

3D MODEL-BASED COLLABORATION IN DESIGN DEVELOPMENT AND CONSTRUCTION OF COMPLEX SHAPED BUILDINGS

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SUMMARY: *The successful implementation of complex-shaped buildings within feasible time and budget limits, has brought attention to the potential of computer-aided design and manufacturing technologies (CAD/CAM), Building Information Modeling (BIM), and the need for integrated practice. At the core of an integrated practice vision lies the intimate collaboration between the design team and construction team and a digital three-dimensional model, often with parametric and intelligent characteristics. With the shift from two-dimensional (2D) paper-based representations to three-dimensional (3D) geometric representations in building information models (BIM), architects and engineers have streamlined 'inner' design team communication and collaboration. However, practice conventions have posed significant challenges when attempting to collaborate on the designer's 3D model with the 'external' design team – involving the architect (or engineer)-of-record, and contractor, construction manager or fabricator, etc. Focusing on the execution of complex-shaped buildings, the objective of this paper is to illustrate varying collaborative approaches to understand how design teams use 3D models to control geometry. The authors attempt to provide specific responses to the following questions: What are the issues when collaborating on 3D models? What are the mechanisms that design teams adopt to surpass practice conventions? The findings from three case studies suggest that collaboration methodologies on 3D models differ with the architects' approaches to geometry control. The authors will demonstrate that successful model-based collaboration occurs either on a contractual or non-contractual model issued by the architect.*

KEYWORDS: *3D, geometry, representation, control, CAD/CAM, BIM, inner-, external-, collaboration, design development, construction documentation, integrated practice, complexity, contractual, liability*

1. INTRODUCTION

1.1 Background

The adoption of digital design and manufacturing technology and BIM technologies in construction have opened up new opportunities for architects who are willing to adapt towards integrated processes to assume leadership roles in the creation of the built environment (Bedrick, 2006). Architects have begun to assimilate and incorporate model-based design processes to augment or substitute traditional paper-based procedures to enhance value for the client (Bedrick, 2006; Kolarevic, 2003). While these new processes offer various benefits to clients, they simultaneously require careful rethinking of traditional teamwork models. This study attempts to *investigate the hypothesis that control of the geometric model coincides with the distribution of design responsibilities during design and construction*. This research was first inspired to investigate the collaboration mechanisms that empower the architect to enhance control of geometry in complex-shaped buildings.

Ku and Pollalis (2006) provide an example of successful ‘inner’ collaboration and geometry control facilitated by 3D modeling during the competition design of a bridge, and highlight the critical success factors such as technical competency and ‘trust’ among the team members. We define ‘inner’ versus ‘external’ design teams relative to the contractual relationship between the designer and the other team members. Examples of an ‘inner’ design team are design competition teams or a team of design consultants and engineers who are hired by the designer. We argue that model-based information sharing with ‘external’ teams poses substantial problems in comparison to ‘inner’ teamwork. The literature recognizes the barriers – contractual, legal, procedural, social and technical (Allen et al, 2005; Chaszar, 2004; Kolarevic, 2003) – that impede fully collaborative and highly integrated information sharing.

The issues of geometry control become important for the designer during stages of design development and construction design (Pollalis and Bakos, 1987), when the engagement of additional experts – the ‘external’ team members is necessary. For example, the client may involve an executive architect, architect-of-record, engineers-of-records, responsible for structural and building services engineering, and furthermore, construction managers, contractors and fabricators.

Implementation of integrated practice and the application of BIM are a complex matter because it involves the redefinition of design roles and responsibilities that are embedded in traditional design processes and rational boundaries. Nonetheless, to take the lead in satisfying the changing demands of construction clients, architects have to understand the changing practice parameters related to model-based collaboration.

1.2 Research Needs

While there has been a growing body of interest in BIM and increasing awareness for the imperative of integrated practice models (CURT, 2004; AIA/AGC, 2006), there is need for a more focused look at key aspects of the collaboration process. By constraining the domain of BIM more tightly to look at the specific context of complex-shaped buildings, this study aspires to understand the impact of 3D modelling on the architect’s control of geometry. This study was motivated by the need to identify key variables of model-based collaboration and to provide insights into best practices and opportunities to empower the architectural profession.

1.3 Research Objectives

The objectives of this study are:

- To understand architects’ motivations for 3D modeling in complex-shaped buildings
- To identify key factors of model-based collaboration
- To define collaboration strategies for enhancing geometry control

2. DESIGN AND CONSTRUCTION OF COMPLEX-SHAPED BUILDINGS

2.1 Form Finding of Complex-shaped Buildings

In contemporary architectural practice, new novel shapes and “non-standard” forms are generated, represented, and realized within feasible budgets (Kolarevic, 2003). Digital design media are taking on central roles in the conceptual and schematic design processes of firms pursuing such forms. The means by which schematic design processes incorporate digital media for form development is a significant topic of interest in its own right, albeit somewhat outside the scope of this study. Variability exists in the use of digital media as part of architects’ schematic design processes. Some practices have developed hybrid digital / physical design processes, where physical or traditional media remain a primary means for design exploration, but these media are integrated through emerging digital media including 3D and 2D CAD, photographic and video image processing and digital storage and distribution technologies. The development and increasing availability of digitizing and rapid prototyping technology has facilitated the transfer of design information between physical and digital media realms.

Other firms are pursuing the development of form directly through manipulation of digital media. Digitally adept designers may interactively manipulate 3D geometry, using NURBS (Non-Uniform, Rational B-Splines), triangulated, or other CAD based geometric constructs combined with shape construction and modification capabilities of software packages, such as morphing, triangulation, and twisting, etc.

Still other firms have begun to experiment with computer-generated three-dimensional forms as a new way of exploring formal concepts. This approach relies on formal algorithms allowing architects to develop their own shape construction procedures. This approach involves extensive computational techniques engaging rule-based approaches, including cellular automata, fractals, or constraint-based stochastic search (Terzidis, 2006). These three general approaches to the development of form through digital media present a wide array of unconventional shape generation possibilities to designers.

Irrespective of the form development process used by the designer, the schematic design results in a 3D digital sketch model, representing preliminary *design intent* of the project. The sketch model may include system intentions at varying levels of detail, and varying degrees of enhanced BIM information or other model intelligence. This paper is primarily concerned with the development of exterior envelope representations.

The advent of NURBS-based CAD modeling tools (i.e., either conceptual modeling software such as Rhino, or sophisticated CAD programs such as CATIA) has important implications for architectural representation and resulting communication with other design and construction team members. Due to the accurate geometric definitions of these CAD environments, designers can represent geometries beyond the limits of Euclidean geometries or Cartesian projections of plan, elevation, and section. However, as such geometry is based on internal geometric constructs of the specific CAD environment instead of explicit abstractions on paper drawings; this raises questions in regard to geometry control conventions: (1) how do we communicate via digital models instead of drawings on paper? And (2) how do designers (the information producer) and contractors, fabricators (the information consumers) agree on the level of detail so that the model actually satisfies the needs for effective geometry control?

2.2 The Issues of Geometry Control

To understand the changing practice arrangements when collaborating on a digital model with ‘external’ team members, this paper introduces the concept of geometry control. Geometry control is defined as the capacity of the architect to execute the original design intent and concept as represented by his/her geometric definitions. Geometry control includes conformance with the architect’s geometric model to achieve the intended design qualities. The discussion includes coordination issues

introduced during the process of building system rationalization, as modifications to system geometries are introduced to enhance constructability through rationalization of component geometries. This paper concentrates on two types of issues for project geometry control: (1) transcription errors that are introduced via paper-based data transfer between stand-alone CAD applications of various design organizations (Gray and Hughes, 2001); and (2) discrepancies between the architect's geometric intentions and the fabrication means or constructability constraints.

In contrast to conventional forms founded on Euclidean geometries, in non-standard architectural shapes, the inherent geometric constructs within distinct CAD environments may slightly deviate from each other. Thus, it is important to establish modeling protocols to avoid the risk of transcription errors. On the other hand, technical refinement for the manufacturing of building components impose constraints on the ideal designer's geometry, to achieve economies of fabrication that may dictate the performance criteria for the system (Shelden, 2002). In non-standard projects, especially in projects incorporating compound surface geometries, the detailed surface characteristics of the building envelope require substantial design development of technical details to translate the conceptual shapes into actual building components. To address material behavior and other constructability concerns, the level of detail in the designer's model, must represent sufficient understanding of what the fabrication logic and details will impose on the form.

The degree to which the designer's model is accepted by external team members and how constructability requirements are incorporated into the design model is central to the inquiry of this research. We believe that this issue is also critical to the consideration of changes to modes of practice suggested by BIM-centric project delivery methods. These considerations are at odds with conventional divisions of responsibility between the design and construction teams, because aspects of the specific means and methods for construction are incorporated in the design intent of the model. Related changes to contractual project delivery models and the roles and responsibilities of the project participants is a topic in its own right for the future of building practice, hence the full treatment well beyond the scope of this paper. The question of who controls the model and when fabrication considerations are introduced into the project description is a distinction between the cases presented. If fabrication considerations are not incorporated into the design intent as expressed by the digital design model, the architect is at risk of loss of geometric control of the design intent.

3. CASE STUDIES

This part of the paper presents the three examined case studies (Ku, 2005). Table 1 summarizes the CAD programs that were utilized for collaboration between the architects, engineers, contractors, and fabricators. The type of CAD software (Schodek et al, 2005) ranged from entity-based drafting programs to design development and fabrication oriented programs. Table 2 illustrates the variety of conditions of locations, construction budget, project size, and delivery methods. The small sample of detailed case studies was appropriate to identify the key variables for model-based collaboration, but a larger number of case studies are necessary to generalize the findings to a practice model.

TABLE 1: Case study outline

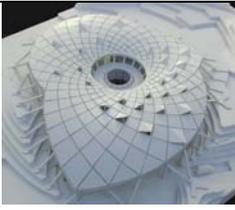
Project	Location (Completion Date)	CAD Systems	Geometric Characteristics
	Cambridge, USA (2004)	CATIA, AutoCAD SDS/2	The building enclosure is composed of brick and metal, highly articulated into smaller masses and planar and curvilinear surfaces. The geometric model facilitated computer-aided manufacturing of the complex shape of the sheet metal cladding systems and steel structure.
MIT Ray and Maria Stata Center			
	Yokohama, Japan (2002)	AutoCAD, AutoLisp VAD	The main feature of this building is the undulating roof structure which is a system of steel folds and girders. 3D geometric modeling was the primary project documentation means to describe the geometry to the contractors.
Yokohama Port Terminal			
	St. Austell, UK (2005)	Microstation V8, Excel spreadsheet, CADWORK	The project is characterized by a timber grid-shell roof structure that is based on phyllotactic patterns. The fabrication employed CNC-cutting processes driven by 3D geometric modeling.
Eden Project ERC			

TABLE 2 Case Study Contractual Data

Project	Location	Budget	Size	Type	Project Delivery Method
MIT STATA Center (Private project)	Cambridge, USA	US\$284m	730,000ft ² (67,800m ²)	Office, research, education	Construction Management (at-Risk)
Yokohama Port Terminal (Public project)	Yokohama, Japan	JP¥23.5b	43,843 m ²	Passenger cruise terminal	Design-Bid-Build (Lump-sum and design competition)
Eden ERC (Public project)	St. Austell, UK	UK£13m	5,190m ²	Education/ exhibition	Design-Build (GMP and 50/50 profit sharing)

3.1 The MIT Ray and Maria Stata Center

3.1.1 Description of geometric characteristics

The complex shape of the MIT Stata Center project consists of a variety of highly articulated tower masses that intertwine irregularly in alternating cladding material of brick, metal, and glass (Fig. 1). The volumes evolved through an iterative process that began with sculpting physical design models that were essential to capture Gehry's gestural hand sketches. Once the basic volume and shape emerged, the physical model was digitized into CATIA, and then reproduced into physical scale models using rapid-prototyping, CNC milling and hand-built modeling. Node points and spline geometries were refined and verified against physical models utilizing these techniques. The external surface geometry resulted in irregular flat and curved surfaces that established the reference geometry of the building.

