MOVING TOWARD AN 'INTELLIGENT' SHOP MODELING PROCESS

SUBMITTED: August 2007
REVISED: April 2008
PUBLISHED: June 2008
EDITORS: T. Olofsson, G. Lee & C. Eastman

Robert Leicht, PhD Candidate, Department of Architectural Engineering
The Pennsylvania State University;
rmleicht@engr.psu.edu and http://www.engr.psu.edu/ae/cic/people/leicht.aspx

John. Messner, Associate Professor of Architectural Engineering,
The Pennsylvania State University;
jmessner@engr.psu.edu and http://www.engr.psu.edu/ae/messner/

SUMMARY: *This paper focuses on the value and challenges of implementing 3D modeling for trade shop drawings on a case study project, the new Dickinson School of Law (DSL) Building on The Pennsylvania State University campus. While planning for this project, the Construction Manager (CM) required 3D models and Building Information Models (BIM) from the specialty contractors along with the submittal of trade shop drawings. Several papers and articles have discussed the many benefits and challenges of implementing BIM for constructability and coordination. This paper specifically focuses on the 3D CAD models and the BIM assembled by the CM and all of the specialty contractors on the DSL project.*

The use of BIM was initiated by the CM on the project, not by the owner. The interest of the CM in the process and the value to the owner makes this a very transparent and well documented process. The process used by the CM to develop the specialty contractor packages, a breakdown of the 3D and BIM requirements by specialty contractor, the steps to begin coordination, and to carry out coordination as new trades are discussed. The evaluation of BIM usage for construction planning was determined at the end of the Schematic Design phase. The paper explores the complexities of evaluating the value of 3D or BIM for each trade, which trades were excluded from the requirement, which should submit BIM's or 3D geometry, as well as the level of detail and embedded information required from each of the specialty contractors.

Feedback from the owner, the CM, and the specialty contractors on the process and the challenges met to date are presented. A background of 3D model use on projects for Penn State, the owner, and their interest in expanding into BIM for future projects is also discussed. The use of 3D CAD and BIM shop models will serve as a first step toward having an As-Built BIM of the Dickinson School of Law (DSL). Having an example model to test and evaluate will enable Penn State's Office of Physical Plant to establish the value of BIM in their project delivery process and facilities management as they develop future buildings.

KEYWORDS*:* *BIM, shop drawing, clash detection, coordination, case study*

1. INTRODUCTION

> *Our dilemma is that we hate change and love it at the same time; what we really want is for things to remain the same but get better* ~ Sydney Harris

The Architecture, Engineering, and Construction Industry is known for its low spending on research and development into improved technology and processes (Gallaher et al, 2004). With its unique, large scale projects, short period teams, and high dollar values, it is not surprising that the industry members have difficulties employing new technology and processes. However, these challenges are exactly the reason why exploration of new methods is needed. Recently, Building Information Modeling (BIM) has offered new potential benefits for improved design quality, improved communication, and potential constructability benefits (Kiviniemi et al, 2005). This study seeks to explore how these benefits can be implemented in the detailed design coordination through the study of BIM use on the Dickinson School of Law project at The Pennsylvania State University (Penn State).

The Construction Manager (CM) on the new Penn State Dickinson School of Law (DSL) project incorporated unique requirements of the specialty contractors on the project. All of the specialty contractors, with a few exceptions such as the painting contractor, were required to submit 3D modeled geometry of the building systems along with the traditional project shop drawings. All of these models were developed as 2D conversions from the project documents, not from design models. For some of the contractors, the required models also include embedded object data in addition to 3D geometry. The primary goal within the shop modeling process was to enable 3D geometric clash detection for the detailed coordination of the building systems. The project traits that make the DSL requirements unique are: the range of specialty contractors required to submit models, the requirements for additional embedded information, and the long term intent of turning over an “As-Built” model of the entire facility to the owner.

The use of 3D geometry for coordination, while not typical for the building industry, is still not a new concept (Neggers and Mulert, 1993). The use of 3D for coordination is usually limited to the building areas which are the most intense in the need for coordination, such as the mechanical penthouse and other support spaces. The systems requiring 3D coordination are also, typically, those found in the mechanical, electrical, or plumbing systems and usually require the structural system models (Riley and Horman, 2001). The requirement for DSL, however, is extended to almost every trade on the project. The use of the 3D models is intended to identify early conflicts between the systems, so the conflicts can be resolved before the systems are installed. Since the intent of models for clash detection is for problem identification, rarely are the models updated to an “As-Built” condition, or turned over to the owner with the final project documentation.

