ITcon

www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

CONTRACTUAL STANDARDS FOR ENHANCED GEOMETRY CONTROL IN MODEL-BASED COLLABORATION

PUBLISHED: June 2009 at http://www.itcon.org/2009/24

EDITORS: Kazi A S, Aouad G, Baldwin A

Kihong Ku, Assistant Professor,
Myers-Lawson School of Construction, College of Architecture and Urban Studies, Virginia Tech, Blacksburg, VA, USA
kku@vt.edu; www.bc.vt.edu/faculty/kku

Spiro N. Pollalis, Professor of Design,
Technology and Management, Graduate School of Design, Harvard University, Cambridge, MA, USA
pollalis@gsd.harvard.edu; www.gsd.harvard.edu/~pollalis

SUMMARY: *This paper discusses the definition of contractual standards for ICT-enabled business models and value-driven business models, focusing on model-based collaboration for enhanced geometry control.*
While a growing number of highly publicized international complex-shaped buildings have demonstrated the usage of three-dimensional (3D) modeling as the primary means for geometric representation, the authors have observed a lack of contractual standards around the 3D model. Process complexities that are deeply embedded in practice conventions, along with legal constraints and risk allocation, pose challenges to the establishment of standard agreements. As a result, individual project teams often struggle to define and find adequate design agreements to facilitate effective control of geometry around the 3D model. Ineffective geometry control may result in schedule delays when project participants disagree on the representation of the 3D model, or even change the original design intent, eroding the integrity of the design. Thus, the proliferation of 3D tools and owner demand for complex-shaped buildings creates a great need for standard design agreements over the control of the architect's geometric 3D model, in order to define control and authority, as well as a mechanism to access and verify the validity of the 3D geometry. The study presents an in-depth review and analysis of (1) the existing body of literature on effective geometry control; (2) case study examples of geometry control as a project metric; (3) an analysis of sample contract terms and the effect on geometry control approaches; and (4) recommendations for effective geometry control contract terms, processes, and strategies for owner-architect and owner-designer standard agreements. The paper's principal value lies in (1) its definition of geometry control as a performance metric and (2) its guideline for standard contract terms to facilitate effective geometry control via design agreements. The results will complement existing industry efforts by owner organizations such as the Construction Users Roundtable and design organizations such as the American Institute of Architects.

KEYWORDS: *model, BIM, collaboration, legal, contractual, integrated practice, complexity, liability, derivative*

REFERENCE: *Ku K, Pollalis S (2009) Contractual standards for enhanced geometry control in model-based collaboration, Journal of Information Technology in Construction (ITcon), Vol. 14, Special Issue Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning, pg. 366-384, http://www.itcon.org/2009/24*

1. INTRODUCTION

1.1 Background

As the building industry comes to recognize the comprehensive benefits of Building Information Modeling (BIM) (Eastman et al., 2008) and as architects expand their usage of three-dimensional (3D) digital modeling for form generation and geometric representation (Ku et al., 2008; Kolarevic, 2003), professional organizations such as the American Institute of Architects (AIA) and the Associated General Contractors of America (AGC) have sought to define and develop guidelines and strategies that will allow effectively collaboration using these new tools and processes. The AIA has emphasized the potential synergy of adopting BIM tools and integrated project delivery processes (AIA CC, 2007). Larson and Golden (2008) emphasize that it is critical to develop an effective team composed of the owner, and the key modeling parties including the architect, general contractor, selected sub-consultants, subcontractors, and suppliers. The key is to define the owners' objectives and the role of BIM as early as possible so that the benefits of BIM can be optimized. While project teams may choose to share digital models via paper-based drawings, or models for-reference-only purposes, or as contractual documents, there are benefits in each method of adopting BIM for design development and construction purposes. The first two options will most likely involve each stakeholder creating individual models after the initial design model is composed, while the last option allows parties to reuse the design model, which may make the design process more efficient. Within this context, industry organizations are striving to establish standard contract language that facilitates the effective use of BIM. The AGC ConsensusDocs 301Building Information Modeling Addendum (2008) and the AIA Document E202 - 2008 Building Information Modeling Protocol Exhibit attempt to achieve industry consensus on BIM-related contract terms. These guidelines are encouraging efforts towards an evolving general framework that will allow BIM to be contractually addressed as an integral part of the design and construction processes.

The authors have identified that regardless of specific BIM technologies which may (or may not) support parametric objects, or object-based database characteristics, model-based collaboration requires that the designer pay particular attention to geometry control (Ku et al., 2008; Ku and Pollalis, 2006). Effective control mechanisms are needed in order to avoid nonconforming design changes (Atkins and Simpson, 2008) of the original design intent. When parties fail to understand the implications of collaborating on geometric representations for design intent, a number of legal, contractual and procedural questions arise. What are the risks of ineffective geometry control when collaborating on a model? Does effective geometry control involve reallocation of traditional design responsibilities and liabilities? How should the designer's digital model be shared with downstream participants and what are the contractual arrangements around the model? What are the risks of sharing the designer's digital model with the non-compatible CAD platforms of other participants?

Bedrick (2006) sees great opportunity for architects to embrace this technology-enabled collaboration process and take on the leadership role in a radically improved delivery process; otherwise they risk being left behind, watching other professions take the lead, to the detriment of the profession and its values. Thus, the second section of the paper defines geometry control as an important performance metric that will allow owners and designers to better understand the value of geometry control. The third section analyzes BIM-related legal and contractual terms based on a literature review and standard agreements by the AIA and AGC. The fourth section discusses the authors' view of how model-based collaboration will evolve and what impact it is likely to have on the future AEC industry.

2. DEFINING GEOMETRY CONTROL AS PERFORMANCE METRICS

An essential role for the architect and/or designer is to establish a comprehensive design philosophy for a project so that every design decision on the project ensures integrity (Gray and Hughes, 2001). As an important aspect of these decisions is the appearance of the project, Atkins and Grant (2008) point out that "nonconforming work that adversely affects the appearance can unfairly compromise the building design." The representation of the building design essentially relies on and is limited by the means of representation that is available (Evans, 1995). As the means of geometric representations have evolved from two-dimensional (2D) abstractions to geometric constructs based on computer-based NURBS (Non-Uniform, Rational B-Splines), the collaboration between architects and other key (modeling) participants has had an impact on paper-based practice conventions (Ku et al., 2008). This is particularly obvious when non-standard, complex-shaped buildings employ novel shapes that rely on non-standard geometries.

In contemporary architectural practice, many examples illustrate how crucial geometry control is to the process of design development and construction. Comparing the design of the Sydney Opera House and the Bilbao

Guggenheim Museum, Mitchell (2001) highlights the impact that means of geometric representations have on the communication process for engineering and fabrication. Both projects demonstrate that geometric representation is essential for effective communication with the engineers and for detailing, which is also intimately linked with the available means of production processes and technologies. With advances in digital design and manufacturing technologies, the construction of large and complex-shaped buildings has become feasible within reasonable time and budget constraints. A growing number of case studies have documented that model-based collaboration has become a more common approach (Ku et al., 2008; Eastman, 2008). While research has focused on the role of digital modeling as an enabler for implementing complex shapes and geometries (Ku, 2005; Mitchell, 2004; Kolarevic, 2003; Shelden, 2002) little research has focused on identifying and quantifying the benefits of model-based collaboration from a design perspective. It is the belief of the authors that project geometry should be controlled by the design- architect and/or engineer who is responsible for establishing the comprehensive design philosophy; this process will ensure that no gray area or room for speculation is left to downstream participants. The authors suggest that '*geometry control*' deserves a closer look if it is to be considered as a performance metric.

