footsteps to GPs will likely hold two major biases towards sponsoring CAD/CAM software; firstly, the software itself becomes based on a design style specific "Gerhy-style" work. Although creative and popular, "only Frank Gehry can design like Frank Gehry."(Balmond 2004) What this implies is that creative designers will be reluctant to sacrifice their integrity for an unoriginal style, in which case they must interpret the software's abilities to fit their own style. This potentially poses large investments in terms of R&D and experience. The second bias comes from the resource being tapped by GTs who now takes advantage of the propagation of the software into the industry. Regarding the five forces, figure 21, GPs holds a strong position within the industry. GTs occupies the supplier's role by distributing the CATIA software. The buyers and the substitutes are represented by the alternative architecture offices. These offices are also impeded by scale. Unless they are of the same stature as GPs and can afford the investment; small independent offices would be out of their league. Therefore limited participants involved in this scheme and the monopoly of roles occupied by GPs puts him at win-win advantage. If the software sells successfully, there is a profit to be made on the selling of licenses. Even though the volume of industry competitors will increase the new entrants' learning curve will be extensive and initially pose limited threat. If the alternative architecture offices decide to ignore the CATIA wave this leaves GPs to absorb all the profits within this new style niche.

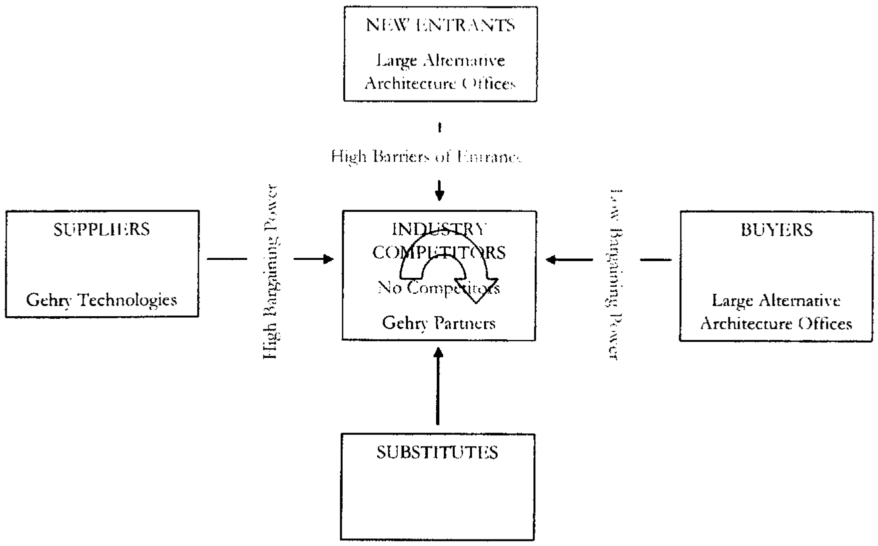

Figure 21: Five Force Model with respect to architects

4.6.2 Impact on the Engineers

The consulting engineers associated with CAD/CAM projects will see CATIA as a document translator necessary to resolve the avant-garde structures conceived by the architects. In many ways they will be at the mercy of the architect's choice of software, or else suffer the time and cost of interpreting the 3-D design files. The shapes and forms generated by the architects do not abide by conventional structural theory. Inclined columns and curvilinear surfaces are not traditional shapes that conform to structural theory. As mentioned before CATIA is a powerful software and incorporated within its multiple platforms are structural analysis tools. These can be applied by the engineers but unfortunately with a lot of ambiguity. The inability to calculate simple principals by hand based on structural theory will leave engineers blind and at the mercy of the computer. Legally what does this infer? Should failure occur in a structural member, where does the liability lie? Will software packages need to be accompanied by endless liability clauses relieving them of any unforeseen accidents? Unless the engineer is able to resolve the problems using conventional theory, a high amount of risk is being taken on by becoming so dependant on the software.

Conventional simplicity and reduction techniques will not apply. This is why when most modern avant-garde structures are examined from a structural perspective they are over-designed due to shear apprehension to the over all system. Therefore, either the theory behind the structural profession needs to evolve or else more faith, i.e. risk, has to be placed in the software.