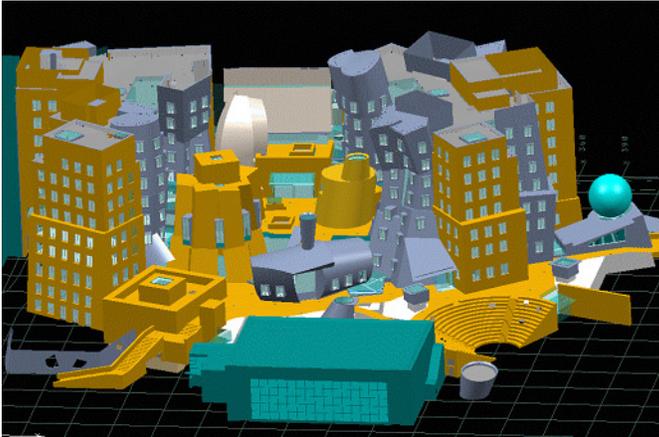


FIG. 1: MIT Stata Center CATIA Model (Source: Gehry Partners)

3.1.2 Organization of the 3D model

GP describes the CATIA model as the master model which governs geometry control of various building components, to rationalize the geometry, and to coordinate between various systems, and to calculate quantities. It documented five building systems (i.e., external surface geometry, cladding framing elements, cladding pattern and structural concrete and steel), representing the convergence of physical models and their corresponding digital descriptions. The external surface geometry was first established and then offset towards the interior to define the location of structural elements (e.g., concrete and structural steel) from the exterior wall. The interim space between the external surface and interior surface was used to define the cladding panel and framing components and attachment connectors.

3.1.3 Project organization

Gehry Partners (GP), LLP, the architect of the project, was selected by MIT, through a two-stage process. GP hired an associate architect, Cannon Design, who primarily designed the substructure, and laboratory programming, and the concrete model of the superstructure. The structural engineer, John Martin Associates, and a variety of consultants were hired by GP. The CM-at-Risk, Beacon Skanska (currently Skanska USA Building, Inc.) was brought on the team shortly after to collaborate with GP prior to construction. The metal cladding contractor, A. Zahner Company was hired by Skanska, to participate as design consultant of GP prior to the bid. The steel fabricator and erector CAPCO hired by Skanska also collaborated closely with GP for steel detailing via the designer's model. Fig. 2 illustrates the project organization.

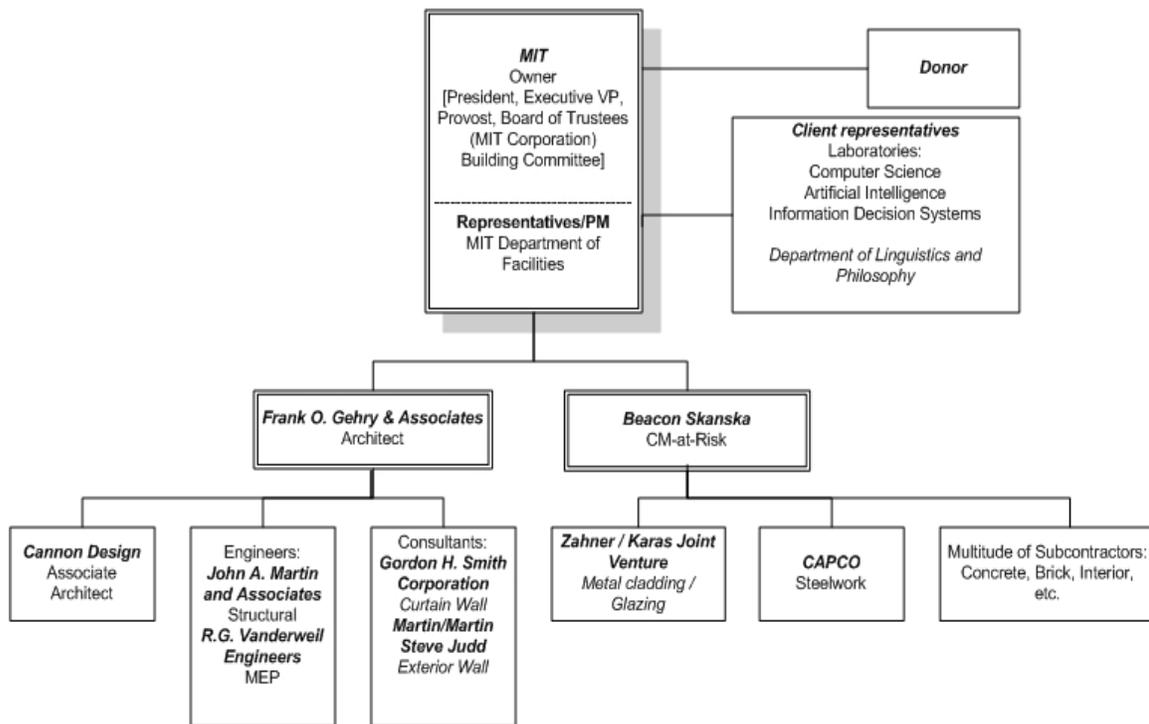


FIG. 2: The MIT Stata Center Project Organization

3.1.4 Collaboration on the model

The collaboration of the parties on the model required a clear definition of control. GP contractually issued the CATIA model as the primary project documentation to represent the building geometry and dimensions. Simultaneously, comprehensive 2D general arrangements drawings and detail drawings were referenced to the CATIA model, utilizing reference points and axes, to derive dimensions and position of elements in assemblies.

GP's design model was shared with their inner design team of the associate architect, structural engineer, and the façade consultant. Overlaid on GP's model, the structural engineer developed a structural steel wireframe and solid-based concrete structural model. Structural analysis was performed on the wire frame model, and the engineer's solid structural model was overlaid on the architectural and mechanical models to allow coordination of the systems. Environmental system engineers also utilized the CATIA model to perform day lighting studies.

Early in the process, Skanska assisted GP to define and determine the representational conventions, parameters and coordination issues associated with the application of CATIA. The level of data development and appropriate geometric representational formats not only had to be considered within the economical range of design fees, but furthermore correspond to the project responsibilities allocated to the design team. For example, the concrete model was composed in solid form, reflecting the surface necessary to develop the formwork. In contrast, the metal cladding was precisely defined in the external surfaces with all definitions of shingle patterns, panel joints, material, finishes, along with the cavity space for the cladding structure. The cavity space was designated to be refined by A. Zahner. Similarly, the steel frame developed by the structural engineer contained nominal steel members including web and flanges. Still, the connection detailing was left for the steel fabricator to define bolt holes, splices, weld specifications, etc. Skanska, also sent key personnel for training to GP's office and equipped their jobsite offices with the CATIA software to collaborate on the architect's model. James Becker, former President and CEO of Skanska, emphasized that it was important to gain Skanska

estimators' confidence in the digital quantities of GP. An estimating algorithm developed by GP allowed quantity take-offs from the CATIA model that supported project control efforts by the CM. Skanska also applied 4D modeling on the project (Hastings et al, 2003).

During construction document phase, design-assist arrangements were established between GP and A. Zahner for final engineering and detailed design of the metal façade panels. A. Zahner pointed out panel areas with conflicts or discontinuities. They reviewed the model to determine areas that required changes for watertightness or to enable fabrication. Robert A. Zahner, Vice President of A. Zahner Company, described this work as, "the time when we perform our engineering to make the concept expressed in the model constructible. There is no official stamping to validate the work we perform." The detailed panel design entailed adjustments to the architect's concrete model at slab edge conditions, as the fabrication approach introduced changes from the architect's original stick-built frame system to a prefabricated panel system. Incorporating the fabrication requirements, GP took responsibility to update the master model as part of their role for overall project coordination. Robert A. Zahner described this process as, "We never make a change to the master model. If something is wrong, the process is to submit a Request for Interpretation that may need changes to GP's model but the change is facilitated and performed by the architects."

For all subcontractor pre-bid meetings, Skanska included a CATIA demonstration, and specified CATIA as a project requirement in descriptions and setup packages. Successful bidders were required to be (or become) CATIA capable on one of 3 pre-defined levels: level 1 for full use including 3D shop models (e.g., metal cladding and steelwork); level 2 for familiarity with a viewer product as well as the ability to extract dimensions when needed (e.g., concrete structure); and level 3 for basically no 3D requirement (e.g., contractors for toilet partitions, carpet, paint, etc., who typically did not need 3D). For example, the concrete subcontractor only used 2D drawings for formwork fabrication and coordinates to calculate concrete volumes and to set out the formwork (Fig. 3).

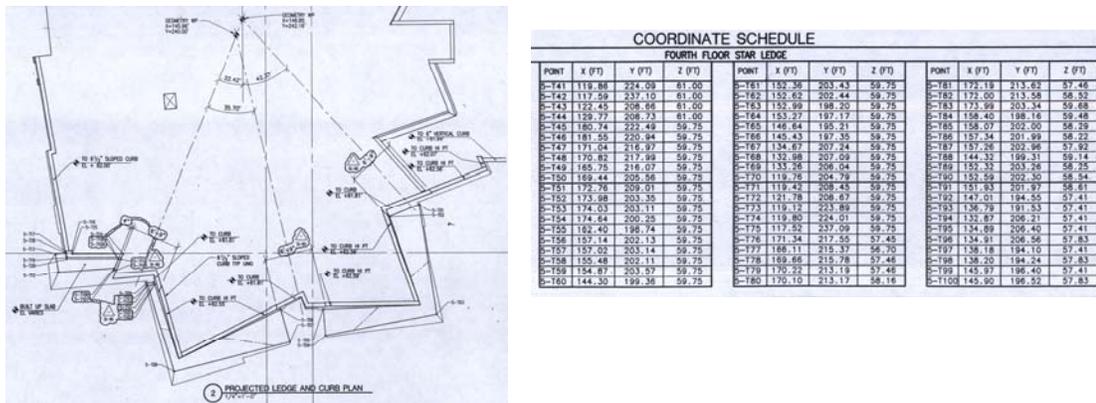


FIG. 3: 2D representation of concrete structure and floor node point coordinates for formwork construction (Source: Cannon Design)

During pre-construction, the architect issued his digital models via an FTP site for sharing within the 'inner' design team and with the general contractor. For construction, Skanska acted as the information manager that maintained an FTP server on the jobsite to manage the data transfer with its subcontractors. In particular, Skanska managed the versions and distribution of the latest files and updates to the subcontractors. An extranet service hosted by MIT was employed to control the flow of documents and to document who was made aware of what and when.