The paper also examines geometry control to answer the main question: *Can model-based collaboration enhance geometry control and ultimately empower the designer?* The notion of geometry control concentrates on nonconforming geometry changes that are introduced by downstream participants (e.g., engineers, contractors, etc.) who force design changes for economic, technical, or managerial reasons, or as a result of miscommunication or misunderstanding. Such changes may seem trivial to the initiator but may compromise the integrity of the design intent. The authors have collected empirical evidence of such design changes by conducting case studies of complex-shaped building and infrastructure projects (Ku et al., 2008; Ku, 2005).

Table 1 summarizes the findings on geometry control of five case studies that were developed by the authors (Ku and Pollalis, 2006; Ku, 2005). The design changes identified in these case studies were reported by the architects as changes that impacted the original design concept or involved changes that required reworking the architect's model or construction documents to accommodate the downstream participants' geometries. The table first identifies the design changes and relates them to the initiators of the alterations and the reasons given for the changes. These changes are then associated with the design phases during which the parties collaborated on the model. Finally, the table specifies the design arrangements on the designer's digital model and describes whether the model was contractually binding or issued for information purposes.

TABLE 1: Case study outline

Project	Design Changes	Change Initiator's Reasons & Initiator	Phase of Collaboration	Design Agreement Terms
MIT Ray and Maria Stata Center	Not observed	Not applicable	Concept design through construction and fabrication	Contractual digital model shared for design and construction
Yokohama Port Terminal	Apex of folds structure detail geometry	Fabrication constraints by general contractor / subcontractor	Design development through construction and shop drawings	Paper-based construction documents & model-for-information-purpose
Eden Core Project	B-spline of grid-shell roof structure	Incompatibility of geometric constructs between architect's and fabricators CAD system	Design development through construction and shop drawing phase	Paper-based construction documents, node coordinates & model-for-information-purpose
Main Street Bridge	Arch shape, location of struts	To comply with customary approach by engineer-of-record	Design competition to detailed engineering phase	Paper-based construction documents & model-for-information-purpose
London Bankside Loft Extension	Not observed	Not applicable	Research & development, prototyping phase	Complete fabrication model developed by architect

2.1 Defining Geometry Control as a Performance Metric

Among the five cases studied, three project architects (the Yokohama Port Terminal project in Japan; the Main Street Bridge project in Columbus, Ohio; and the Eden Core project in Cornwall, UK) reported changes to their design intent. The first two projects illustrate changes in which the initiators – the general contractor (the Yokohama project) and the engineer-of-record (the Main Street Bridge) – argued that the changes would not substantially change the design. In contrast, however, the designers complained that these changes did have significant impacts on the integrity of the designs.

The Yokohama project is composed of a complex-shaped steel girder and folds structure that supports a free-form undulating roof surface. The architects developed an elaborate 3D geometric model in AutoCAD R14 to represent the global geometry of the curved girder and roof folds structure. The 3D model was shared for reference purposes along with the geometry generation rules (explaining the geometry generation concept and sequence) and contractual construction drawings. To ensure the accuracy of the data, the general contractors extracted node coordinate values from the model and created their own model to use for coordination and conformance checking. During the detailing and prefabrication of the steel folds unit a design change that impacted the design intent of the architects was introduced. The Yokohama project architects report:

> In the most controversial and disappointing case regarding the supervision of the steel structure, Kajima Corporation was capable of constructing the apex of the folds as specified in the detailed drawings, but unfortunately Shimizu Corporation and Toda Corporation, the other members of the JV, were not able to build the ends of the folds (Fig. 1) properly, in what appears in the building as an embarrassing mistake for those two contractors and an important achievement of Kajima Corporation. (Ferré, 2002)

FIG. 1: Folds Structure Component (Source: Shimizu Corporation)

FIG. 2: Apex Detail (Photo courtesy of FOA)

The architects explained that the project posed challenges in regard to the tight construction schedule and organizational complexity of managing three different general contracting joint ventures (Kajima Corporation, Shimizu Corporation, and Toda Corporation). Each of these general contractors represented a joint venture of contractors who were responsible to manage the work of multiple factories for their respective zones; the project involved eight steel fabricators that were dispersed throughout Japan, Korea and Shanghai (Ferré, 2002). According to the architects, changes to the design intent were attributed to different managerial attitudes among the general contractors who mediated between the designers and factory staff to supervise the different manufacturing methods of the steel fabricators. The difficulty of reviewing the fabricators' 2D shop drawings in correlation with the designer's 3D model was compounded by the difficulty of standardizing the detailing of the finish quality of the steel plates, welding beads, and face plates of the folds structure (Ferré, 2002). The architects attributed the challenges to the complexity of managing the various manufacturing methods of the many factories involved under the very tight schedule. Although the architect had produced specifications and detailed drawings, the general contractors had authority over the construction coordination process. This process would be completed in one of two ways: either in sequential order from the detailed design in 3D and 2D to the shop drawings, or concurrently with the shop drawing process proceeding while they worked carefully with the factories to ensure the accuracy of the geometries. The second option made scheduling easier. Because of the extremely tight schedule, the project manager of Shimizu Corporation explained that they decided to proceed with the second option. This example of geometry control focuses on the detailing of local components rather than global geometries of the project.

The Main Street Bridge design (Fig. 3) features an innovative arch bridge design that involves a nonsymmetrical cross section with an inclined low profile arch. The project designer emphasized the importance of geometric consistency in this design competition scheme. The form development and generation process was integral to the final arch shape and configuration of the various elements including the location and angle of vertical struts, and the profile of decks. The modeling tool (Rhino, a NURBS concept modeler software) was integral to the specific form generation sequences, which were crucial in deriving the specific design concept (Ku and Pollalis, 2006). In order to effectively communicate this geometric consistency to the engineer-of-record who was responsible for detailed engineering of the bridge, the designer, who is also a professional engineer, issued the 3D design model for reference purposes along with contractual paper-based drawings.

FIG. 3: Renderings of the Main Street Bridge (left: original design; right: modified design by engineer, image courtesy of Genesis Structures & HNTB)

Although they were sharing the 3D model, the engineer-of-record (EOR) introduced a series of geometric design changes to the original design during detailed engineering; justifying these changes, he said they would enhance the constructability of the erection process and allow them to meet construction time constraints under a reduced budget (Rogowski et al., 2005). The EOR claimed that the intriguing geometry of the original design was not compromised. The revisions that concerned the designer were related to the arch shape, the rotation of the arch cross section, the location and angle of struts, the location of piers, and the connection of the detailed configuration of struts to the arch. Figs. 4 and 5 superimpose the original model over the revised model and illustrate the deviation from the designer's geometry (the red area shows the trajectory of the modified geometry, the green area shows the profile of the original design, and the yellow area shows the area of overlap between the two profiles). The revised design follows a 2^{nd} degree parabola as opposed to the designer's 4^{th} degree best-fit polynomial curve. According to the EOR, the fabricators were accustomed to using the 2^{nd} degree parabola to define curves.

FIG. 4: Superposition of shape of the original arch geometry and modified geometry

The arch section was also displaced and rotated, resulting in connection configurations where the cables failed to maintain the pure perpendicular relationship to the lower arch's surface which was a feature of the original design (Fig 6). Figs. 7 and 8 demonstrate how the dislocation of struts along the bridge ignores the carefully developed design logic of placing the centered struts in relation to the handrail posts.