With respect to the five forces, figure 22, again Gehry maintains considerable pull on the major factors. Similar to the architecture industry GTs is the distributor of the software and the industry competitors are likely to be only the large firms who can afford the software and have the qualifications to work on avant-garde architecture. The barriers of entry will therefore be relatively high. Within the industry itself, GPs hold considerable pull by having the luxury of choosing which firms to work with. By not working exclusively with a single a firm he can force feed the software on many firms and reap the benefits from all the different consumers. Current engineering firms are aware of this industry extortion, and therefore have to decide on a path to take.

Still, it is without a doubt that effective analysis software is an imperative for contemporary structural engineers. Although CATIA claims to represent the epitome of software design, then why has it not been welcomed by the industry with open arms? Simple logic argues that if there exists a profit to be made then a competitive package will be introduced. Although CATIA aspires to be the platform of the future, perhaps there exists little or no market to absorb it.

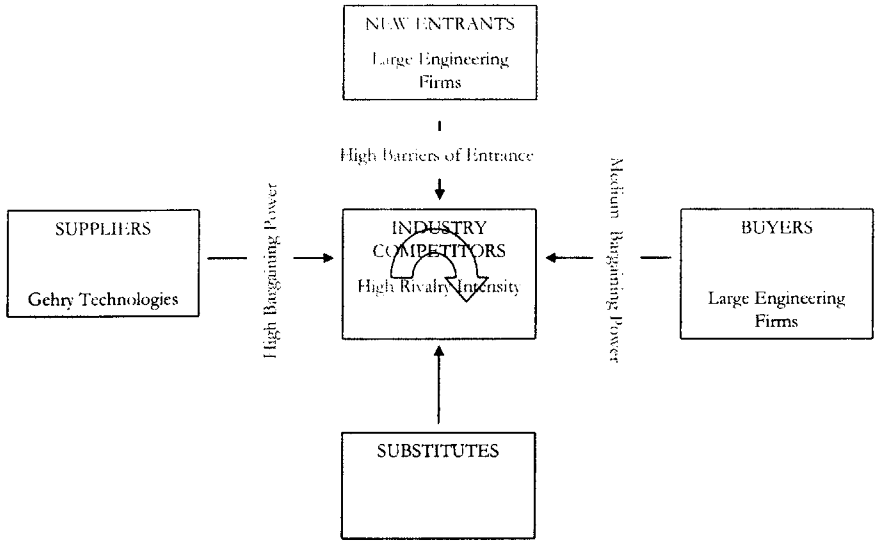

Figure 22: Five force model with respect to engineers

4.6.3 Impact on the Contractors

Contractors are probably the farthest players who might see benefits from using the software. They are aware that it connects the designers to the fabricators, but there is no unique feature to attract them to apply CATIA to their process responsibilities. Their power in the construction process still remains in the control of the lines of communication. They can dictate what order of events can occur and how the players legally interact.

A design build situation where all the players are under one roof appears most reasonable for a single software platform like CATIA. But in this case the general contractor dictates the design execution. When clients embark on this type of design contract the goal is usually to receive a project at the lowest cost and shortest time possible. Frankly speaking, CAD/CAM technology has not proven to optimize time or cost with respect to owners perspective. Therefore, although design-build would objectively speaking be an ideal arrangement, convention claims otherwise. GPs have become aware of this and typically introduce a construction manager who participates on behalf of GPs. With representatives available on site throughout the entire construction process has allowed him to actively influence the sequence of events and execution of designs in the construction process. Theoretically, perhaps the next business venture is for GPs to branch off to become Gehry Construction…? It is not all together unheard of, but requires some serious business considerations and planning before it can actually be even proposed.

With respect to CAD/CAM influence on general contracting, the process of change might be more incremental. Maintaining multiple project logs provides legal umbrellas for potential disputes. This duplication of effort is inherently inefficient, and Gehry has made the point that convincing the owner and contractor to share one log, posted on-line, is in itself a step in the right direction. Still, it will only be when all the players are willing to stick their collective necks out and go to an owner to deliver the entire project for a fixed price and make their profits by squeezing the inefficiencies out of the system will this technology be fully unveiled.