The recent interest from the AEC Industry in the use of Building Information Modeling (BIM), however, has created new possibilities improve project documentation (Leicht and Messner 2007). Interestingly in the US, contractors, and not designers, have been the first to release a guide introducing BIM (AGC 2006). The DSL construction team utilized this guide as a basis for using BIM, and is trying to develop their own systems to employ, more fully, the resources BIM offers within their projects.

2. CASE STUDY PROJECT BACKGROUND

The Dickinson School of Law was merged with the Pennsylvania State University in 1997 (Steinberg 1997). The school has continued at its original location in Carlisle, Pennsylvania, USA since that time. By creating new facilities at the University Park Campus, the Dickinson School of Law will be the first law school with a program split across two campuses. They started the new construction of the facility at Penn State’s University Park campus in January of 2007 and substantial completion is scheduled for November of 2008, with classes expected to commence in January of 2009. The ground breaking ceremony took place shortly after the release of the Design Development documents, and taking into account some recently released revisions, the project design is nearly complete. Currently (as of April 2008), the building is more than one year into construction, with the structure complete, the curtain wall system more than halfway installed, and the interior system rough-completed for the lower two floors.

The new facility at the University Park campus, as shown in Figure 1, will have a total cost for design and construction of approximately $60 million. It will have 113,000 ft^2 (10,500 m^2) of space, including a 250 seat auditorium, three (3) 75-seat tiered classrooms, a 50-seat courtroom, its own law library, and outdoor gathering spaces. In addition, the facility will include study spaces, faculty offices, and a café (Dickinson School of Law 2007). In accordance with Penn State’s goals of sustainability, the project is pursuing a Silver LEED rating.

Figure 1: Rendering of the Dickinson School of Law design, from http://www.opp.psu.edu/construction/projects/dickinson.cfm

The DSL project is not Penn State's first project utilizing modeling, just the most comprehensive use to date. In fact, Penn State has encouraged the use of technology and has seen its use in several different forms. When constructing the IST building, Turner Construction Company used 4D simulation to plan the steel erection sequence of the structure bridging Atherton Street, one of the town's main thoroughfares. When planning the East Sub-campus projects, 3D modeling was used to view the relationships of four separate projects being concurrently designed and built. During the construction of the Stuckeman Family Building for the School of Architecture and Landscape Architecture, 3D and 4D modeling were employed to help identify schedule conflicts and coordinate trade flow (Gopinath 2004). While Penn State's Office of Physical Plant does not perform the modeling internally, they are very encouraging and supportive of its use on their projects, and the use on DSL provided an opportunity to move from 3D and 4D, into the use of BIM.

3. METHODOLOGY & METRICS OF STUDY:

Several methods were employed to document the impact of 3D and BIM on this case study project. The intent was not to generalize the use of BIM to the entire construction industry, but to identify specific impacts to the DSL project through observation, tracked metrics, and participant perceptions. Since the use of BIM on the project was exploratory in nature, the focus was on identifying the process used, and the challenges and benefits of that process. In addition to mapping the process, project metrics were tracked and compared to other projects that Penn State delivered using traditional trade coordination methods by the same CM.

3.1 Research Goal:

The expected outcome of the process for the CM, as stated in the scope requirements for the specialty contractors, is:

> *To create a model that is used for coordination of all trades throughout the construction process, with the final product being an as-built model of the Dickinson School of Law which contains all of the major elements of construction that could be used by PSU for future operation and maintenance of the building.*

Since the modeling efforts focused on the use of 3D and BIM during the coordination process, this was also the focus of this research. The nature of the AEC Industry makes generalizations about any one project challenging, so research methods are focused upon putting the measured and perceived impacts into the specific context of the project.

The incorporation of 3D and BIM modeling into the specialty contractor requirements was an added requirement; above and beyond the traditional work package requirements. The addition of a 3D geometric model and BIM submissions did not, however, replace the requirements for 2D shop drawings. The intent was to augment these 2D drawings for the purposes of coordination, and to determine the potential use of the as-built model by the owner. In tracking the process, the focus is on the development of these added requirements, since these were unique for this project. Since the project is currently ongoing, processes presented are based on the project status within the first year of construction. Certain uses of BIM on the project, such as the turnover to the owner, are therefore beyond the scope of this paper.