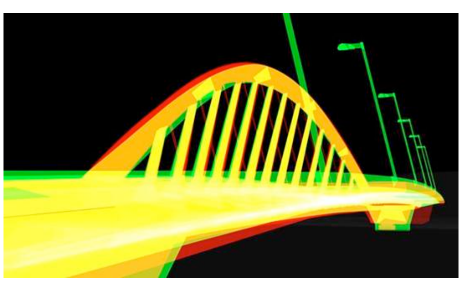

FIG. 5: Superposition of arch shape

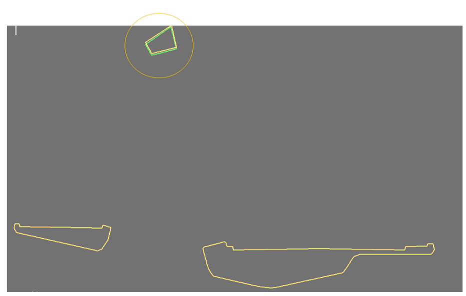

FIG. 6: Rotation of arch cross section

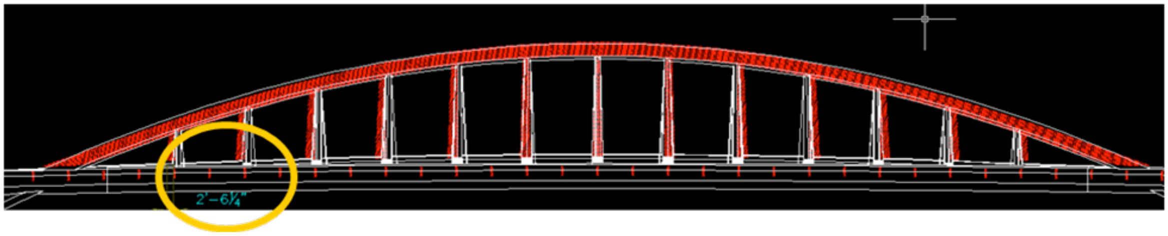

FIG. 7: Dislocation of struts (hatched red lines present original design; white lines present modified design)

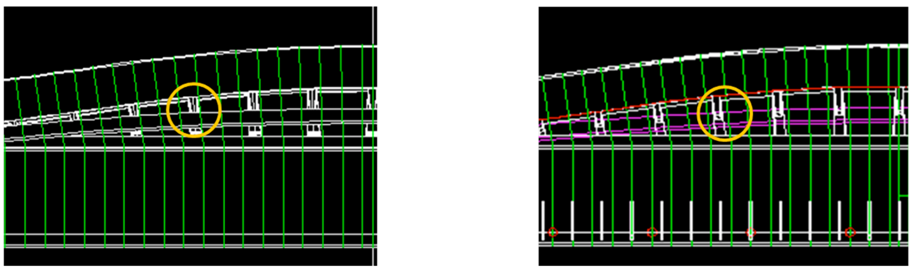

FIG. 8: Enlarged plan view of strut dislocation (left: modified design; right: original design; green lines show railing post location; modified design ignores original position of struts which were centered between railing posts)

The engineers describe in detail (Rogowski et al., 2005) how their revision improved the low inefficient arch profile and the challenging composite steel-arch concrete-core structure. Their reasoning was to proportion a taller span-to-arch ratio and a larger cross section. Additionally, they focused on the nonuniformity of the individual tapered 13-strut elements which were designed to have varying cross sections at the bottom cross section of the vertical struts and varying widths and heights at the horizontal legs. The redesign incorporated true pin connections at the top and bottom of the vertical members, along with I-shaped vertical members and floor beams, eliminating the need for posttensioning and thus reducing cost. While these improvements are considered to be valid developments during the typical detailed engineering process, these design considerations should have been accomplished within the designer's concept of the geometric configuration and by the designer. Thus this case study highlights the issues that arise when the designer's geometry is altered at the global geometry level.

The design changes that were identified in the Eden Core project highlight a slightly different aspect of geometry control. The Eden Core project roof (Fig 9.) is a timber grid-shell structure; to model it the architect employed a spiral phyllotactic pattern similar to the natural growth pattern of pinecone scales or sunflower heads. Using MicroStation V8 the architect developed a 3D model that defined the double-curved timber beam configurations via B-Splines in the CAD software. To complete the detailed engineering of the timber grid shell beam members and roof panel components, the architect collaborated directly with the fabricator. The architect supplied the extracted node coordinate values as part of the contract documents to be used for site layout, shop drawing development, and assembly. The 3D model was also shared for informational purposes.

FIG. 9: View of the Eden Core roof in the foreground (Photo courtesy of SKM Anthony Hunts)

FIG. 10: Timber grid-shell structure showing the B-Spline shaped timber beam components during construction (source: Grimshaw)

Because the design and construction team experienced file translation errors when it imported the MicroStation 3D model directly to the fabricator's CADWORK software, the fabricator decided to create his own model, based on the node coordinate values supplied by the architect. The node coordinates were accurate, but only relatively late in the process did the team discover slight deviations between the CADWORK B-Spline geometries and the MicroStation B-Spline geometries. The deviations did not impact the architect's aesthetic intent, but the slight discrepancies caused coordination conflicts with interfacing trades such as interior partitions and concrete embeds. As the schedule for the detailed engineering prefabrication of the timber component had priority over the interfacing trades, the design team decided to respect the fabricator's geometry for these components. Consequently, the architect revised the interfacing construction drawings and details to accommodate this change. This example illustrates how subtle geometric changes may creep in because of discrepancies in the geometric constructs of specific CAD platforms.

The three case studies examined here represent three classes of design alterations introduced during collaboration with downstream participants: (1) a local geometry change during detailed engineering of components (Yokohama project); (2) a global change in the overall geometry (Main Street Bridge); and (3) alterations due to a discrepancy in the geometric constructs between different software platforms (Eden Core project). The third category of alteration is directly related to technical issues between the software systems and is relatively easy to address. But the first two categories of changes require further discussion to understand how they can be better controlled.

In both case studies, the initiators of the design changes argue that the modifications were necessary for objective reasons such as constructability, assembly, construction, and/or fabrication concerns, to meet the given budget and time constraints. However, the designers in both cases claim that this is not necessarily true. In the Yokohama case study, the architect counterclaims that one of the three general contractors implemented the construction detailing as specified by the architect. This indicates that the contractors' position on initiating changes may not have been based on absolutely objective reasoning but rather on relative or subjective concerns. Similarly, the designer of the Main Street Bridge explains that the engineer's arguments for enhancing the structural efficiency and constructability of the design were not necessarily associated with the geometry changes introduced by the engineer. Instead, he attributes these alterations to misunderstanding and miscommunication of the geometric intent. The designer claims that the engineers created their own model using a software package that was not compatible with NURBS modeling – 3D Studio Max – and did not sufficiently understand the designer's geometry and the 3D Rhino model.

In comparison to the three studies mentioned above, the architects of the MIT Stata project (Ku et al., 2008) and the Bankside Loft extension project (Ku, 2007) case studies did not report design alterations to their design intent by downstream participants. The Bankside Loft case study describes the research and development efforts of the architect who devised an innovative complex-shaped light-weight composite roof panel system. The design efforts went far beyond the scope of traditional design development efforts involving physical production of prototypes of the roof panel system. Utilizing a parametrically-driven geometric model (based on the CATIA platform), the architect aspired to create a variable roof panel system over which he could execute both global geometry and local component geometry control, to respond to environmental, fabrication, site, and construction constraints.

The design intent of the MIT Stata project was to control the building envelope shape which was articulated around intertwining irregular tower shapes covered with various cladding materials including sheet metal, glass, and brick veneer. To effectively coordinate the geometric elements of the building such as the steel and concrete structure, exterior cladding, glazing, and exterior panel framing, the architects adopted the CATIA platform and collaborated with the construction manager, design consultants, and subcontractors. The architect was conscious about using effective geometry control to achieve the aesthetic intent within the client's given time and budget constraints.