To track changes GP used a feature in CATIA V4 called 'Groups'. Any elements that had changed from the previous model were placed in 'Group 1' so that the contractors could easily highlight them, similar to clouding marks on 2D document revisions. Model revisions were tracked on a simple

spreadsheet. Skanska set up a read-only directory on their server for current models. When a new model was issued, it was added to this directory and the old one was archived. Team members were trained to only use and build from models in the current directory.

For shop drawing review purposes, subcontractors, submitted traditional 2D shop drawings (Fig. 4) as well as 3D shop models (Fig. 5). Skanska and GP typically reviewed the shop models for geometry, sizing, system components and coordination with other shop models, while the 2D shop drawings primarily illustrated the construction details. Both were necessary to fully review the systems of the subcontractors.

Skanska also used surveying software, ‘Eagle Point’, ‘Survey’, and a ‘Total Station’ to transfer node point coordinates from the CATIA model to the field.

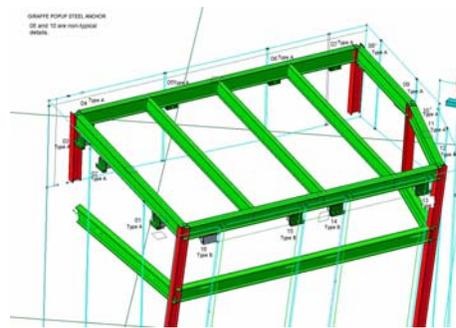
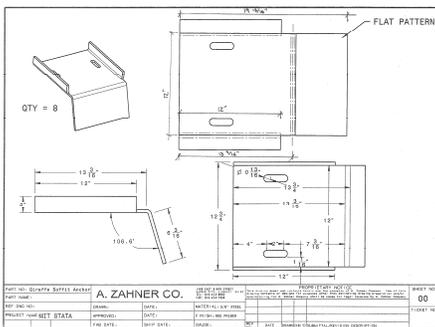


FIG. 4: Shop drawing of a metal cladding component (Source: A. Zahner)

FIG. 5: Detailed shop model showing Zahner's cladding framing component (green angle attachments and blue-lined frame elements) on top of steel structure (Source: A. Zahner)

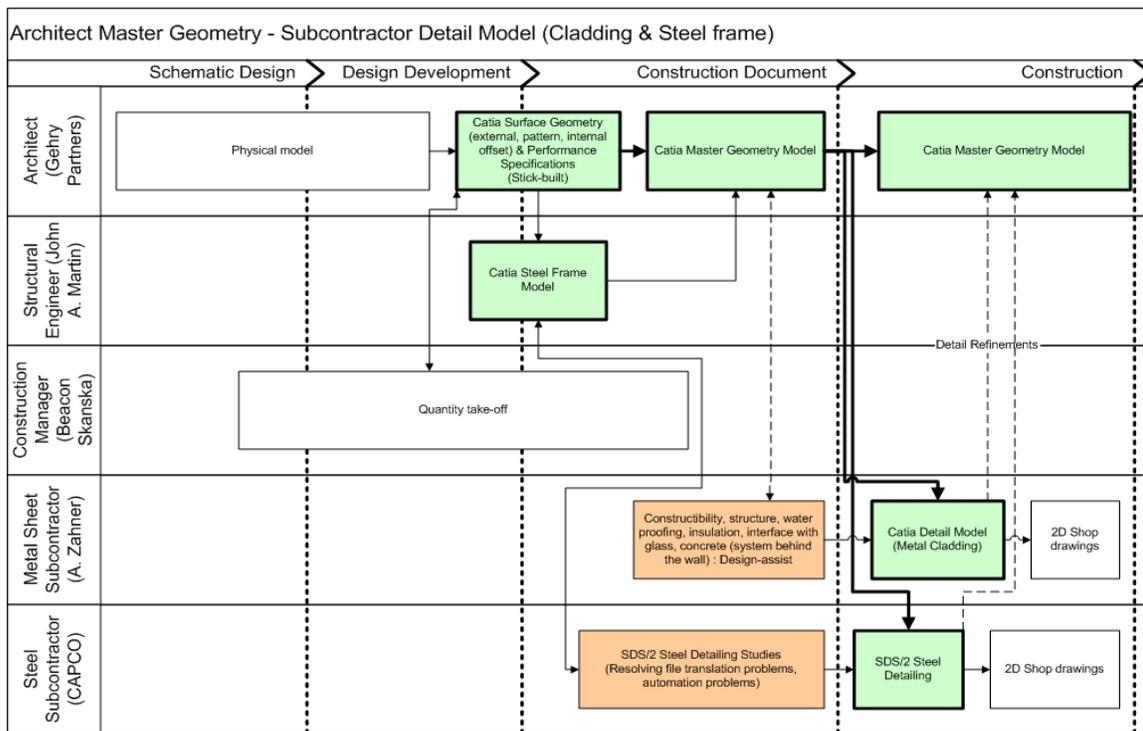


FIG. 6: Control of digital model and data-sharing of participants

Fig. 6 summarizes the main collaborators on the 3D model and data exchange. GP's design process formulated around the master model, controlled by the architect and directly utilized by the external design team (i.e., the general contractor and subcontractors). The master model was contractually the primary reference for geometry and dimensions, partially incorporating input from the fabricators. The steelwork contractor transferred CATIA data into their SDS/2 steel detailing software which selectively was re-imported into the master model.

3.2 The Yokohama Port Terminal

3.2.1 Description of geometric characteristics

The primary geometric complexity of this project is in the undulating structural surface of the roof and supporting steel folds and girder structure. Foreign Office Architects (FOA) started from a formal concept of a warped surface to emulate a topographical ground. Applying a strategy that integrates the surface geometry and bifurcations with the building circulation diagram, the building mass is spread out to occupy the maximum area available within the pier site. The initial curved roof surface was generated by sections and ruled surfaces that morphed adjacent sections together (Fig. 7, 8). During design development, the architects refined a structural concept of a structural one-way folds system composed of large girders and arching folds. This idea had been originated to relate to the local tradition of Japanese "Origami" construction. To enhance constructability of the scheme, the geometry of the girders was standardized through the use of repetitive components. The architects developed a technique producing "control lines" (i.e., complex curves composed of combined arc segments instead of the original splines to simplify representation) for the longitudinal girders. Consequently, regular girder cross sections were swept along the control lines to generate the girders. The transverse folds geometry then was locally adjusted to connect to the girder stiffener locations. Thus the final shape evolved into a composition of simplified linear sections as opposed to the original morphed sections. While the on a global scale the undulation was maintained, the local geometry was rationalized and standardized. The development of the scheme of linear folds segments and the swept girder sections allowed both fabrication economies through increased repetition, and simultaneously, simplified geometric representation through the explicit faceting of triangulated folds and geometric generation rules for the girder construction (Fig. 9).



FIG. 7: FOA's rendering of the Yokohama Port Terminal (Source: FOA)

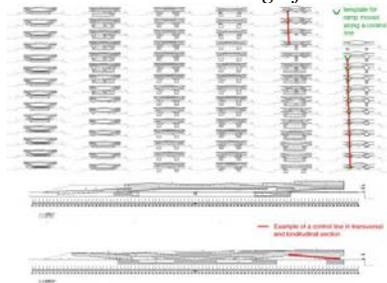


FIG. 8: Transverse sections that guided the morphed surface generation and longitudinal girders (Source: FOA)

3.2.2 Organization of the 3D model

In addition to the primary geometry for the steel structure (folds and girders), FOA created 3D representations of the glazing, handrails and wood deck components (Fig. 9). The steel structure model was the main model being used for communication with the construction team.

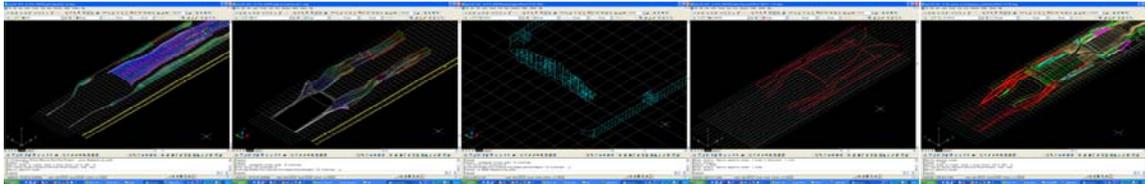


FIG. 9: FOA AutoCAD model of the steel structure (folds, girder), glazing, handrails, and wood deck (Source: FOA)

3.2.3 Project organization

After selecting FOA through an international design competition in 1996, the project went through an extended period of two Basic Design phases (corresponding to schematic design and design development in the US system: This is based on the author's interpretation. Due to differences between the Japanese and US design practice, it is difficult to exactly match the corresponding design phases. The Japanese general contractors typically take on more detailed design responsibilities and hence the architect's construction documentation may include fewer details than in the US system.). Finally in January 1999, the City of Yokohama decided to proceed with the construction of the project and announced the plans to open the new terminal in time for the 2002 FIFA World to be used during the games.

As a public project, both the local and state government – the City of Yokohama and the Ministry of Construction (i.e., renamed to Ministry of Land, Infrastructure and Transport) – were closely involved with the building process. The Port & Harbor Bureau (PHB) was responsible for overall project management, composed of: (1) Osanbashi Terminal Construction subdivision (one director, one manager, and four assistant managers) and (2) Design Division (one manager, one assistant manager, five staff members).

This project used a traditional delivery method because other alternative delivery methods had not been used yet in public projects at that time. Because of the scale of the project, the Port & Harbor Bureau divided the bid packages into three zones (47%, 30%, 23% in size), so that the project could stimulate the industry by allowing as many contractors as possible to participate in the project. General contractors were allowed to bid for one or more zones.

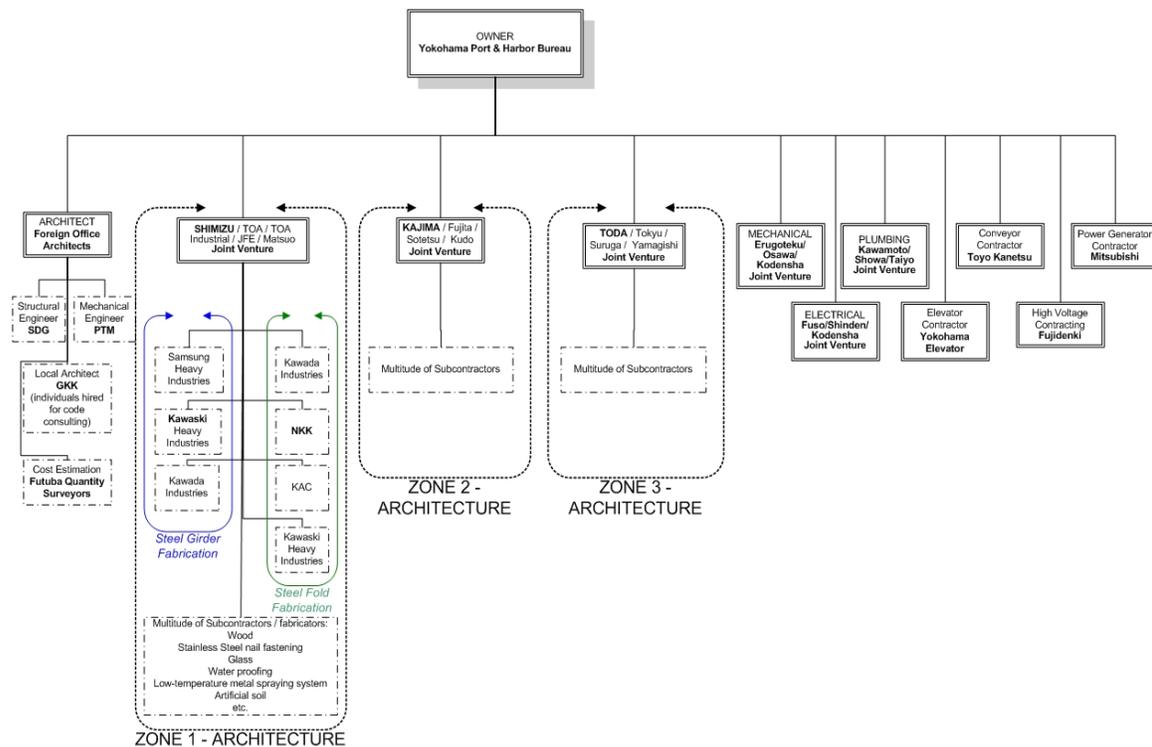


FIG. 10: Project organization of the Yokohama Port Terminal project.