4.6.4 Impact on the Sub-Contractors

The sub-contractors play an integral role is the installment of the uniquely manufactured parts that go into avant-garde designs. Proportionally, by increasing the complexity in design will require an increased skill capacity to execute the installment. Therefore skilled laborers will become a commodity and have the leverage to charge a premium for their talents. It can be compared to hiring portrait artist to paint you house. The barriers to entry for these types of laborer industry are very high because only experience can provide the ability to execute at such a high level. The general contractors become the buyers of the subs services and they will have limited bargaining power because of the subs commodity value. Still, although complex geometry may carry a premium in labor and material, these factors can be understood in terms of real impact on the cost of construction, and not buried in excessive cost contingencies to protect the contractor from unknown risks.

4.6.5 Impact on the Manufacturers and Fabricators

The manufacturers are unique because they can easily maximize their efficiency because of their increased understanding of the digital documentation. The coherent language between designers and fabricators will increase the volume of suppliers and thereby lowering the overall cost of unique parts. Manufacturing tools will be the deciding factor of the capacity of the manufacturers. Requesting complex parts that can only be provided through precision equipment will distinguish the abilities of the manufacturers. Still, the fabrication resources are usually available but designers just haven't been aware of their potential until now.

Concerning CATIA, manufacturers may already possess the software or perhaps not be as dependant on it as other professionals in the assembly line. The value comes from the digital interpretation of the surfaces that can easily be translated into manufacturing codes. Like any project the choice of material will significantly affect the manufacturers pricing. Although material cost may appear relatively high, the closer collaboration between professionals allows for more transparent building costs.

5. CONCLUSION

Industrial architecture has been eclipsed by new software altering pre-design conceptualization and also project delivery services. Developing an opinion of modern architecture is purely subjective but can likely be appreciated by anyone who is concerned with the surrounding built environment, figure 23. Preference to work done by architects like Foster and Gehry are open to wide range of opinion ranging from both admiration to antagonistic. Whether design and construction will be swayed into a new direction is quite possible. In one sense these designers' motivations may be purely capitalistic intending to monopolize a certain style and then force feed software that is compatible to this fashion. The question becomes will small firms be forced to acquire this technology in order to compete and even worse survive? A clear parallel can be equated to Microsoft, who now recently is constantly being accused of unfair business practices by taking competitive advantage by forcing hardware vendors to install both their windows operating system and also their explorer web navigator. Settling antitrust lawsuits is reducing their profits and forcing them to reconsider their business strategies. It is conceivable that a firm like GPs may one day walk down an equally precarious path.

Nevertheless, technology for designers is in its adolescence. It's difficult to envision how exactly it will transform aesthetics or structural practice. But projects with roots in digital innovation offer reason to be enthusiastic or at least curious about its implications.

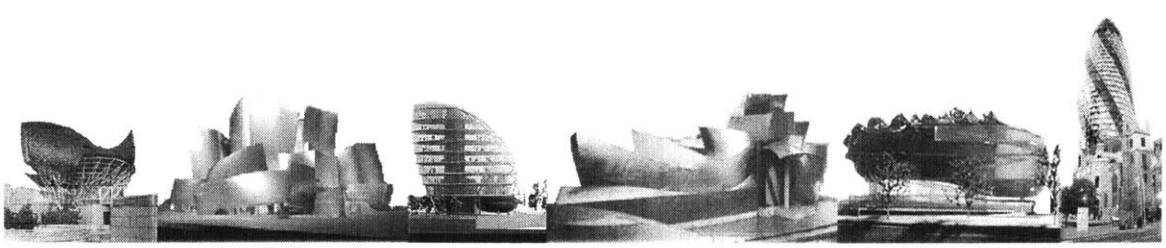

Figure 23: *From L-R; Barcelona Fish-GPs, Walt-Disney Concert Hall-GPs, GLA-Foster, Guggenheim Bilbao-GPs, Kunsthaus Graz-Peter Cook, Swiss RE-Foster.*

This research is a call for action; designers must embrace technology's potential or run the risk of being marginalized by those who do.

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