The five case studies examined here describe the usefulness of geometry control as a performance metric, specifically within the context of complex-shaped buildings. From the architect's standpoint, effective geometry control defending the design integrity is crucial both to achieve the envisioned visual quality of the final product and also to effectively coordinate the trade packages during the design and construction process. Geometry control needs to be understood in the context of collaborating with 'external' design participants (Ku et al., 2008) who work under different organizational boundaries than the designer. External design participants on any given project are downstream participants who are hired by the owner as opposed to the design firms or team members contracted by the designer. Simon (1996) explains that bounded rationality causes people to simplify and interpret the world from the particular organizational vantage point with which they identify themselves. Borrowing the notion of bounded rationality, the authors explain that ineffective geometry control can occur because designers, engineers, or contractors each work within different organizational boundaries that limit their understanding of the design intent. Miscommunication and misunderstanding occur under bounded rationality unless an effective medium links the different thought worlds. Hence, explicit representations or common geometry platforms can enhance control. Geometry control can be enhanced by adopting explicit communication protocols of geometry generation rules, communicated via 2D/3D diagrams, and/or combined with a common 3D geometric platform that provides a continuum between the different organization members and design phases, cross-linking the different participants' organizational boundaries.

2.2 Model-based Collaboration for Enhanced Geometry Control

The case studies reviewed above indicate that architects and external project team members do not always share the 3D model directly. Those who contractually share their model with external team members intend to enhance geometry control. While collaboration on a 3D model is ideally envisioned to occur on a central model that acts as a central data repository, in the current state of practice each participant creates and maintains control over its own model (Ku et al., 2008; Larson and Golden, 2008; NIBS, 2007; Ku, 2005; Kam et al., 2003). Under such a dispersed modeling arrangement, global geometry control can be effectively improved by sharing a design model, as in the MIT Stata project, inducing the targeted recipient to create derivative models. The Main Street Bridge project would have benefited if the engineers had directly extracted the geometry from the designer's Rhino model for detailed engineering.

On the other hand, the bridge's primary geometric characteristics applied to a limited number of structural components (e.g., the arch, struts, deck, etc.) compared to some building projects that involve greater complexity in the numbers of components and associated geometric variations. From this perspective the bridge geometry could have been effectively described by explicitly sharing the steps of geometry generation and the key relationships between the components such as the placement of struts within the rhythm of handrails, or the 4th degree polynomial best-fit curve of the arch. Such a geometric statement approach was adopted in the Eden Core project and it would have proven successful if the geometric discrepancy between the B-Spline constructs among the software platforms had been discovered in advance. Similar approaches have been adopted by UK firms such as Foster + Partners who never directly issue a digital model to the construction team but only a Geometry Method Statement (Peters, 2007) that specifies the critical geometric rules of the design intent. The legal and contractual implications of this approach will be discussed in the next section.

The geometric discrepancy (as observed in the Eden Core project) that exists between the discrete CAD platforms used by the independent project participants can and should be resolved as early as possible in the design process. Project organizations typically have invested in their own CAD systems that integrate with their own business operations such as the fabricator's CADWORK platform, and the architect's MicroStation software. In such cases, the party that is responsible for the overall project coordination must be the one to resolve the geometric compatibility. Accordingly, the recipient's geometric constructs need to be aligned with the project model geometry that is used for overall project coordination.

Finally, the control of local geometries such as the component detailing of the folds apex in the Yokohama project case study may be better addressed by creating a direct link between the fabrication organization and the designer, in addition to the intermediary entity, the general contractor. However, this involves careful arrangements of design responsibilities and closer collaboration between the design team and construction team than is typical in conventional project delivery. For example, Ku (2007) examines the extensive prototyping efforts by the architect in the Bankside Loft project to develop a CATIA model that could control not only the global configuration of the project but also the detailed fabrication geometries to be issued directly to a manufacturer. For example they could specify complete fabrication instructions such as the templates for computer-numerically-controlled cutting including such details as bolt holes and window insert rims. Such efforts are needed to ensure that the constructability concerns are addressed in advance so that project intermediaries fully understand the design intent. If the architect is to determine the right level of detail, however, the control of local geometries at the component level needs to balance the required resources during early design collaboration and risk allocation between design and construction.

Depending on the level of geometry control that the architect plans to exercise, the appropriate level of responsibility and risk the architect is ready to assume, and the associated geometric complexity of the project, the architect may choose to share the model directly with downstream recipients, or to issue a statement of explicit geometry rules to be followed. Architects who decide to remain in charge of the overall project coordination through the digital model must understand who the intended recipients of the model are, along with the model-sharing constraints and technical requirements, and then determine the appropriate level of detail. If a contractual model is issued, appropriate legal and contractual arrangements must be incorporated into the design agreements. The following section discusses the legal and contractual considerations involved in sharing a digital design model.

3. LEGAL AND CONTRACTUAL CONSIDERATIONS

Having established geometry control as a performance metric for design quality, this section discusses the challenges that are associated with sharing a digital design model. Ku et al. (2008) and Ku and Pollalis (2006) outlined liability concerns and technical competence as the main challenges to model-based collaboration. Digital models raise questions related to conventional risk allocation and the division of responsibilities between design intent and construction. Liability concerns relate to the risk involved in validating and owning the model, and controlling access, as well as fee constraints. Technical challenges relate to the competence of the model sharer and recipients to establish a common modeling protocol and resolve software translation issues between their respective CAD platforms. Similarly, Larson and Golden (2008) outline the primary legal and contractual considerations for BIM contracting. These include (1) the issue of traditional risk allocation of design versus means and method; (2) the reliability of the sharer's model and control of recipients' alterations; (3) interoperability concerns; (4) the role of the model manager; (5) intellectual property concerns; and (6) other technical concerns involved in remote digital information sharing.

This section discusses two common collaboration approaches associated with 3D models and relates these approaches to traditional contractual considerations.

3.1 The Geometry Statement and Reference Model Approach

Under the federated (NIBS, 2007) modeling approach which is common in current model-based collaboration practice, one strategy is to have each key modeling party create its own model. Many project teams prefer this approach, as they are unfamiliar with the potential design liabilities involved in sharing a digital model. This attitude fits conveniently into common architectural practice because each modeling party creates its own model, maintaining separation from the others' design responsibilities. While collaborating via derivative models can contractually maintain similar lines of responsibilities between the participants, the advantage of the geometry statement approach is that it can be applied directly without anyone making changes to traditional design agreements.

Under this approach, the architect develops a digital design model for form finding and representation of the design intent. To facilitate geometry control during collaboration with downstream recipients, the architect issues a paper-based statement that describes the rules of geometry construction and key characteristics; it may include key 3D node coordinate values, schematic diagrams of geometry construction sequences, geometry diagrams, etc. This statement can be issued to downstream participants with or without a "for information only" design model. Several UK architects, including Foster + Partners, Grimshaw, and FOA, utilize this process. Because each participant owns and controls its own model, it is the recipient's responsibility to validate the model. Hence the sharer of the model is not responsible for ensuring the reliability of the digital model.

While this approach fits easily into conventional design agreements without changing typical design roles, compensation structures, and responsibilities, there are trade-offs from a geometry control perspective. First, certain geometric complexities cannot be conveyed effectively via such geometry statement rules alone. For example, free-form sculptural shapes, such as those in Frank Gehry's Bilbao Guggenheim Museum or the MIT Stata Center, cannot be simplified to a set of geometric construction rules; they require representation via a digital model. Another potential risk of this approach is that when certain geometric constructs are shared between participants' respective CAD platforms, they may include geometric discrepancies that create conflicts for the overall project coordination. An example is the B-Spline definition in the Eden Core project.