Although FOA did not have a local presence in Japan, the Japanese architectural system allowed FOA to legally practice under the license of their staff who were registered architects in Japan. FOA hired some individuals from GKK, a large local architectural firm, for building code consulting. For structural engineering, the architect employed a local firm, SDG, who had established a reputation working with international architects such as Rafael Vinoly on the Tokyo International Forum. During the design competition, FOA had briefly collaborated with Ove Arup, an international engineering firm well known for its innovative approaches, to suggest a creative structural fold concept. The architect also hired the mechanical engineer, PT Morimura, large local services engineering firm. In addition, FOA employed Futaba Quantity Surveyors for cost estimation.

The Port and Harbor Bureau awarded each of the three construction zones to large joint ventures lead by large general contractors: (1) Zone 1 was led by Shimizu Corporation, (2) Zone 2 by Kajima Corporation, and (3) Zone 3 by Toda Corporation. Each joint venture had separate contracts with the owner, each managing and only responsible for their own zones. Thus, each joint venture selected their subcontractors, information technology platforms and CAD systems, without the involvement of the owner and FOA in the qualification processes. The joint ventures reported to the owner and FOA after awarding the subcontracts. Fig. 10 represents the overall project organization.

3.2.4 Collaboration on the model

The design teams' intensive efforts in the evolution of the structural system to implement the original curved surface concept, represents the main technical innovation of this project. The structure was developed together by FOA and SDG utilizing the AutoCAD model to refine the geometry. The final model satisfied fabrication and budget concerns and also established clear geometric rules of form generation that the construction team could understand. During construction FOA, issued a non-contractual 3D model along with 2D construction documents, to communicate the complex geometry of the folds and girder structure. Because of time constraints FOA did not issue node point coordinates of the structural components to supplement the 3D model. On the other hand, FOA provided the

geometric generation rules of the girders to assist the interpretation of the model (Fig. 11). The architects explained the applied shape generation rules for setting out of girder templates. This strategy allowed accommodation of manufacturing and construction considerations and necessary modifications that would surface during the construction process.

1. Generator and Paths: Paths of the girder sectional templates are combination of arcs (circles) and lines, rotated in longitudinal section for ramps.
2. Dimensions and Rolling: The paths are divided and 2D lines of the girder stiffener sections are manually copied and placed along the path. These 2D templates were modeled into solid objects during construction documentation stage.
3. Sectioning with Planes: The girder sections were trimmed by intersecting planes such as floors and inclined planes.
4. Rings and Junctions: Closing of certain girder templates locations into rings and combination of two floor levels of girders into joint structures.
5. Structural Continuity: Girders are continuous all along the building in longitudinal direction. Therefore, one ramp starts from the ground and needs to be connected to another at the upper level.

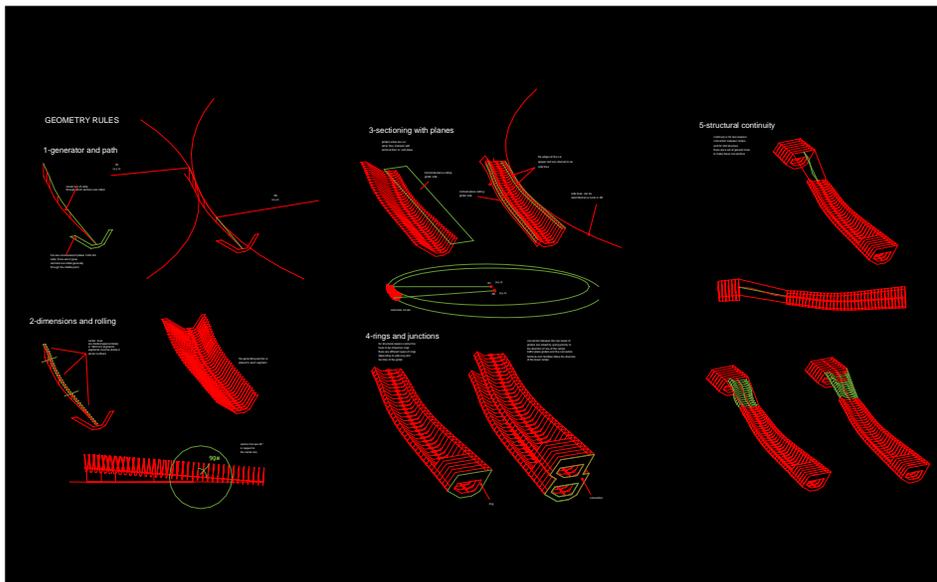


FIG. 11: FOA's girder structure geometry generation rules (Source: Shimizu)

From a modeling standpoint, Yoichi Obi, Project Manager of the Shimizu portion, explained that they extracted coordinates from the designer's 3D model and constructed their own model. Additional information (e.g. thickness of steel plates, sections of the members), derived from the architect's 2D drawings, were added and modeled within their proprietary CAD platform VAD (Fig. 15, 16).

Each of the three joint ventures utilized different CAD platforms: Shimizu Corporation utilized their VAD system, while Kajima and Toda used AutoCAD r14.

Shimizu's engineers used the coordinates extracted from FOA's 3D model, to develop and refine their own 3D model for construction purposes, including cost management, schedule management and construction management. Shimizu's 3D model comprised steel elements and imported HVAC data (i.e., 2D AutoCAD drawing and 3D model) from the mechanical contractors to communicate and coordinate with the subcontractors (Fig. 12, 13). Shimizu used the Yokohama project as an opportunity to test their VAD system modeling the complex geometry of the project. Acting as project coordinator, Shimizu maintained their own model independently from the architect's model. The model was used for clash detection between the structure, the PC steel cables, and the MEP systems. In addition, the thickness of the steel plates where stress concentration occurred was checked to analyze deflection

during site assembly of the structural folds and girders. Yochi Obi described, “FOA’s model was a geometry model mainly focusing on the shape of the building to illustrate the designer’s idea. Shimizu’s model contained more details, including the thickness of the elements, joints between differing thickness, to check constructability, coordination, and specification. We needed to strictly obey to the designer’s drawing, especially in this project, because the shape was so important. Shimizu primarily used the coordinates from FOA’s model. Then we used the designer’s drawings and our model to work from the coordinates.”

Because of tight schedule constraints the structural steel fabrication involved five factories for the girder production and eight factories for the folds construction. While the Shimizu shared node point coordinates with the fabricators who utilized 3D modeling for production, the subcontractors only submitted 2D shop drawings instead of sharing 3D data for review and approval. The general contractors acted as mediators between the subcontractors and FOA, to check the accuracy of the fabrication geometry. However, the shop drawing approval was very challenging because of difficulties to correlate the 2D shop drawings with the 3D design geometry under the short timeframe (Fig. 14).

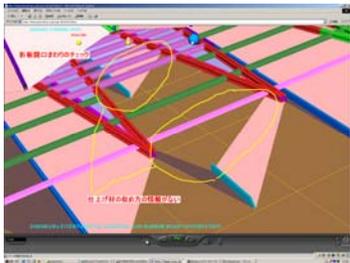


FIG. 12: Shimizu VAD folds model (Source: Shimizu)

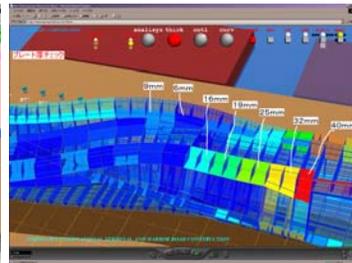


FIG. 13: Shimizu VAD girder model with stiffener plate (Source: Shimizu)

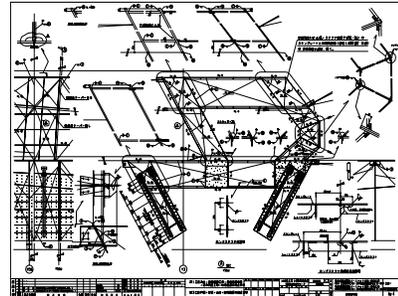


FIG. 14: Shop drawing of girder connection detail (Source: Shimizu)

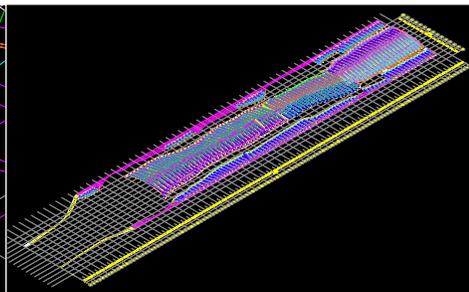
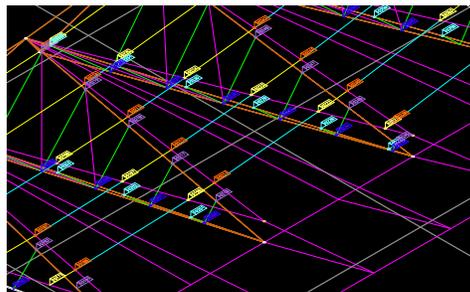


FIG. 15: Shimizu VAD folds model with node point coordinate annotation and folds global model view (Source: Shimizu)

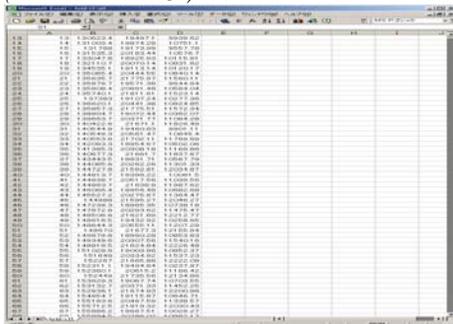


FIG. 16: Shimizu folds model extracted node point coordinate values on spreadsheet (Source: Shimizu)

Fig. 17 illustrates the structural model exchange and the main participants including the Shimizu joint venture division, and the various steel folds and girder factories. It is recognized that each participant created and operated on their model. While the architect's model provided the base geometry of the project, the control of fabrication detailing and construction coordination was transferred to the general contractor. Thus, once the node point coordinates were extracted from the architect's model, the general contractor maintained its own 3D database to control the construction and fabrication processes. The communication between the general contractor and subcontractors relied on 2D shop drawings causing substantial coordination challenges with the designer's 3D geometry and the factories' respective CAD platforms.