3.2 Process Modeling

To properly identify the areas of impact, the processes being studied were modeled using the IDEF0 process modeling method. The IDEF0 modeling method uses activities to breakdown functions into their component parts. Each activity is represented by a box, with inputs as an arrow entering from the left, and outputs as an arrow leaving from the right (KBSI, 1992). Also, constraints and mechanisms are shown to demonstrate the constraints that govern an activity and the means by which an activity is carried out, respectively (SofTech, 1981). The process modeling efforts were focused on three areas: 1) the development of the work packages, 2) incorporation of new work packages into the clash detection process, and 2) the typical process employed for running geometric clash detection and conducting coordination meetings using the submitted models.

3.3 Metrics

The current literature was reviewed in preparation for the tracking of project information, but there was little found in regard to established metrics for tracking BIM usage in construction. There has been some consideration of defining new metrics, but most are proposed for better evaluating the building performance and design considerations (Morrissey et al, 2004). The metrics that do address construction and effective modeling efforts (Hartmann et al, 2006) focus on the effectiveness of model creation, but do not measure the value of the model itself. With little established as 3D or BIM specific metrics, it was necessary to either rely on standard industry metrics, or to create new metrics. This paper will employ standard industry metrics, with the potential for identifying new metrics as an outcome of the process. The metrics chosen were the quantity of requests for information (RFI) and change orders to the contract.

4. PROCESS FOR DEVELOPING SPECIALTY CONTRACTOR WORK PACKAGE REQUIREMENTS

> *The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency. The second is that automation applied to an inefficient operation will magnify the inefficiency.* ~ Bill Gates

The actual process used by the CM for developing the coordinated 3D shop models for the DSL project contained three main tasks which were 1) determine work packages, 2) integrate new work packages, and 3) coordinate the models These processes are shown in Figure 2. The processes occurred iteratively as new work packages were developed and new specialty contractors became involved in the process.

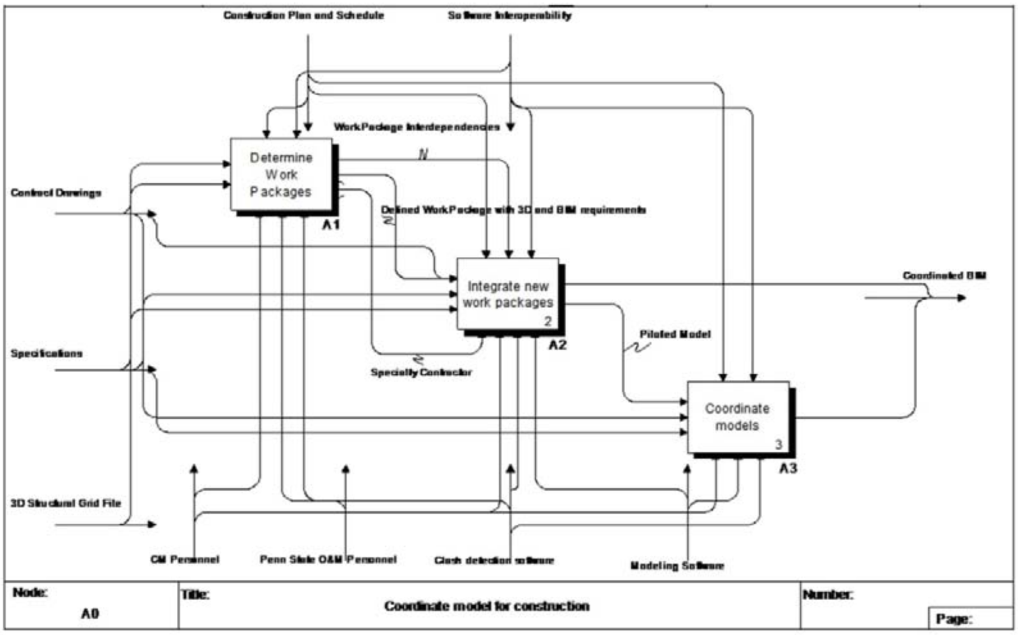

Figure 2: Process for developing the coordination models for DSL.