3.2 The Contractual Model and Derivative (Larson and Golden, 2008) Modeling Approach

Another approach for collaborating on the designer's model is to issue a legally binding design model so that the downstream participants can create derivative models. This approach has often caused concerns among project participants. Larson and Golden (2008) show that the division of responsibilities between design and construction is the largest obstacle associated with a seamless BIM-mediated process. Quoting the Spearin Doctrine, they explain that contractors' concerns over a BIM-enabled process stem from the fear of exposure to general design liability embedded in potential early collaboration during the design phase. This attitude acknowledges traditional risk allocation in common architectural practice where the architect's documents represent only the finished design of the work. Atkins and Simpson (2008) explain that the architect's documents allow the contractor to begin "the contractor's required work which includes the preparation of detailed construction documents such as shop drawings and submittals, coordination drawings, and alternate sketches, all of which set out the specific and final details required for procurement and placing the finished work." The hesitation to engage in model-based collaboration stems from the concern that these conventional lines of responsibilities become ambiguous if the contractor's model becomes part of the design model and vice versa. However, Larson and Golden state that this concern can be addressed reasonably well if project teams maintain the distinctions of the traditional roles of designers, contractors, and suppliers in corresponding BIM agreements and modeling protocols.

The MIT Stata Center project case study shows that traditional lines of responsibility can be maintained well. The project architect maintained control over his own master model which he alone edited and updated regularly. This master model was shared with the individual subcontractors via the general contractor. Derivative models were created by the sheet metal subcontractor and structural steelwork contractor; they each maintained control over their own models. These models were checked and reviewed as shop models, and used for coordination by the architect. However, the architect never directly reflected into or updated these derivative models, which maintained the lines of responsibility of design versus means and methods. The architect's model was part of the contract documents, which included both 2D construction drawings and 3D models. To remain free of any responsibilities for means and methods, the architect also incorporated a provision into the design agreement describing the contractual use of the CATIA model but avoiding any responsibility for means and methods.

This contractual model and derivative modeling approach raise several legal and contractual questions. How does the design team ensure that the proposed geometry can be implemented within the owner's budgetary, time, and technical requirements? How is the model validated and how are alterations of the model controlled? Who owns the model in the case of derivative models? What is the role of the model manager? What level of detail is appropriate for the designer's model? And what are the impacts of technical translation errors and how should they be handled? The following sections discuss ways to deal with these issues within the boundaries of traditional risk allocation.

3.3 Division of Design Responsibilities and Geometry Control

Professional organizations such as the AIA have emphasized the division of design responsibilities during design and construction to reflect common traditional practice conventions. The consensus is that the architect's drawings are conceptual in nature and that the contractor needs to supplement coordination drawings and shop drawings to implement the actual work. Such designated lines of responsibility (i.e., AIA Document A201) seem to clearly define lines of control but in fact also obscure effective geometry control and discourage fluid (specifically digitally-mediated) collaboration environments. For instance, the design engineer for the Main Street Bridge project carefully defined the geometry concept based on his careful engineering studies of the innovative low arch system. However, his contractual documents included only conventional plans, elevations, and sections, which proved insufficient to describe the geometry. Knowing the representational shortcomings of the 2D drawings, the designer also issued the Rhino model for informational purposes. When the owner tasked a separately hired engineer-of-record to develop the design, the key geometric characteristics were modified to reduce the construction complexity of the original design because the budget was decreasing. The design engineer argues that the engineer-of-record's structural system modifications could have been achieved without changing the geometry. Similar ambiguities were observed in the Yokohama project. The fact that one general contractor executed the folds structure detail as specified by the architect while the two other contractors modified the detail, suggests that more effective protocols or agreements need to be developed to define the responsibilities for geometry control more clearly. Why do architects avoid issuing their digital model for construction?

The Eden Core project architect explained that he was afraid to accept an unconventional liability for construction means and methods if the design model was issued directly to the contractor who then used it for construction (Ku et al., 2008). The first reaction to this concern is the practice used by UK architects: the geometry rule statement describes key geometric constructs and development procedures, avoiding the use of a contractual model. Other architects have overcome this concern by exploring alternative arrangements that maintain traditional lines of responsibility while allowing higher levels of geometry control. The MIT Stata Center project architect used a carefully crafted design-assist arrangement to engage the metal cladding fabricator as a design consultant during the design development and construction document phases; this let him use a design model within the boundaries of traditional design responsibilities. While the project architect was in charge of creating the design model, the proprietary prefab cladding system was incorporated as the basis for defining the building skin geometry. The architect included a provision about using the CATIA software to convey information to the contractor and the subcontractors but referred to standard AIA contract language to avoid any responsibility for construction means, methods, techniques, sequences, or procedures (Sapers, 2002). In addition, the architect's design agreement included a provision for aesthetic control which gave the architect the right to refuse to refer to the architect by name if the owner were to order negative design changes.

The efforts of prototyping by the Bankside project architect illustrate extensive design development efforts to address the fabrication, assembly, and construction requirements of a novel roof panel component system. The architect took charge of the model and specification of final fabrication drawings to control the geometry for the final detailing level of the proposed system. Such prototyping activities allowed the architect to ensure that his geometry definitions were feasible from the global geometry level down to the local component level.

These case studies indicate that project teams need not change the traditional lines of risk allocation to collaborate on a 3D model for geometry control, as the designer can still take charge of creating and controlling the design model while referring to the knowledge or skills of external collaborators during development. Larson and Golden (2008) recommend that architects "include agreed-to roles, responsibilities of the parties, the required content of the various models at the various stages of development, and the agreed-to rights of reliance on the models of others." They list tentative topics to be covered in contract terms for the modeling protocol to maintain the division between design and means-and-methods responsibilities:

- The models to be developed for the collaborative use of the team, the parties (designers, contractors, and fabricators) responsible for preparing the models, and the required content of the models. Depending on the agreed-to purposes of a model, the required content might be greater or less than the content required for the model creator's own purposes, and it might be greater or less than the content of the 2D drawings prepared by the model creator.
- The milestones at which the models are to be available, and the required degree of completion at each milestone. A possible starting point for consideration, at least for model content that will also be included in the 2D documents, is the corresponding degree of completion of the 2D documents at the same milestone, a relatively-familiar frame of reference. For instance, if the required content of an architectural model includes door hardware, the door hardware would appear in the model at the same time as it would appear in the development of the 2D drawings. Such a standard could of course be varied as deemed appropriate by the team based on the needs of the project.
- Clear descriptions of those aspects of the work to be designed by contractors and suppliers, whether through design-build scopes or performance specifications.
- A description of the specific collaborative responsibilities of the parties that includes only design-related responsibilities for the designers and only means-and-methods-related to contractors and suppliers; the description should address those clearly-defined design responsibilities as well.
- A provision to the effect that the collaborative efforts do not make the designers responsible for means and methods nor the contractors and suppliers responsible for design, with exceptions for any clearly-defined design responsibilities of contractors and suppliers.
- A requirement that each model be modified only by the party that created the model on that party's information technology system, with narrowly-defined exceptions if necessary (and appropriate process guidelines for any exceptions).
- A clear statement in the definition of contract documents as to whether any digital models will be deemed to be contract documents and, if so, for what purpose.
- Appropriate provisions in the shop-drawing and submittal terms as to whether submittals in the form of digital models will be acceptable (or required).
- Appropriate provisions in the terms concerning requests for information as to how contractor and supplier requests for information, along with designer responses, will be documented in the collaborative process.
- References in the protocol to the contract change provisions, and appropriate processes to ensure that changes in the contractors' work are properly documented in the contract documents.
- An appropriate process for incorporating construction-phase design changes into the working models.