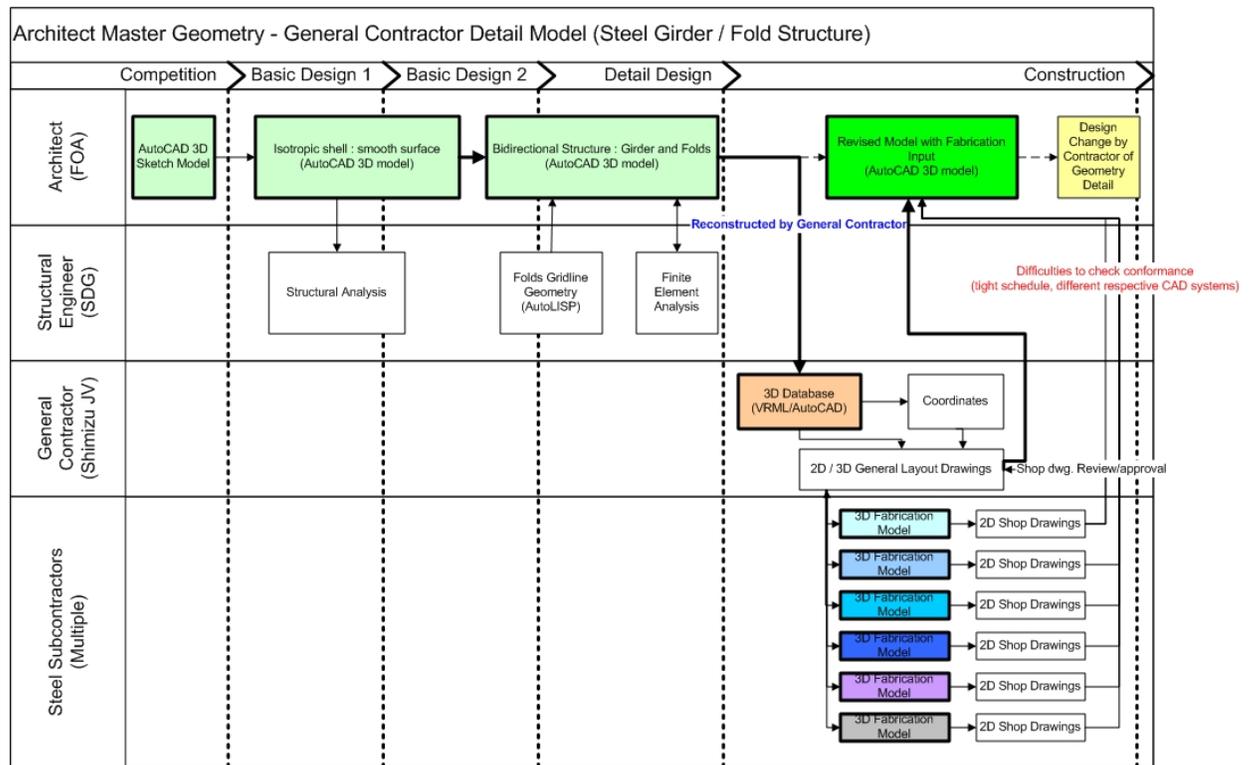


FIG. 17: Control of digital model and data-sharing of participants

3.3 The Eden Educational Resource Center (ERC) Project

3.3.1 Description of geometric characteristics

The form evolved from the idea of mapping Fibonacci spiral grids onto a torus (Fig. 19, 20) which was applied to a timber grid shell concept. This grid pattern evolved into a spiral phyllotaxis pattern which is observed in the arrangement of scales on a pinecone or the seeds in a sunflower head, to produce an efficient structural system. A parametrical formula of the primary roof structure geometry was generated in an Excel spreadsheet which calculated the two dimensional (2D) grid points (i.e. in xy coordinates) of the spiral timber beam node coordinates and the z coordinate of the timber beam top surface (Fig. 18). The architects then utilized 3D B-Splines (i.e. predefined free form curves in the MicroStation software) to define the shape of the structural elements and to apply triangulated in-fill roof panels.

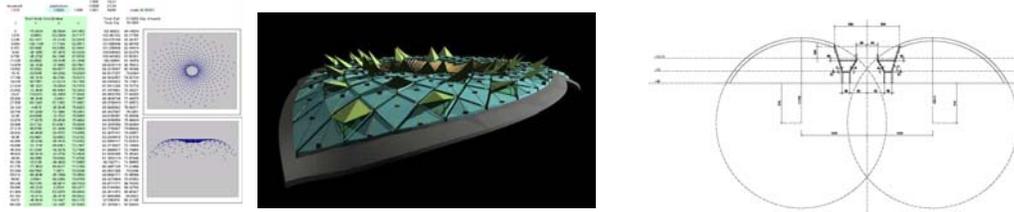


FIG. 18: Phyllotaxis pattern generation in Excel spreadsheet and Rendering (Source: Grimshaw)

FIG. 19: Section view of torus (Source: Grimshaw)

3.3.2 Organization of the 3D model

The application of the model was exclusively concerned with the final engineering and fabrication of the timber roof structure. The architect's model only contained the timber girders as single lines, and roof panels by their top surfaces, omitting any additional details. Node point coordinates were issued as part of the legally binding contract documents, while the 3D model was included as a reference model to be used by subcontractors at their own responsibility (Fig. 20).

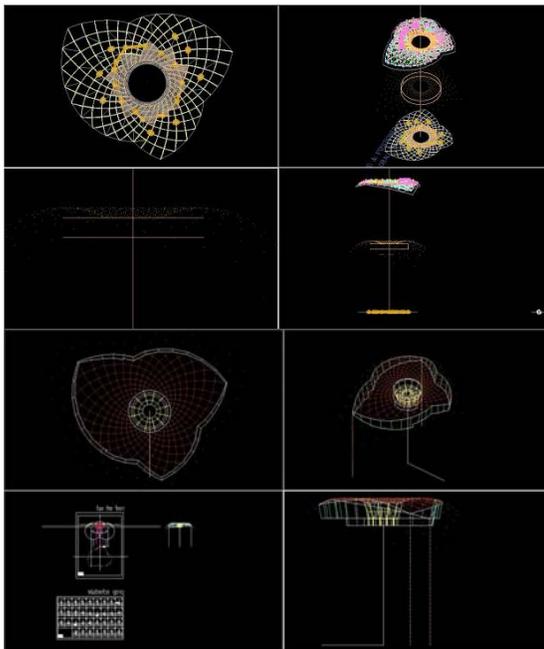


FIG. 20: MicroStation model of timber grid shell and roof panels (Source: Grimshaw)

3.3.3 Project organization

The Eden Charitable Trust set up Eden Project Limited to act as the legal entity responsible for development and management of the project and its commercial success. Davis Langdon Everest was brought on as the owner's project manager and cost consultant, and Scott Wilson as design manager to verify drawings and engineering. Eden Project Ltd (Eden), the owner, complying with the guidelines for public funded projects, advertised the ERC job in the Official Journal of the European Community, for a design-build project. With only one competitor against McAlpine Joint Venture (McAJV), the owner reselected Nicholas Grimshaw and Partners (Grimshaw), Anthony Hunt Associates (Hunt), Buro Happold (Happold), and McAJV. The selected design and construction firms had a long history of working together since the mid-1990s when the earlier phases of the biomes construction were initiated. Many of the individuals had collaborated with each other since the previous Biome phases, growing from junior staff status to project manager level, thus forming a strong trust-based relationship. In addition, Eden also hired sculptor Peter Randall-Page to introduce art into the building.

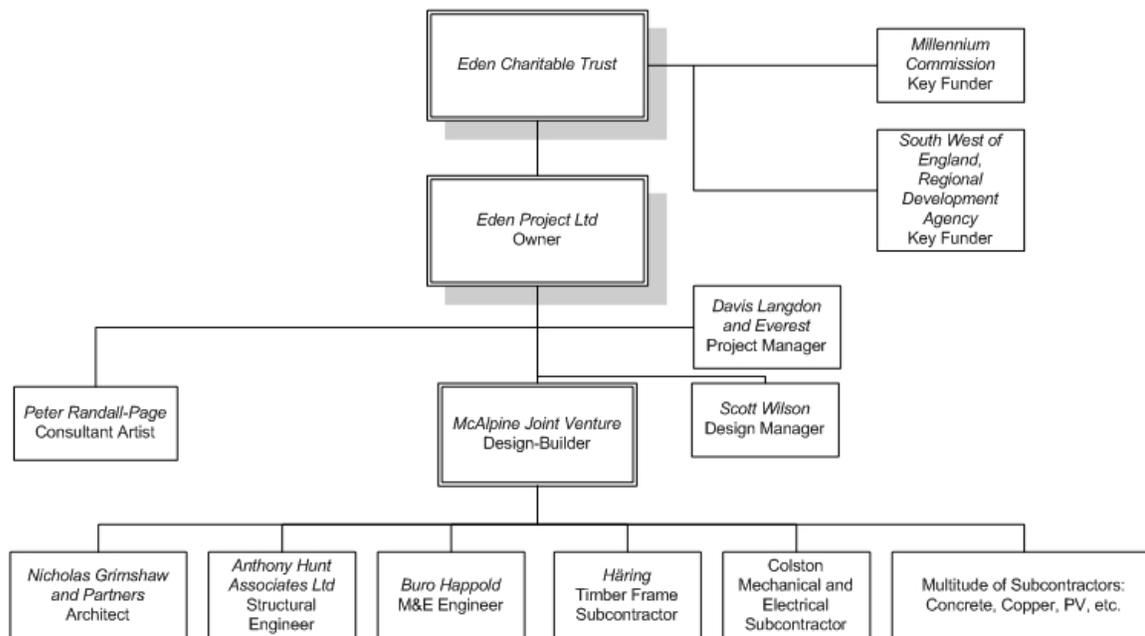


FIG. 21: The Eden ERC project organization

Following the same strategy of the first stages, McAJV entered into contract with a Guaranteed Maximum Price (GMP) with profit sharing provisions, splitting 50/50 between the contractor and owner. After McAJV negotiated a GMP contract with Eden, the design team members were hired by McAJV via ‘novation’ (i.e. the transition process of the design team from the owner to the contractor). Fig. 21 shows the project organization structure.

3.3.4 Collaboration on the model

Based on relatively straightforward geometric principles of double-curved B-Splines, Grimshaw’s 3D CAD model was made available to every contractor who needed it. Only Häring, the timber frame subcontractor actually had capability to handle the model while other contractors depended on 2D information. Both Grimshaw and Hunt, in MicroStation V8, had collaboratively worked on the 3D timber grid shell model, making the structural connections between columns to girders, and girders to girders, and architecturally refining the roof panel cladding details. Based on the structural engineer’s calculations the girder were determined to be 800mm-deep glue laminated roof beams, and the setting out points had been established at the top of the beams, allowing for adequate headroom space beneath. This arrangement enabled the architect to continue working on the roof panel design, while Häring began working on the roof beam fabrication.