Determining the modeling requirements for the work packages was subdivided into three processes, as shown in the process model in Figure 3. The first process was to determine the work packages for the specialty contractors. Once a work package breakdown was defined with consideration to local trade practices and experience, the requirements for the 3D model submission for a trade was determined. Finally, after defining the geometrical requirements of the model, the requirements for additional embedded information were identified and incorporated into the trade requirements. With these aspects determined, the request for proposals for each work package was disseminated to potential specialty contractors with specific requirements to include the modeling into their bid.

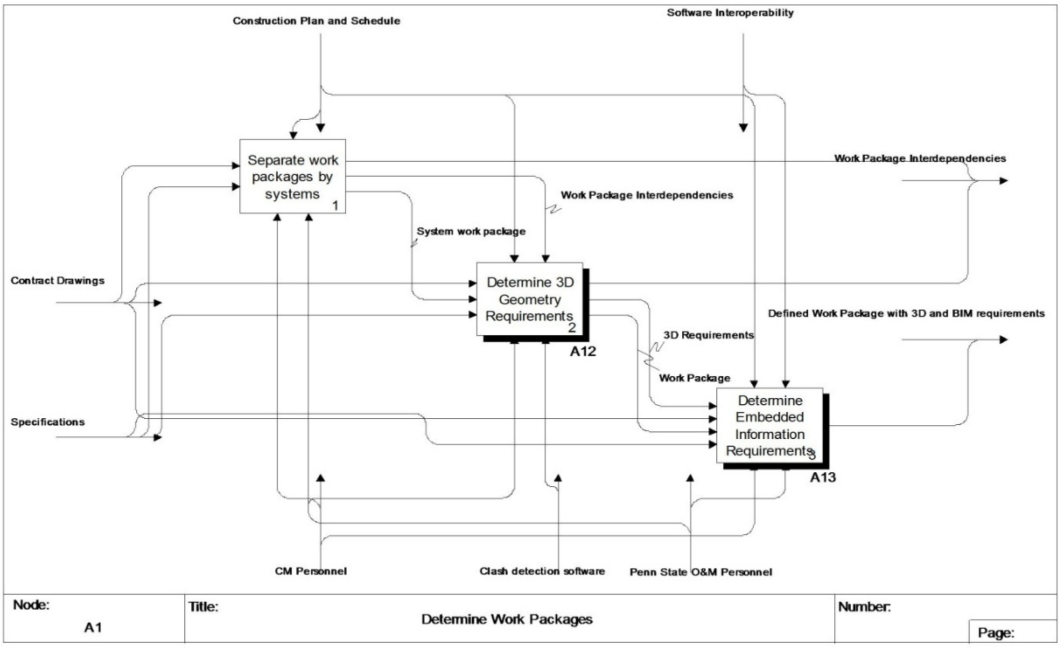

Figure 3: Steps to determining work package requirements for specialty contractors.

4.1 Defining 3D geometrical requirements

The first step, determining the work packages, is not the area of contribution of this research, so the mapping of the process is focused on the second and third processes: determining the geometric requirements and defining the needed information. The goal when defining the geometry to be modeled was to have the specialty contractors develop the model content to visually represent the systems which they will be installing, to a necessary level of detail to plan the means and methods necessary to construct the system, and to convey the understanding and plan to the designers for approval (Pietroforte 1997). There are two purposes for which the models are employed in this regard, specialty contractor coordination and submission of the as-built model. With the project goal of a fully modeled building in 3D, the expectation was for each work package to include 3D modeling. There were a small number of packages with no modeling requirement; though this only occurred when there was little or no geometry to be modeled with a particular package of work, such as the painting package.

When defining the 3D geometry requirements for the work packages, as shown in the process model in Figure 4 , the first step was to determine which system components should be included in the model. The system was first considered from the point of view of the owner receiving the as-built model. The project system components were reviewed with this perspective and an outline of system components was developed. Once the components were developed into an outline, the system was considered, component by component for the level of detail to require. Determining the correct level of detail was found to be one of the challenging aspects for defining the coordination requirements. The determination of the level of detail was based mainly on four factors:

1. Interaction with other systems;
2. Sequence of installation;
3. Prefabrication of components; and
4. Layout considerations and density of systems.