3.4 Model Validation and Access Right for Alterations

If the design team decides to share the design model for geometry control purposes, it is imperative to include the model in the contract documents. As observed in the case studies, project teams are typically composed of ad-hoc organizations with bounded rationalities. As each organization has its own pressing concerns and priorities, geometry that is open to interpretation by the recipients allows design changes that can have negative impacts. Without any legally binding rules or models, it is difficult to enforce the use of the proposed geometries as definitive prescriptions. The primary concern of the model recipient is ensuring that the supplied model is reliable. As a result, models that are shared for informational purposes only are seldom adopted for derivative model creation; instead, recipients refer to them to create their own model to ensure the integrity of the data and conformity with the contractual 2D documents. To streamline this process, the model sharer should validate and guarantee the accuracy of the model so that the recipients can rely on the data without having to create their own model from scratch. Larson and Golden (2008) propose that the owner should acknowledge the additional efforts required to validate the model and adequately reimburse those parties that are sharing their models.

On the other hand, the model sharer is concerned about liability for error creeping in during the transfer of electronic data between individual CAD systems, or improper use, reuse, or alterations of their design (Larson and Golden, 2008). The MIT Stata project case study provides insights into how model management can handle these issues (Schodek et al., 2005; Matsushima, 2004). The architect's office maintained a central FTP site where chronologically ordered folders with the architect's master models were posted and time stamped, so they could keep record copies of each version the architect issued. Similarly, the general contractor maintained its own on-site server to log the different model versions and issue them to their related subcontractors. This practice of keeping logs and time-stamped versions of the model follows traditional practice rules.

The general notes of the MIT Stata Center project architect contained provisions about the CATIA model usage that they could refer to for geometries and dimensions such as exact size, location, and geometry of exterior surfaces, or joint locations of the cladding material. The notes required the contractors to report any discrepancies between the drawings and the CATIA model for the architect to clarify. As the CATIA model was the primary legal document describing geometries and dimensions, these instructions specified the specific use of the CATIA model and stated its dimensional accuracy for the recipient's usage.

The architect's CAD activities also supported the translation of data between the CATIA file format and the fabricator's proprietary CAD formats, and the development of translation processes to help the receiving contracting organization. However, that service remained "for reference only" and the CATIA master model remained as the official contract model. Thus, the architect could warrant the accuracy of its CATIA model but left to the recipient the responsibility of using translated files. This area remains ambiguous in regard to liability exposure that relates to translation errors, and is a barrier to fluent model exchange.

Within this context, Larson and Golden (2008) produced a list of tentative topics for contract provisions that can serve as a helpful guideline:

- Identification of the aspects of shared models on which reliance is permitted. (Shared models may include more information than is required or desired by downstream users.)
- Identification of the parties entitled to create derivative models from the specified models of other parties and the permitted purposes of the derivative models.
- Appropriate compensation for parties sharing their models with a right of reliance and making their models available for the creation of derivative models by others.
- The agreed-to standards of reliance. A useful starting point for consideration of this issue, at least for information that will reside in both the 2D documents and the models, is to require that the information in the model be consistent with that in the 2D documents, be they design documents or shop drawings, at the equivalent milestone. For model information over and above the information that may be contained in the 2D documents, other appropriate standards will have to be developed, depending on the nature of the information and the needs of the project.
- The process for creating and retaining record copies of models downloaded to and uploaded from the sharing site. The process should include the party responsible for preserving the record copies (assuming that the hosting site does not do it automatically), the form in which the record copies

will be preserved, how they are to be marked or titled, the minimum length of time for which the record copies will be preserved, and the method of access by the various parties if the sharing site itself will not be operational for the requisite period.

- A provision requiring users of models created by others to report any errors actually discovered in those models.
- Allocation of the risk of degradation of data during transfer.
- A waiver of consequential damages.

3.5 Model Management

The sharing of digital models among multiple project participants requires agreement on how to control and coordinate the various models being created by designers, engineers, and contractors; how to manage the versioning of these individual models; and how to control rights of access and modification. File translation issues among the designer's CAD model and the recipient's proprietary CAD file formats have to be addressed as well.

Larson and Golden (2008) describe the role of the model manager as an evolving one, which could be limited to the traditional gatekeeper role of project designers and contractors for maintaining the file transfer site and overseeing access rights. Or, the manager could take on more comprehensive roles such as compiling and packaging models from individual project members and disseminating them in a useful form to all project stake-holders. From the standpoint of geometry control, the project may also need a model manager who can resolve file translation errors between proprietary CAD formats. The file translation issues in the Eden Core project raise the question of who had responsibility for ensuring file compatibility. The design team and fabricator resorted to creating a separate fabrication model because of file translation issues when data were transferred between the MicroStation software and CADWORK software. Even in the MIT case, the project architect's non-contractual file translation services between the CATIA software and the contractor's proprietary CAD software reveal how responsibilities can become ambiguous when these services are offered "for reference only." Early in the process, project teams should assess the risk of translation errors to decide on the most effective strategy for sharing the project geometry and assign a responsible party to resolve these issues if necessary as part of the model management plan.

Establishing scopes for the roles and responsibilities of the model manager in project agreements and modeling protocols will help to address these issues.

3.6 Model Ownership

Collaboration on digital models complicates the definition of ownership of each participant's model. The cases examined above maintained relatively simple relationships in respect to ownership of the model. In the MIT Stata project, within the design team, the structural engineer's own steel model was integrated as part of the architect's model. Collaboration with the contractors was typically shared in a top-down way without reincorporating any of the derivative models that were developed by the collaborating sheet metal fabricator and steelwork contractor. Thus, the architect maintained ownership over the key geometry while the contractors maintained control over their detailed fabrication contributions in the model. This notion of ownership can create complications when the digital models are fluently exchanged between the internal and external design teams (Ku et al., 2008).

To Larson and Golden (2008), proprietary ownership of the model is less important than "the appropriate allocations of the legal rights to reproduce, use, make derivative works, distribute, and publicly display the models." Considering how valuable the models are for the owner throughout the life of the facility, particular attention should be given to the owner's intended use (Allen et al., 2005). Thus, allocations of rights to use the model for specific purposes should be discussed and agreed to as early as possible in the process.

4. THE FUTURE: GEOMETRY CONTROL IN MODEL-BASED DESIGN

Within the past ten years the construction industry has witnessed rapid advances in BIM and modeling technology, the expansion of industry CAD expertise, as well as a better understanding of digitally-mediated practice and integrated delivery systems. The authors have tracked the legal and contractual developments in model-based collaboration since 2001, and acknowledge that the recently published BIM agreements by the AIA and AGC, and the AIA Integrated Project Delivery Guide, are encouraging efforts. Such industry efforts indicate that the design and building trades have recognized the changing practice environments and are striving to reach industry consensus about new practice arrangements.

4.1 Current State of the Art: A Paradigm of Fragmentation

While BIM technology is beginning to change traditional design processes, current multi-disciplinary communication continues to be based on 2D traditional document sets. Misinterpretation of traditional contract documents by external design teams are frequently the source of design changes which may compromise the integrity of the design intent. Manual spotting of such individual but not always explicit changes is difficult to be effectively conducted by conventional methods of overlaying physical drawings or digital layers (Chaszar and Glymph, 2003). As examined above in the case studies, a number of innovative architects have adopted 3D modeling tools to develop and represent project geometries. Some communicate their design intent via elaborate 2D instructions extracted from a digital model about the geometric set out and node positions and connectivity, while others issue 2D construction drawings which are backed up by reference models, or contractual models. Each of these approaches requires an understanding of adequate levels of technical competencies, liabilities and risk allocation. Misunderstanding of these methods may result in unwanted changes to the original concept of the designer because the intent is not conceived to be feasible by external participants (e.g., engineers-of-record, contractors, fabricators, etc.) for technical, financial, and managerial reasons. Advancements of BIM technologies are expected to improve geometry control through automated conformance and interference checking.