Although Grimshaw had shared their 3D model, Häring re-built from Grimshaw’s node point coordinates their 3D model in the CADWORK software (Fig. 22, 23). Jerry Tate, Grimshaw project architect, explained that this was because of file translation problems between MicroStation and the CADWORK software. The CADWORK software enables direct translation of a 3D model into CNC machine code to cut and fabricate beams and panels (Fig. 22). During final engineering, Häring submitted shop drawings for approval usually as email-attached PDF files which were printed out by the architect and structural engineer and reviewed as paper copies, then physically stamped to assign a status. This reviewed/approved drawing was scanned back and returned as PDF file attachment to the contractor.

The architect, structural engineer, and timber subcontractor exchanged information to coordinate the roof structure with foundations, roof cladding packages, and internal walls with embedded floor steel frames for wall stud connections. Sharing mainly coordinates and DWG/DXF files, it transpired at a

relatively late stage in the development of the structure that Häring's grid file slightly deviated from Grimshaw's B-spline curves. This occurred because gluelam specific CAD packages generate more realistic gluelam curves than general CAD packages. Accordingly, the architect adopted Häring's grid file and swapped the DXF grid files, adjusting interior wall lines and cladding packages to suit Häring's roof component geometry.

In addition to 3D model-based geometry definition, Grimshaw and Anthony Hunt produced numerous 2D sketches to communicate design intentions. The scope and applicability of these details depended on the trade contractors' actual fabrication processes and were adjusted in close collaboration between the design team and the trade contractors taking into account actual production concerns. Grimshaw's sketches convey broader intentions, said Jerry Tate, "We draw everything but kind of badly. We don't know the actual sizes of the elements, but we know what we want it to look like. It may be aesthetic, but in general it's more about coordinating the interface between different trades."

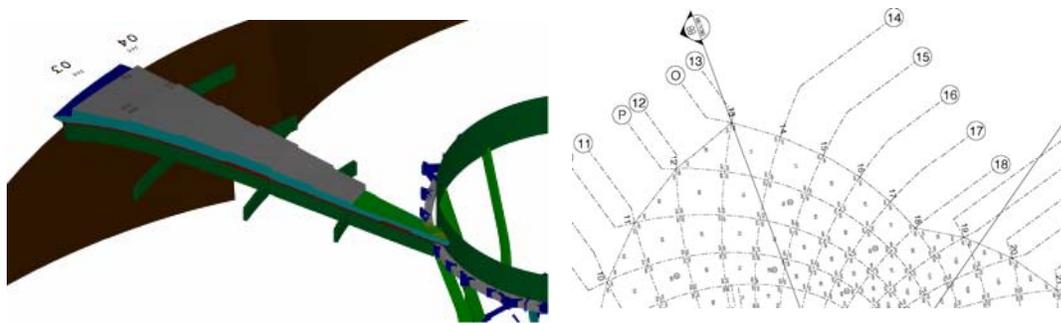


FIG. 22: Eden ERC project subcontractor's model (Source: Grimshaw)

FIG. 23: Eden ERC project architect's node coordinates (Source: Grimshaw)

Drawing file exchange occurred primarily via email attachments of 2D/3D CAD drawing files, PDF converted files (i.e. either from CAD drawing files or paper scanned drawings). As there was no central master model maintained on a centralized server or extranet, each consultant and contractor worked on their own set of files. The architect's construction drawings were generally issued in PDF format either converted from scanned signed-off paper design sketches, or directly converted from dated MicroStation CAD files accompanied with a signed-off and scanned official letter. Fig. 24 shows the model flow from the design team to the timber frame contractor and highlights geometry translation via node point coordinates to Häring during construction documentation phase.

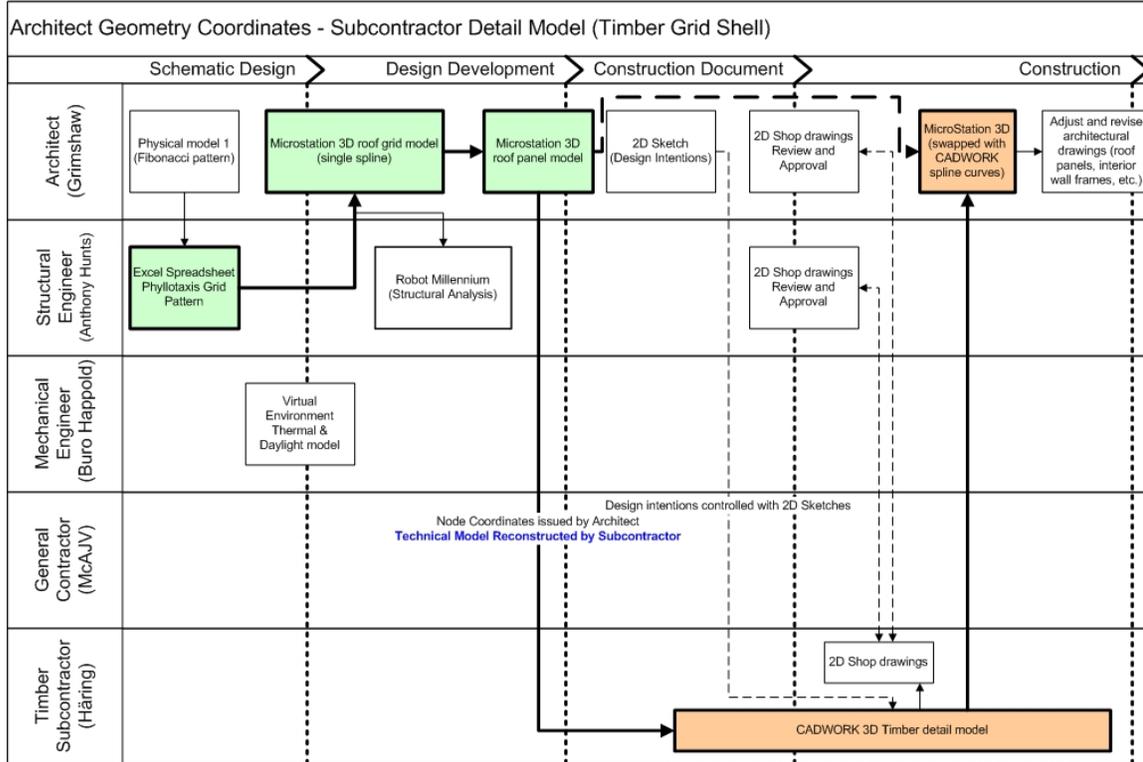


FIG. 24: Control of digital model and data-sharing of participants in the Eden ERC project

4. ANALYSES AND FINDINGS

Having outlined the particular process of model-based design development and construction on three case studies, the role of 3D modeling as a vehicle for geometry control is examined.

4.1 Classifying Geometry Control – Beyond ‘Design Intent’

In traditional architectural practice, contract documents, including technical plans and specifications capture the intent of the building to be constructed. These documents are handed over to the builder who is responsible for the execution of ‘means and methods’ complying with the design intent (Allen et al, 2005). Thus, practice conventions require communication via working drawings that are being translated by contractors, manufacturers, subcontractors, and consultants, for constructability review and shop drawing development (Pietroforte, 1995). Traditional paper drawings, utilizing abstractions in plan, elevation, and section, are usually sufficient for the designer’s geometry control when sharing normative shapes through Euclidean geometries or Platonic forms. However, the use of compound curvature surfaces or NURBS model creates ambiguities when the designer attempts to transcribe the model into paper format. The designer carries potential risk of design changes, particularly, when design responsibility is divided between an ‘inner’ and ‘external’ design team. For example, because of liability reasons an ‘executive architect’ may not directly work on a non-contractual model of a ‘design architect’ but rather rebuild the model. This division between a ‘design architect’ and ‘executive architect’ can result in loss of ‘geometric intent’ by transcription errors that are either introduced by mistake or by misunderstanding. Similarly, the geometric logics of fabrication and construction may introduce uncoordinated changes to the design intent of a 3D model created by the architect if not facilitated by an appropriate communication platform and protocol.

4.1.1 The contractual model

The case of the MIT Stata Center presents a *digitally-mediated* geometry control process that is based on GP's contractual model. GP's model-based process evolved to augment Frank Gehry's long-established sketch-and-physical-modeling design methodology. This methodology provided GP with the means to control geometries and dimensions and to document projects to maintain and execute the 'subtle' gestures of Gehry's hand sketches integrating knowledge of manufacturing and construction early in the design process (Zaera, 1995). The model was the primary documentation governing the design geometry while drawings on paper were referred to for construction detailing. GP refers to this design process as the 'master model methodology' (Shelden, 2002). Accordingly, downstream participants who operated on digital models, including the CM-at-risk, metal cladding subcontractor and steel contractor, directly imported the model to develop their own work. GP employed various mechanisms to facilitate this digitally-mediated process. Their enhanced geometry control through the 3D model relied on design-for-fabrication communication channels (design-assist arrangement with A. Zahner) which allowed GP to incorporate prescriptive detailing geometries before issuing the construction document model. This was critical to maintain their central role as project coordinator of the model. By involving not only the fabrication companies who already possessed modeling capabilities, but also closely collaborating with the CM-at-risk for quantity take-off and schedule coordination, the architect acquired the necessary support to establish the role of the 3D model as the central database for geometry control.

4.1.2 The reference model

On the other hand, in the Eden ERC project and Yokohama Port Terminal project, the respective design teams relied on 3D modeling both for form generation and representation purposes. Regarding project documentation for bidding and construction, both projects' architects supplied the model as supplementary documentation, while the construction participants were using the design model at their own responsibilities. In both projects, the geometry was translated via node point coordinates. Both projects' geometries, conceptualized in CAD environments, are structural floor/roof surfaces in comparison to the exterior cladding shapes of the MIT Stata Center project. In the Eden project, node point coordinates were supplied by the architect as legal documentation, while in the Yokohama project, node point coordinates were directly shared via the architect's referential 3D model, mainly because of a very tight schedule. Farshid Moussavi, co-founder of FOA, explained, "In our case, we adopted 3D modeling never as an interface to communicate with other participants. It is a way to conceptualize as we can not design in two-dimensions. If you design in 2D and then translate it into 3D, you loose opportunities that only emerge in three-dimensions."

The model recipients, such as the timber frame contractor in the Eden ERC project, or Shimizu, one of the general contractors in the Yokohama project, built their own model utilizing the architects' node coordinates at their own risk. This procedure coincides with the traditional distribution of design responsibilities between the designer and recipient, where the recipients are both responsible for the design information they create and control of their component geometries independent of the designer's model. In both case studies, the recipients added more technical details for project coordination and production.

4.1.3 Beyond design intent

The contrast of design responsibilities around the 3D model between the MIT Stata case study and the two other case studies, illustrates that control of the geometric model coincides with who takes charge of the overall project coordination. To establish the 3D model as the primary project documentation for geometry control and dimensions, GP incorporated inputs of fabrication geometries during construction documentation phase, which specified particular construction means and methods of the metal panel system. Because this caused liability issues within current practice conventions that acknowledge the architect's documentation only as design intent, GP devised an elaborate set of

disclaimers to waive any contractual responsibilities associated with the incorporation of means and methods in the 3D model.