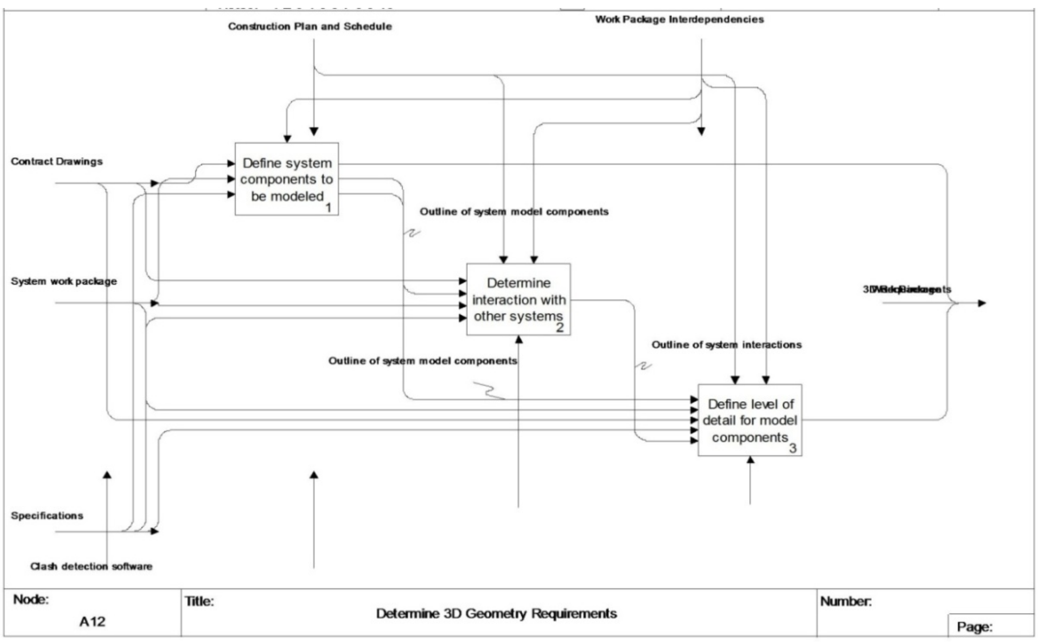

Figure 4: Steps for defining 3D level of detail requirements for clash detection.

For example, when considering the level of detail to model the concrete geometry, the metal decking was not considered important to model to a high level of detail, but necessary to demonstrate the overall thickness of the decking. The only system which affects its layout is the structural steel, there are no prefabrication needs, and layout considerations are minimal. Also, incorporating the corrugations into the model would provide a high amount of detail, which could slow the rendering capabilities of the computer when viewing the model. It is important to note that this does have some limitations since the automation of quantities and potential detailed coordination issues may not be completely accurate, but the project team felt comfortable with these limitations. However, when considering embeds and penetrations in the concrete slabs, a high level of detail was required because these elements involve relationships between the concrete trade and other systems. Ensuring the embeds are correctly placed involves planning work performed by other trades, layout is very important for their success, and their sequence of installation requires planning between multiple trades.

Once these needs were identified, the level of detail was defined as an aspect of the components to be modeled, as they were outlined in the first step of the process. For each component, a level of detail necessary was provided as a minimum requirement for the submission of the model. The 3D requirements were defined alongside the traditional 2D shop drawing requirements, and utilized those requirements as a check to verify the level of detail which was appropriate. In almost every component requirement, the 3D model required less detail than the traditional 2D shop drawings. For example, in the concrete requirements the rebar requirements were only in 2D and read as follows:

> *Concrete reinforcing shall be detailed on 2D drawings only. These should show all penetrations and the rebar details around all penetrations, openings, pour stops, etc. Detailing will incorporate all requirements for openings, sleeves, laps, etc., required by the Contract Documents. The 2D rebar detail drawings shall include at a minimum…*

This does not mean that the 3D model was less important, but that it was being used for coordination between trades, not for the legal form being reviewed by the designers to ensure design compliance and code requirements. It may be possible and more productive in the future for the 3D model to contain the information to meet these requirements and simplify the shop drawing and trade coordination process for designers. However, for this project the 2D shop drawings were still the legally required submittal to the designers, and the 3D was required for the coordination process by the CM. It is also important to note that some systems may be more time consuming to model in 3D such as concrete reinforcing due to limitations in the efficiency of the current 3D modeling tools.