4.2 Target State: Towards Integration

Model-based design processes will be driven by the growth of integrated practice, and technological, environmental, societal, and economic factors. Automated tools will support version and compliance checking, design reviews, and interoperability between various modeling applications (e.g., REVIT, CATIA. Rhino, AutoCAD, IES VE, etc.). Owners will demand consistent and coherent models that improve information quality and support multi-disciplinary design analyses and optimization of structural, thermal, lighting, LEED compliance, cost estimates, and furthermore, applications for maintenance and operations.

To transition towards full model-based geometry control, the designer will incorporate parametric modeling practices to gain control over design variations that capture the design intent rather than fixed geometries of a single design scheme. To take advantage of these enhanced design and communication tools, related workflow and processes will be redesigned towards integrated project delivery that are based on shared building information models as opposed to 2D drawings that are derived from models. Parametric modeling technology will allow analysis software to rapidly examine various design alternatives to optimize design solutions. The architect will manage and coordinate multi-disciplinary models with the assistance of automated tools to generate accurate digital documentation which incorporates the constraints of available means of production (Chaszar and Glymph, 2003). By eliminating the efforts of external design team members such as the contractor to interpret and re-present the architect's design, greater geometry control will achieve more cost effective and ambitious designs. To achieve similar team competencies and fluid information sharing environments as in internal design teams (who are employed by the architect), external team (i.e., the team members are hired by the owner and thus external to the architect) relationships need to be based on trust and long-term partnerships. Table 2 shows the target state against the current state-of-the-art.

TABLE 2: Comparative analysis of "as-is" and "to-be" state

	Current State of the Art	**Target State**
Process Paradigm	Fragmentation	Integration
Integrated Design Team	Internal (members hired by architect)	External (members hired by owner)
Modeling Strategy	Control over fixed geometry	Parametric control over variation
Design Analysis and Optimization	Limited alternatives due to time constraints	Multiple alternatives enabled by parametric variations and interoperable tools
Geometry Coordination	Manual overlay of drawings and digital layers	Automated conformance / conflict checking
Geometry Control	Geometry statement (2D document derived from model)	Shared geometric model

4.3 Usage Scenario: Shared Liability Agreements

Integrated project delivery arrangements allow for sharing of building information models via centralized or federated models. As the architect develops adequate levels of details of the digital model which may directly drive computer-numerically-controlled manufacturing equipment and incorporate construction planning and management decisions, the designers will be involved with means and methods decisions. The contractors can also contribute to design via the model, to advise on constructability or value-engineering decisions. In such cases, contractors should obtain Contractor's Professional Liability coverage. The Yokohama case study illustrates that Japanese general contractors typically obtain professional liability coverage. On the other hand, designers should look for exclusions that limit coverage for means and methods if designers assist with sequencing or construction services (AIA CC, 2007).

4.4 Usage Scenario: Information Management Services

As BIM will allow the seamless integration of parametric objects between various software platforms including structural, thermal, lighting, acoustical analyses software, fabrication software, and furthermore import of intelligent suppliers' catalog models, the role of a professional model manager will become crucial. This role will be conducted by the architect for design coordination and by the contractor for construction coordination. To ensure proper geometry control, the architect should become familiar with software that conduct automated checks and also be technically competent to specify and maintain consistency across federated model sets (Eastman et al., 2008). If specific construction-related activities such as the coordination of construction methods impact the design intent, the architect should be involved with model management during construction as well.

5. BUSINESS IMPLICATIONS

Effective geometry control in model-based design will empower the designer to make better design decisions while maintaining control over design changes that compromise design integrity. Team relationships need to be based on trust and partnerships to achieve team synergies, so that architects, engineers, and contractors, can bridge traditional rational boundaries, such as the fundamental distrust between architects and contractors, or the conventional boundaries between architecture and structural engineering. Architects will need to gain technical competency in handling the increased complexity of building design and data structures, and be able to synthesize and coordinate the abilities of contractors. By producing accurate geometric models that contractors can rely on, architects will need to be able to suggest construction systems within the constraints of available construction and manufacturing technologies (Chaszar and Glymph, 2003). Contractual standards will need to support BIM and digital models as contract documents and also allow for the organization of long-term, interdisciplinary networks of collaborators to deliver long-term life cycle services (Elvin, 2007).

5.1 Empowerment of the Designer

The notion of geometry control in normative buildings has been relatively well defined within the conventions of 2D abstractions. However, the emergence of new representational media in the form of 3D digital modelling, combined with computer-aided manufacturing technologies, requires a redefinition of the designer's responsibilities notwithstanding promises of better control over the final product. Taking advantage of these enhanced communication capabilities, the designer may envision and conceive novel designs driving construction innovation that can better respond to the more complex and large-scale demands of the end users and the built environment. Based on several years of research into this topic and first-hand industry experience, the authors are optimistic about the potential leadership of the designer as a master-builder who retains tight control over the project geometry. Those designers who understand the impact of these new media will use it to collaborate with constructors early in the design process to inform design decisions that result in improved project quality and budget control. Those who do not will be left with little recourse and may find their work appropriated by external design teams, so that they lose to others their core control over geometry decisions. To meet the challenge of integrating model-based collaboration with enhanced geometry control, the designer, whether a large firm or an individual, will need to provide leadership based on strong design and coordination skills to generate, validate, and manage the design model. The case studies examined in this paper show this trend in both large-scale projects like the MIT Stata Center and small-scale projects like the Bankside Loft. While a growing number of innovative architects will lead this trend towards model-based collaboration for enhanced geometry control, integrating innovative building systems and materials in new ways, many conventional firms will continue to design normative building projects that may still be abstracted and communicated with conventional 2D paper-based drawings.

5.2 Standard BIM Contract Terms

The AIA and AGC have begun to address the legal barriers to collaborative technologies and practices and drafted contract terms that encourage its adoption. Both contracts include language that attempts to resolve the discrepancies between traditional practices and collaborative design using technology.

In response to the current restrictions of the AIA-A201 General Conditions Form for construction services, which limit contract documents to a static set of paper records, the AIA-E202 BIM Protocol Exhibit acknowledges and authorizes the use of a digital Building Information Model as part of the contract. Similarly, the AGC ConsensusDocs 301 BIM Addendum addresses the use of BIM. This provision is a first step toward model-based collaboration.

In regard to proprietary ownership of contract documents, the AIA-E202 defines model ownership to limit the ownership right to the model author's own contributions. Furthermore, any recipient's use of developing derivative models is being limited to the design and construction of the project, thus prohibiting the owner from using the model throughout the life cycle of the facility. The AGC ConsensusDocs 301 outlines intellectual property rights in models to allow the sharing and exchange of models between project participants via the provision of limited, non-exclusive licenses to reproduce, distribute, display, or otherwise use others' contributions for the purposes of the specific project. As with the AIA documents, the use of the model is limited and prohibits the owner from leveraging the model throughout the building's lifecycle. Such nonexclusive limited licenses limit the potential for the owner or participating parties to use derivative models for marketing and educational purposes. Further legal considerations should focus on how to leverage the full potential of BIM throughout the life cycle of a facility as opposed to focusing on traditional ownership of models.

The AIA-E202 defines a protocol for model management to allocate the responsibilities of the model manager. The architect is initially designated the role of model manager and has the traditional gatekeeper roles: set up the base coordinate system, manage file storage, transfer, access and archiving, conduct clash detection, manage access rights, log incoming files, validate file compatibility, and aggregate model files for viewing. The AGC ConsensusDocs 301 include an Information Management provision which assigns an information manager to act as gatekeeper for the model; this person is responsible for transferring files, managing access rights, archiving, and maintaining model security. The AIA-E202 is more comprehensive and specific than the AGC document in regard to validating the completeness of files and compliance with applicable protocols. Still, the issue of file translation errors between proprietary CAD system file formats – important from a geometry control standpoint – will have to be addressed in the future. Future protocols should assign and address liability exposure by the model manager and other parties who are responsible for managing file translation errors.