The architects of the Eden ERC and Yokohama Port Terminal case studies issued the 3D models for design intent only. In the former case study, the final engineering and geometric component model of the timber gridshell structure is the responsibility of the timber frame contractor. Subtle deviations between the architect's and subcontractor's component geometries were observed as a result of shortcoming of node point coordinates as the coordination mechanism between the two systems. In the latter case study, Shimizu one of the general contractors, who carried design liability, took actual ownership by reconstructing their coordination model and managing the various building systems and construction process on their technical model.

4.2 Team characteristics

We observed in all three case studies, innovative collaboration between the main projects participants that allowed the successful implementation of the projects. However, to understand the differences in attitudes towards 3D modeling, the team characteristics are analyzed.

4.2.1 The owner

Public owners are usually more constrained than private owners in regard to procurement strategies and regulations. As a public project, the Yokohama project had to use a traditional bidding strategy. The owners were not interested in including the CAD model as part of the contract documents because of bidding regulations that prohibit impropriety.

The Eden ERC owner, a publicly funded non-profit organization, used a design-build strategy. In this case, use of modeling was at the risk of the design-build team.

The MIT Stata project as a private institutional project was not constrained by public bidding regulations. The owner chose a CM-at-risk to handle the complexities of the project and also endorsed the contractual use of GP's 3D model for collaboration. MIT was supporting the use of GP's model because it understood the reduced risk of better coordinated project documentation that result in better project control and fewer design errors.

4.2.2 The architect

Among the three architects, GP manifests an explicit 'master model methodology' for geometry communication and control purposes. This methodology evolved from the need to translate Gehry's gestural hand sketches and tactile physical modeling process into feasible construction components. The other two architects, FOA and Grimshaw, focused on the generative potential of a set of geometric rules that addressed construction constraints and created the complex shapes. Rather than utilizing the model as coordination means with external team members, the main usage was for form conception and geometric representation.

While GP and Grimshaw have had well established practices, FOA was a small and young firm, with little track record when they were selected through an international design competition for the Yokohama project. Therefore, FOA chose to comply with industry standard software AutoCAD so that recipients could easily use their model. GP's master model methodology in contrast, based on a non-standard CAD platform (CATIA), illustrates a top-down information data sharing strategy which leveraged Gehry's unique position as a well renowned signature architect. GP took the role of project coordinator of the model to gain better project control and budget control.

4.2.3 The general contractor

The three examined case studies, demonstrate close and innovative collaboration between the designers, contractors, and fabricators, although three different project delivery methods were employed (i.e., CM-at-Risk; Design-Bid-Build; Design-Build). However, the distribution of design

responsibilities regarding model-based information sharing differs among the projects. Most notably varies the role of the general contractors. In the MIT project, Skanska, the CM-at-Risk, acted as a *facilitator* between GP and A. Zahner, the metal cladding contractor. Skanska employed A. Zahner, to arrange early information input from the trades into GP's model and design. Thus, A. Zahner acted as advisor to GP during construction documentation phases, to discuss the real needs for construction and the appropriate level of detail required for fabrication.

The team organization of the Yokohama project followed a different approach. The three joint ventures of general contractors acted as *mediators* between FOA and the fabricators. They assumed the role of proactive project coordinators who coordinated and controlled fabrication strategies and channeled design intent sometimes conflicting with the designer's intent (Ferre, 2002). It is noteworthy to understand the greater extent of design roles of general contractors in the Japanese construction system. First, the large general contractors conduct substantial amounts of design-build work in private project (Coxe, 1994), generally carrying design responsibilities. Second, unlike other countries, the large construction firms carry large research divisions engaged in development of construction systems, methods, and materials, (Coxe, 1994), thus bridging information between design and construction. Last, general contractors hold professional liability. These factors contribute to the greater design responsibilities and roles of the general contractor as overall project coordinator.

In the Eden project, as a design-build project, the general contractor took a reactive position to the model. The general contractor did not get involved in the model-based information exchange between Grimshaw and the timber frame contractor, because they saw no value in the model for themselves. In parallel, Grimshaw carefully issued the model as a reference document to protect them against potential liability issues related to sharing a legally binding 3D model.

These distinct team roles correlate to respective approaches to risk allocation in the projects which are discussed later in this paper.

4.2.4 The specialty contractor

The subcontractors who manage the production process are the ultimate consumers that should pull the information from the information producer, the designer (Gray and Hughes, 2001). Thus, designers need to agree with the contractors who will use the design model in their production processes, on the level of detail of the model, the data format, and the data compatibility between the CAD/CAM platforms. Sophisticated sub-contractors have adopted 3D CAD technologies to improve their fabrication procedures, and are in well-equipped position to collaborate via model-based information. One example is the steel industry that has converted towards complete 3D detailing and CNC fabrication (Hartman and Fischer, 2007). Another good example is specialty contractors such as A. Zahner, the metal cladding manufacturer, in the MIT project. Because such companies are operating in a highly specialized market niche, it is observed that GP has long-term relationships with such companies for repeating business. This direct design communication is reinforced through innovative delivery strategies such as design-assist delivery methods which allow early information input and prescriptive specification of products before the bidding process. Similarly, in the Eden case study, early collaborations between the timber frame contractor and the architect were observed. Data exchange via specific CAD/CAM platforms used by these companies is a key aspect of these collaborations. This type of relationship is less applicable in public projects because bidding policies prohibit use of specific technologies to avoid impropriety of the bidding process. Accordingly, early design-for-manufacturing collaboration or contractual data sharing of the design model were not observed in the Yokohama project.

4.3 Communication Strategies

4.3.1 Early user information input

Without input from the contractor, architects must expect what potential information the downstream user needs. The Yokohama case study illustrates the intensive and extensive efforts of the design team to develop a feasible structural folds/girder system, without having the input from the steel fabricators. Thus, the geometric model describes the geometric rules that allow accommodation of expected fabrication requirements which may be required by the contractors who refine the actual project geometry. In contrast, GP employed design-assist methods to work with the fabricator before completing construction documents and also collaborated with the CM-at-risk to identify downstream information requirements.

4.3.2 Level of detail

Communicating via 3D documentation raises the need to define the level of detail that is appropriate and adequate for each design contributor to the project. The initial 3D sketch models of the architects represent a macro scale view of the project geometry and do not address the technical details that result from the translation of available production means. Therefore, the architects need to describe an appropriate level of geometric characteristics that serve the intended purpose of the information. A key aspect for collaboration in early stages is to produce appropriate level of details to allow accurate planning by the subcontractors while maintaining flexibility in the design details (Elvin, 2007).

On complex-shaped buildings, architects have often represented the global geometries of external surfaces in 3D – including roofs, cladding, glazing systems, etc. – or primary structural geometries, while component details are supplemented with conventional 2D drawings. In the MIT project, the external surface geometry was offset to create an internal surface that provided space for the fabricator to detail the cladding system. The architect also prepared the brick surface geometry and the concrete solid model and glazing and secondary steel. The structural engineer modeled the structural steel members utilizing libraries of standard steel shapes within CATIA. This provided the provisional basis for planning and estimating by the subcontractors. The steel members were further detailed by the structural fabricator to incorporate splice details, bolt connections, etc. The concrete model provided in full solid form reflected the nominal surface of the formwork construction. The geometries in the architect's CATIA model primarily presented nominal surfaces that provide references for the detailed systems to be developed by the specialist contractors.

Reduced abstractions of 3D building components are also observed in the Yokohama and Eden ERC projects. The architects only represented either centerlines of components or external surfaces via lines which would be further detailed by specialist contractors of the actual components. The projects rely on explicit node coordinates and geometry generation rules.

4.3.3 Surface modelling capabilities

Design development environments such as the CATIA environment in the MIT case study, provide advanced surface modeling functionalities which are not available in standard entity-based CAD systems (i.e., AutoCAD or MicroStation). First, the sophisticated CATIA system provides advanced surface and solid modeling control mechanisms that simplify the operations of localized surface constructions. The two standard CAD platforms – AutoCAD in the Yokohama project and MicroStation in the Eden project – have limited surface modeling capabilities and thus necessitated tedious and time-consuming modeling exercises of line-based constructs to derive important node coordinates by the architects. Second, the NURBS constructs in standard CAD environment may have slightly different geometric constructs from fabrication specific CAD/CAM software such as the CADWORK software for timber component fabrication. This is because standard CAD geometries are not optimized for component fabrication geometries. Third, surface definitions in standard CAD software lack precision and surface manipulation functionalities such as 'intersecting' of planes and

creation of ‘flattened’ surfaces, etc., allowing convenient validation of curved, non-orthogonal surfaces. Such constraints limit the direct use of standard CAD software 3D models by fabricators for manufacturing purposes. These functional differences and capabilities of CAD programs impact the communication strategies of complex-shaped architecture.

4.3.4 3D Data management and access

The observations illustrate the need for an information manager and an information infrastructure to share a central model among project participants for their individual tasks. If multiple parties share a digital model, it is necessary to manage access to the model, track design revisions and changes to the model, and to make sure that the data recipients work on the latest data files. Files can be managed through a central model server or distributed via individual communication means such as emails or data disks.

The case study analyses show various information sharing platforms. In the case of the Yokohama Terminal project, Shimizu, one of the general contractors, retained and managed a jobsite server. Because their model was separate from the architect’s model, access to the model was mainly for internal construction planning and construction drawing preparation as opposed to sharing with other participants.

In the Eden ERC case study, 3D data was transferred directly between the architect and the timber gridshell contractor via email communication.

In the MIT Stata Center case study the general contractor acted as information manager between the architect and the individual subcontractors. They were responsible to share the correct version of the architect’s master model, and also to coordinate the 3D shop models submitted by the subcontractors. For example, A. Zahner, sheet metal contractor for the MIT Stata project, submitted 3D shop models for validation of geometry, sizing, and coordination of interfaces with other systems, which were carefully coordinated with the 3D shop models from the steel fabricator (Fig. 4, 5).

4.3.5 Selection of Architect’s CAD Platform

The CAD software market has been led by a few major vendors, focusing on architects’ primary use of CAD tools for drafting purposes. However, the demand to create and communicate complex surface geometries departs from the conventional drafting paradigm and raises questions about determining appropriate CAD modeling environments.

There are two important factors that impact the selection of CAD systems. First, the learning curve required to work in advanced environments is an important factor for. While parametric modeling technology would have benefitted both Grimshaw and FOA to reduce manual rework on their CAD models during design revisions, switching between different CAD packages involves additional training efforts. Grimshaw had been experimenting with Generative Components (a parametric CAD product by Bentley) but did not implement the tool because it had not been commercialized yet at the time of the project. Architects either work within the same CAD environment from concept to the final product documentation, or switch between different platforms to fulfill the computational needs. This adds another level of complexity to the learning curve.

Second, compatibility of the designer’s model with downstream recipients hinders the use of non-standard CAD systems. The analysis shows that on the Yokohama project, as a public project, the architect could not specify the software as project requirements because standard software packages are not yet compatible with all trades. In such cases, technology has to satisfy the lowest common denominator. In comparison, in the MIT Stata Center case study, the owner qualified CATIA-capable bidders as a project requirement because some of the work packages were dependent on the successful bidder’s capability to process the 3D model. Furthermore, in the MIT project, GP and Skanska worked closely together to train project participants within the construction organization so that relevant

personnel had the required technical capabilities to participate and extract information as required from the architect's model.