4.2 Defining the embedded information requirements

While the existence of a system for defining 2D shop drawing requirements offers potential assistance in defining the level of detail for the 3D geometry, there is no similar reference available when defining the additional information to be embedded in the model. This process, shown in Figure 5, was exploratory in nature, aimed at determining the potential uses of BIM for construction and the long term potential for Penn State. The first step was the determination of the work packages to include additional information requirements for the models, e.g., mechanical equipment data. Similar to the steps employed for the 3D geometry, this was performed considering the potential user of the data, in this situation the facility owner. There are numerous analyses which can be performed on a BIM, but most of them are supportive of information for building design (McDuffie 2006). Since there was no BIM developed during the design process for the project, the productive uses of the information to be embedded in the BIM were limited to construction and operational uses. With the focus on the operational use of the model, and considering the BIM analysis tools currently available, the uses determined to be most relevant were building maintenance and space management. Working from this point of view, the focus of the embedded information requirements beyond 3D geometry were primarily the mechanical, electrical, and plumbing (MEP) systems. The major focus of the operations and maintenance work performed by Penn State is the upkeep, repair, and refurbishment of the MEP systems in all buildings on campus.

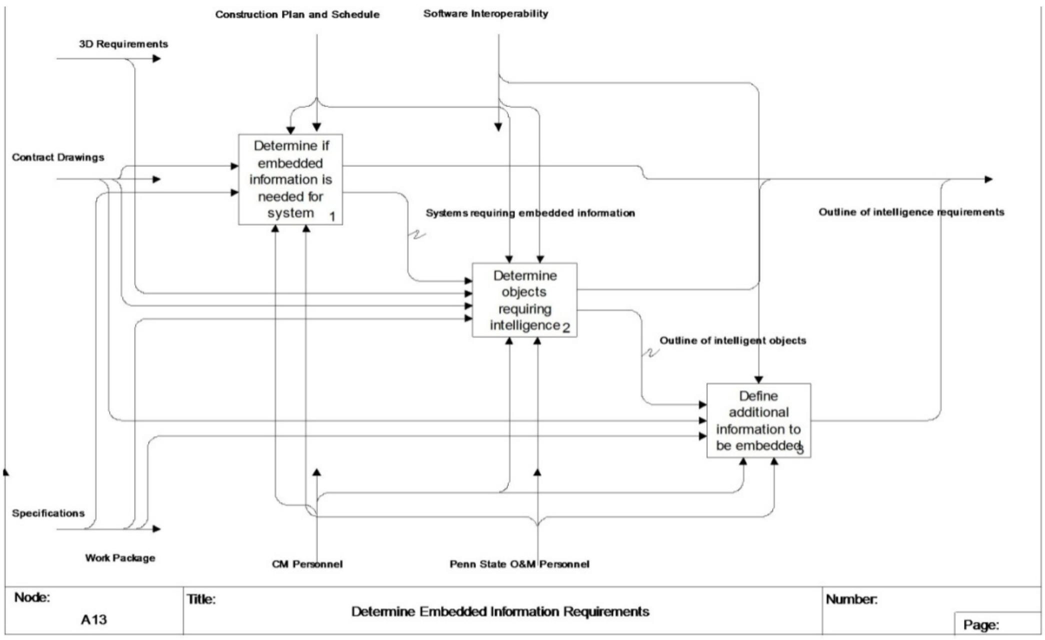

Figure 5: Steps to defining embedded information requirements for coordination and as-built models.

Utilizing the outline of system components developed for the 3D geometry requirements, the systems were again reviewed for additional information requirements. The determinations for BIM requirements had two levels. First, a system was reviewed to determine whether to require the objects to be "intelligent," and second, what additional information needed to be embedded in each object. For the MEP systems, all of the system components which needed to be represented in 3D were chosen to be intelligent. An "intelligent" object is defined by its function and it includes inheritances and relationships (Bazjanac 2003). For example, a piece of rectangular ductwork is not just 3D grouped geometry with "duct" as an attached tag, but includes functional traits such as flow capabilities, as well as relationships to the duct sections before and after it within the system. For the DSL project, the air distribution systems, such as the example piece of ductwork, were required to be intelligent objects with the default relationships and functional inheritance to them. The equipment in the system, however, had additional requirements for embedded information above and beyond the default functions. For example, the plumbing equipment properties are also required to have the manufacturer, product number, serial number, and maintenance schedule as some of the additional information. Though developed independently, the similarity to the COBIE project information requirements of product, equipment, system, and warranty data (East and Kirby, 2006) is noteworthy for its similarity of base information requirements and shows that the information required is focused mainly on operation and maintenance concerns.