The AIA-E202 defines five Levels of Development to specify content requirements and associated authorized uses for component system or assembly portions at five progressively detailed levels of completeness. Within the specified levels of development, each author of specific model elements is responsible for the accuracy and completeness of its model scope so that subsequent recipients can rely on the accuracy of the model. In parallel, the AGC ConsensusDocs 301 includes a design provision for warranting the reliability of the designer's model and further specifies the Contributor's Dimensional Accuracy Representation which offers three options. The contributor to the model can designate the model as the primary source for dimensional reference, or designate a limited part of the model for dimensional representation, or share the model for informational purposes only and represent dimensions in 2D drawings. Both contract terms establish a legally binding base for including BIM or 3D geometric models as part of the contract documents for geometry control; this is an important step toward model-based collaboration. The notion of sharing reliable data necessitates unconventional quality control procedures and resource allocation which require a rebalancing of compensation, risk, and reward. Contractual agreements that operate in parallel with BIM agreements should be developed to facilitate such practice.

5.3 Integrated Practice

Using the AIA-B141 Standard Form of Agreement between Owner and Architect allows the architect to assume full responsibility for the design completeness and to take responsibility for design errors, omissions, and associated cost overruns. Owners have been looking for better practice elements to help them overcome these traditional process inefficiencies. Owners also want project delivery methods for fully integrated, collaborative teams that openly share information and use BIM (Bedrick, 2007). In this new environment, the role of design leader is not guaranteed for the architect; in fact, the architectural profession is at risk if it does not embrace both technical skills and organizational, procedural aspects to allow true and open collaboration with a diverse project team (Bedrick, 2006;

Chaszar and Glymph, 2003). In response to the imperative of integrated practice, the AIA CC (2007) has drafted an Integrated Project Delivery (IPD) guide to leverage the collective intelligence of project teams so that projects succeed. To address the shortcomings of the AIA A201, which places means and methods responsibility solely on the contractor, the IPD guide suggests risk/reward sharing through alternative joint liability and joint venture models, and investigates alternative multi-party agreements: project alliances, relational contracts, and single-purpose entities. Either bound by a single agreement or umbrella agreement, or as a temporary, virtual, or formal organization, the multi-party agreements rely on open-book compensation structures and trust-based relationships. These contractual agreements require substantial procedural and organizational changes, and thus it is essential to engage as early as possible in planning, careful negotiation, and intensive teambuilding efforts.

One primary barrier that must be addressed is the conventional division between design and the means and methods that must be allocated to the project team as opposed to the designer or contractor. While leading architects have managed to implement model-based practices within the constraints of traditional risk allocation by strictly controlling model exchange and sharing during collaboration with external participants, this transitory arrangement must transcend the traditional paradigm to leverage the full potential of model-based collaboration. The IPD guide defines a new process map that reorganizes project phases into conceptualization (expanded programming), criteria design (expanded schematic design), detailed design (expanded design development), implementation documents (construction documents), agency review, buyout, construction (construction/contract administration), and closeout. The goal is to concentrate design decision upstream as far as possible to make more effective and less costly project decisions (AIA CC, 2007).

The architect should not lose this brief window of opportunity to exercise more influence on the built environment and greater project control; missing this window may mean marginalizing the profession's essential values (Bedrick, 2006). Thus the importance of effective geometry control cannot be overemphasized, as architects may be undermined as sole concept providers while owners seeking implementation may resort to other disciplines such as larger executive architects, engineers-of-record, CM firms, and design-builders who may offer better budgetary control but ignore the core values and contributions of designers through nonconforming design changes.

6. CONCLUSION

This paper examined the current state of model-based practice, the geometry control it facilitates, and the legal and contractual considerations that make model-based collaboration possible. The opportunities for designers to seize leadership roles in the design process, along with the risks of losing geometry control, were discussed. A variety of case studies were used to illustrate the impact of design changes that may compromise design integrity, and to discuss the larger implications of other professions threatening the architect's design responsibility of geometry control. The business environment driven by owners prompts architects to implement broad-scale changes in their technical and cultural skills, and to move contractual relationships beyond the institutionalized roles to integrate the wide-ranging skills and expertise of the diverse building professions (Bedrick, 2006).

Furthermore, the architect needs to see the specific opportunities of model-based collaboration or BIM in regard to specific performance metrics. The notion of geometry control is relevant whether working as a design architect tasked for concept design, or as a full-service architect collaborating with constructors, or working under an integrated project delivery method. It is important that the architectural profession provides input to legal counsel, software developers, and the design community, to address the specific challenges of collaborative design. Various efforts are being made in architecture and construction-related education to move toward integrating and coordinating the traditionally fragmented process. In parallel, the industry is making efforts to create standard contract language for BIM, to standardize efforts towards interoperability, and to collaborate broadly between owner and professional organizations to integrate BIM and collaborative project delivery processes. All these efforts will keep the industry moving forward towards more efficient processes, higher quality products, and ultimately a better built environment.

7. REFERENCES

AIA CC(2007) Integrated Project Delivery, *The American Institute of Architects California Council,* , http://www.aia.org/ipdg#ipdguide

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, Hoboken, NJ, 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.

Eastman C., Teicholz P., Sacks R., and Liston K. (2008). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors*, Wiley, Hoboken, NJ.

Elvin G. (2007). *Integrated practice in architecture: Mastering design-build, fast-track, and building information modeling*, Wiley, Hoboken, NJ

Evans R. (1995). *The projective cast: architecture and its three geometries*, MIT Press, Cambridge, MA.

Ferré A. (2002). *The Yokohama project: Foreign Office Architects*, Actar, Barcelona.

Gray C. and Hughes W. (2001). *Building design management*, Butterworth-Heinemann, Oxford.

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, 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, Pollalis S, Fischer M, and Shelden D. (2008). 3D model-based collaboration in design development and construction of complex shaped buildings, *ITcon Special Issue Case studies of BIM use*, Vol. 13, 258-285, http://www.itcon.org/2008/19

Ku K. (2007). CAD/CAM mediated design and construction: A case study of the Bankside Loft Project, Proceedings of the Second International conference World of Construction Project Management, October 2007, Delft, the Netherlands, http://www.wcpm2007.nl/userfiles/file/Conference%20papers/WCPM2007%20paper%5B48%5D%20Ku.pdf

Ku K. (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.

Larson D. and Golden K. (2008). Entering the brave new world: An introduction to contracting for BIM, http://www.mortenson.com/files/Entering%20the%20Brave%20New%20World.pdf

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, *Science*, Vol. 303, No. 5663, 1472-1473, http://www.sciencemag.org/cgi/content/full/303/5663/1472

Mitchell, W. J. (2001). Roll over Euclid, In Ragheb, 353-364

NIBS (2007) National Building Information Modeling standard A/R 106, National Institute of Building Sciences, http://www.facilityinformationcouncil.org/bim/pdfs/NBIMSv1_p1.pdf

Peters, B. (2007). The Smithsonian courtyard enclosure: A case study of digital design processes, *Expanding bodies, ACADIA 2007 international conference proceedings*, October 1-7, 2007, Halifax, Nova Scotia, 74-83

Rogowski D., O'Rorke D., DeMond G. (2005) Main Street Replacement Bridge, Columbus, Ohio, *Transportation Research Record: Journal of the Transportation Research Board*, CD 11-S, Transportation Research Board of the National Academies, Washington, D.C., 565-570.

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, NJ.

Shelden D. R.(2002). *Digital surface representation and the constructibility of Gehry's architecture*, Doctoral Thesis, MIT, Department of Architecture, Cambridge, MA.

Simon H. (1996). *The sciences of the artificial*, 3rd ed., MIT Press, Cambridge, MA