4.3.6 Data Translation Issues

When the architect's CAD files and the fabricators' files are not directly compatible, it becomes necessary to translate between the architect's model and the recipients' platforms. Typically, interchangeable file formats are supported by commercial software, yet the conversion is not flawless and often requires additional processing. Middleware has been developed to convert file formats. Still the technical translation needs human intervention because geometric discrepancies and information losses can occur. Some architects have the capability to develop such translation programs. Gehry Partners on the MIT project helped the steelwork contractor to correct translation errors from CATIA to SDS-2 (steel detailing software). To avoid liability, the service was referential, i.e., provided to the general contractor who had to take responsibility for coordinating data with the subcontractors.

4.4 Liability

While GP's CATIA model was part of the contract documents, the design contract provisions clearly disclaimed any responsibilities for construction means and methods. This is noteworthy because GP collaborated intimately with A. Zahner, the metal cladding contractor, during construction documentation phase defining prescriptive component geometries of the building cladding system. Under traditional practice conventions, the architect and contractor each hold different standards of care: the architect is held to professional liability standard and the contractor is held to a strict liability standard (i.e., product liability for workmanship, warranties, guarantees, etc.). The architect is not responsible for construction defects resulting from the plans and specifications while the contractor is not responsible for design errors, thus leaving the owner at risk against design errors (Elvin, 2007). Overall project coordination by the architect of the 3D model through incorporation of prescriptive fabrication geometries creates ambiguities in the lines of responsibilities. On the other hand, better project coordination through model-based collaboration reduces the owner's risk as more complete information sharing can be facilitated via the model.

Under traditional practice conventions, architects tend to avoid potential risk of product liability by reducing the role of project documentation to design intent. This was clearly observed in the Eden ERC project's final engineering of building systems. Jerry Tate described, "It is fine to say that an architect who produces a 3D model gets exactly what he asks for, but we would prefer to have another party look over everything. For example, Häring know a lot more about timber frames than we do, so we would rather give them a model, point coordinates and some design 'rules of the game' and ask them to check that we have satisfied the design requirements. For complex geometry projects, the contractor is normally responsible for the final detailed design – so it is essential that he or she takes ownership of the model."

On the other hand, as observed in the Yokohama case study, Japanese general contractors carry professional liability, thus taking design responsibility for construction and component design. In the Yokohama project, Shimizu built their 3D model to run various analyses (e.g., structural stress and deflection analysis during construction, clash detection between steel structure, PC steel cables and mechanical/electrical/plumbing components, etc.).

Thus, the issue of liability and risk allocation is deeply intertwined with the arrangements for geometry control. The definition of legal liabilities in model-based collaboration is an area that will continue to evolve along with the developments of integrated practice and BIM.

5. STRATEGIES FOR GEOMETRY CONTROL

5.1 Technical Competence

The notion of model-based collaboration for geometry control relies on a common 3D geometric model that all subsequent participants operate on and retrieve geometry and information for use with their own platforms. To maintain effective geometry control, architects must take the role of the project coordinator who assumes sole responsibility for modifying or approving the model. To accommodate building systems compatibility (i.e., façade, structural systems, mechanical, electrical, environmental systems, construction processes, etc.), the architect must be able to collaborate with engineers and construction managers who should only operate on but not control the model. The architect should have the expertise to guarantee that the model is consistent without errors, and be responsible for updating, modeling all necessary geometric information in 3D, using 2D documentation only to supplement construction details.

5.2 Risk Allocation

Full migration into model-based collaboration is dependent on the identification and adequate allocation of risks. Potential risk associated with model-based communication arises from conventions of design liability. Taking charge of project geometry involves responsibilities of building technologies and production processes. To assume leadership, architects must consider accommodating new standard of care responsibilities of an “integrated” design, comprising not only design, but also owner’s business objectives, construction, production, and operations, etc.

5.3 Future Practice: Integrated Design

To take advantage of the integrative potential of BIM and model-based collaboration, architects need to embrace a radically new practice model which begs for a business approach that integrates design leadership and business planning. Students should be sufficiently prepared to understand the multi-dimensional facets of design that require clear leadership in the business process, and the construction process, executing tight and consistent control of geometry and materials to achieve higher levels of design quality.

6. CONCLUSION

Contrary to the popular vision of BIM as a real-time central data repository, this study of complex-shaped buildings reveals that architects adopt two different collaboration strategies from a geometry control standpoint: (1) direct collaboration on a contractual model that involves increased project coordination responsibilities of the architect to extend control beyond design intent; and (2) a non-contractual model-based collaboration approach in which the architect’s control of the model is limited to design intent. The findings suggest that control of the geometric model coincides with the distribution of design responsibilities during design and construction phases.

While continuity on a single geometric model from design to project management throughout construction and fabrication is a tempting vision, the implementation depends on the level of agreement of redistribution of design roles, allocation of risk, and the technical capability of collaborators. Expanding the role of the architect as overall project coordinator of the geometric model requires changes to practice and project documentation conventions, as observed in the MIT case study. Maximizing the potential of model-based geometry control will require strategic approaches to architectural practice that allow gaining and maintaining design leadership. The two critical factors identified for successful implementation of model-based collaboration are: (1) technical competency to successfully control and handle geometric modeling and engage all essential participants that are involved in the design, coordination, construction and fabrication of the building components; and (2) proper definition and relief of liabilities related to the shifting responsibilities and roles between design

and construction. It is important to adequately understand the competency of the project team when determining applicable geometry control strategies for a particular project.

The in-depth descriptions and insights of the examined projects can contribute to developing a framework focusing on the changing roles and responsibilities of project participants that are necessary to successfully collaborate on digital models for enhanced geometry control. Investigation of larger samples based on these findings can contribute to the theoretical development of emerging practice models and offer the potential to empower the architect. Systematic methods to redefine risk allocation, to facilitate team building, and to improve technical competency, are imperative for project teams that aim to enhance project performance from a geometry control perspective.

7. REFERENCES

- AIA/AGC (2006). Continuing the transformation session, a report on the AIA/AGC construction industry summit, *The American Institute of Architects, The Associated General Contractors of America*.
- Allen R. K., Becerik B, Pollalis S. N., and Schwegler B. R. (2005). Promise and barriers to technology enabled and open project team collaboration, *Journal of professional issues in engineering education and practice*, Vol. 131, No. 4, 301-311.
- Bedrick J. R. (2006). Virtual design and construction : New opportunities for leadership, *The architect's handbook of professional practice update 2006*, The American Institute of Architects, Wiley, 33-45
- Chaszar A. and Glymph J. (2003). CAD/CAM in the business of architecture, engineering and construction (James Glymph of Gehry-Partners on the organizational, contractual and legal issues facing designers and builders). *Architectural design*, No. 166, 117-123.
- Coxe W. (1994). Design-build: Lessons from Japan, *Progressive Architecture*, Vol. 75, pg. 72-73
- CURT (2004). Collaboration, integrated information and the project lifecycle in building design, construction and operation, *White Paper, WP-1202, The Construction Users Roundtable*.
- Elvin G. (2007) *Integrated practice in architecture: Mastering design-build, fast-track, and building information modeling*, Wiley, Hoboken, New Jersey
- Ferré A. (2002). *The Yokohama project: Foreign Office Architects*, Actar, Barcelona.
- Gray C. and Hughes W. (2001). *Building design management*, Butterworth-Heinemann, Oxford.
- Hartman T. and Fischer M. (2007). Applications of BIM and hurdles for widespread adoption of BIM: 2007 AISC-ACCL eConstruction roundtable event report, *Working Paper, Center for Integrated Facility Engineering*, <http://cife.stanford.edu/online.publications/WP105.pdf>, [accessed 21.9.2007]
- Hastings J.; Kibiloski J., Fischer M.; Haymaker J.; and Liston K. (2003). Four-dimensional modeling to support construction planning of the Stata Center Project, Invited Paper to *Leadership and Management in Engineering*, ASCE, Vol. 3, No. 2, 86-93.
- Joyce N. (2004). *Building Stata: the design and construction of Frank O. Gehry's Stata Center at MIT*, MIT Press, Cambridge, Mass.
- Kam C., Fischer M., Hänninen R., Karjalainen A., and Laitinen J. (2003). The product model and Fourth Dimension project, *ITcon, Special Issue IFC - Product models for the AEC arena*, Vol. 8, pg. 137-166, <http://www.itcon.org/2003/12>
- Kolarevic B. (2003). We have seen the future, and it is pixellated, *In Architecture*, VNU eMedia, Inc.

- Ku K. H., (2005). *3D model-based collaboration for complex-shaped buildings: effective practices for geometry control*, Doctoral Thesis, Harvard University, Graduate School of Design, Cambridge, MA.
- Ku K. and Pollalis S. N. (2006). Implementation challenges for 3D model-based collaboration and research needs for contractual standards. *Proceedings of the European conference on product and process modeling*, September 13-15, 2006, Valencia, Spain., 641-649.
- Laiserin J. (2002). Comparing Pommès and Nanjarras, *The Laiserin Letter*, <http://www.laiserin.com/features/issue15/feature01.php> [accessed 21.9.2007]
- Lindsey B. (2001). *Digital Gehry: material resistance, digital construction*, Birkhäuser, Basel, Boston, Berlin.
- Matsushima S. (2004). *Technology-mediated process: case study – MIT Stata Center*, Proceedings of the 23rd ACADIA and the 2004 conference of the AIA TAP knowledge community, November 8-14, 2004, Cambridge, Ontario, Canada, 202-219, http://cumincad.scix.net/cgi-bin/works/Show?acadia04_202
- Mitchell, W. J. (2004). Constructing complexity in the digital age, *In Science*, American Association for the Advancement of Science, Vol. 303, No. 5663, 1472-1473, <http://www.sciencemag.org/cgi/content/full/303/5663/1472>
- Pietroforte R. (1995). Cladding systems: technological change and design arrangements, *Journal of architectural engineering*, ASCE, Vol. 1, No. 3, 100-107.
- Pollalis S. N. (1999). *What is a bridge?: the making of Calatrava's bridge in Seville*, MIT Press, Cambridge, MA.
- Pollalis S. N. and Bakos.Y. J. (1987), *A framework for the design process*, Laboratory for Construction Technology, Graduate School of Design, Harvard University, Cambridge, MA.
- Sapers C. (2002) *Memorandum: Gehry contract provisions*, unpublished.
- Schodek D. L., Bechthold M., Griggs K., Kao K. M., and Steinberg M. (2005). *Digital design and manufacturing : CAD/CAM applications in architecture and design*. John Wiley & Sons, Hoboken.
- Shelden D. R.(2002). *Digital surface representation and the constructibility of Gehry's architecture*, Doctoral Thesis, MIT, Department of Architecture, Cambridge, MA.
- Terzidis K. (2006). *Algorithmic architecture*, 1st ed. Edition, Architectural Press, Oxford; Burlington, MA.
- Tombesi P. (2002). Involving the industry: Gehry's use of 'Request for Proposals' packages, *Arq: architectural research quarterly*, Vol. 6, No. 1, 77.
- Zaera A. (1995). Frank Gehry 1991-5, Conversations with Frank O. Gehry, *El Croquis*, No. 74-5