One of the interesting aspects of the software employed by the specialty contractors was that several contractors adopted BIM (or parametric) authoring software for developing their 3D models, despite already having software suitable to the project requirements. As an example, one of the contractors with purely 3D geometrical requirements had previously performed their shop drawing in Autodesk's AutoCAD. AutoCAD is capable of modeling the necessary geometry in 3D for the contractual requirements on the project. However, they purchased Autodesk's Revit Building software and had personnel trained in its use specifically for this project. Their reflection on this decision had two main points: 1) taking advantage of the opportunity to explore the use of BIM software, and 2) their desire to work for the owner and CM in the future with the possibility that future requirements may focus on the development of more data rich models.

5. INTEGRATING WORK PACKAGE MODELS FOR COORDINATION

Having defined the work package and identified a specialty contractor to perform the work, the process then moved forward to integrating each trade contractor into the project, and to incorporate their model into the central project file used for geometric collision detection. The steps to integrate the models required some planning and piloting to properly coordinate the files, as shown in the process model in Figure 6 below. The first step was for the CM to provide the new specialty contractors with a file allowing each contractor to orient their information modeling work in 3D to align. Once the specialty contractor has the template file for reference, a section of the model was developed and virtually mocked up to work out any 3D geometry issues such as scale or model orientation. The process to coordinate the files and test the clash detection was performed and the results demonstrated to the specialty contractors so they were familiar with the clash detection outcomes as they prepared for regular coordination meetings.

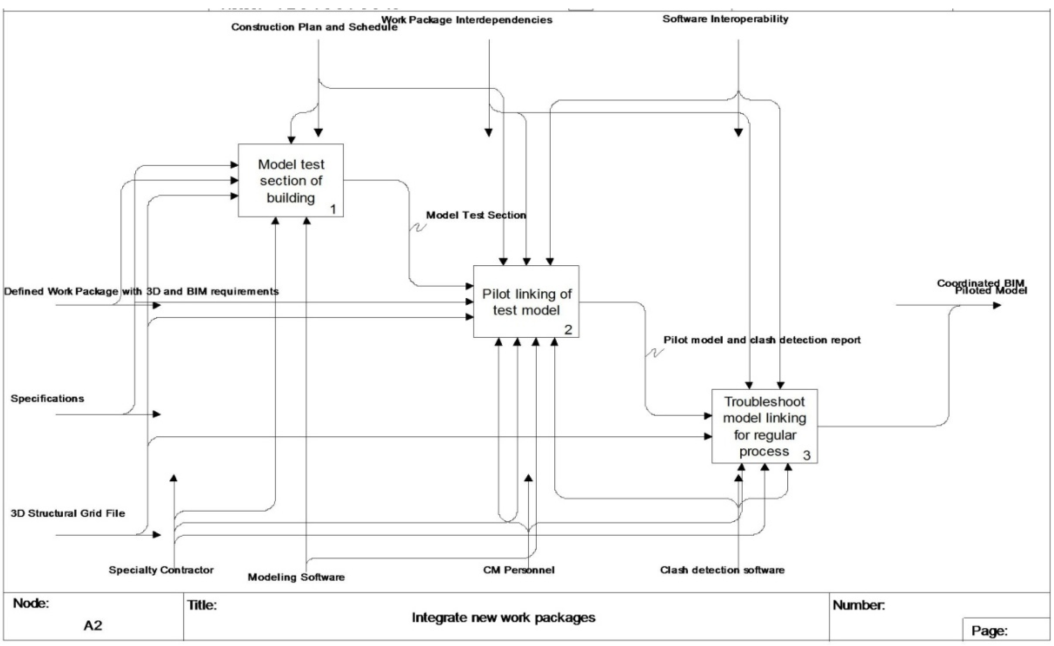

Figure 6: 3D Model Coordination Process.

5.1 Preliminary information to specialty contractors

To begin the process of aligning the files and properly integrating the models, the specialty contractors needed access to reference information, such as points in the model and a scale so their system models aligned with the other specialty contractors' models, as well as a navigable version of the current model. For the first purpose, the CM on the DSL project had a 3D structural grid file developed by the firm performing the surveying. The use of the grid set the orientation of the model, set the scale of the model, and provided reference points for the specialty contractors, which were the same to be used in the actual layout during construction.

Along with the template grid file, a copy of the current coordination model was published from the central model file. The coordinated model files can be published to a cache file, which can be accessed and navigated using a freely available viewer for these published files. The viewer and published models enable the specialty contractors to visualize the current state of the model development and the work being installed by the other trades as they develop their own model.

5.2 Piloting the linking process

With a template file and reference model, the next major step was to pilot the linking of the new specialty contractor's model. The CM chose an MEP intensive support space as a pilot area of the building. The area used for piloting the model was used for the following reasons:

- It contained a representative sample of the building systems;
- It was scheduled as one of the first sequences in most of the system installation; and
- It offered diversity within each system to allow discussion of proper level of detail.

Once the model was developed for piloting, the file was submitted to the CM. The CM would backup the central model file to ensure there was no impact to the current status of the model before linking the new model file to the central coordination file. The use of the 3D grid allows for quick verification of the scale and orientation alignment with the existing scale and orientation, or for identifying the cause of misalignments.

Once a revised model was linked to the central file, clash detection was performed and a meeting with the new specialty contractor was held to review the model. At that time, the discussion focused on the technical aspects of linking the files and how well the model meets the purposes and requirements set forth in the scope of work. Also, discussion included the appropriate geometry for representing components, particularly those which may be able to reduce or increase their level of detail for clash detection and visualization. For example, with the mechanical contractor, the form in which the duct insulation should be represented in terms of geometry was worth discussing in detail. It could extend beyond the square dimension of a piece of ductwork, it could interfere with other trades, and it could be represented as a thickness of the duct or as separate geometry. The value of the initial review mockup was to test the modeling and coordination process, as well as identify and clarify the level of detail for the geometry of the building systems and components**.**

5.3 Coordination interoperability concerns

Beyond the technical aspects of integrating the model, there are other concerns at this early stage which can play a very important role in the success and ease of the clash detection process. The main concern, widely recognized as a current challenge in the industry, is the interoperability of the software files (Gallagher et al 2004). The software used to run the clash detection is a central consideration since it must be able to bring the model files together to identify conflicts between the systems. If some of the file types that are being utilized do not work well with the chosen software, the entire process becomes less effective. At the same time, requiring specific software for the submission could incur extra costs or limit the contractor pool to those familiar with the chosen software.

There were two central aspects to the strategy employed on DSL to minimize interoperability issues for the clash detection process. First, the clash detection software employed, Navisworks Jetstream, was chosen for the wide array of file types it can import and coordinate. Second, when determining the requirements for submission, the model submission requirement was not specific to a single file type, but indicated that it needed to be compatible with the software being used for clash detection. The logic in determining these requirements was to leave the field of available software choices as open as possible for the specialty contractors while still ensuring the file types and information (3D geometry for clash detection) were adequate for the clash detection task.

6. COORDINATION MEETING PROCEDURE

Project coordination meetings were held bi-weekly to coordinate the system geometries. The process used to run the clash detection and hold the coordination meetings started by having the files submitted in advance of the coordination meeting, typically 2 working days prior to the meeting. The next step was to update the central file with the new models, and to run the clash detection analyses necessary for the updated systems. In the software employed, the clash detection can be exported to a report format and distributed to all of the specialty contractors in advance of the meeting. At the meeting, the group then analyzed each of the clashes identified, with the discussions focused on clashes that required project team members to decide appropriate resolution methods. As the clashes are reviewed, the outcomes are documented and distributed after the meeting to all involved project team members.

6.1 Key preparation aspects

To properly prepare for the coordination meetings, there were several planning details needed to ensure a productive meeting. The steps, as shown in Figure 7, begin with the submission of the files from the specialty contractors. The system for these submissions requires some planning due to the potentially large file sizes. The method employed for the DSL project started with the use of a document management system, but shifted to the submission of the files through an FTP site for its ability to upload larger files at higher speeds.

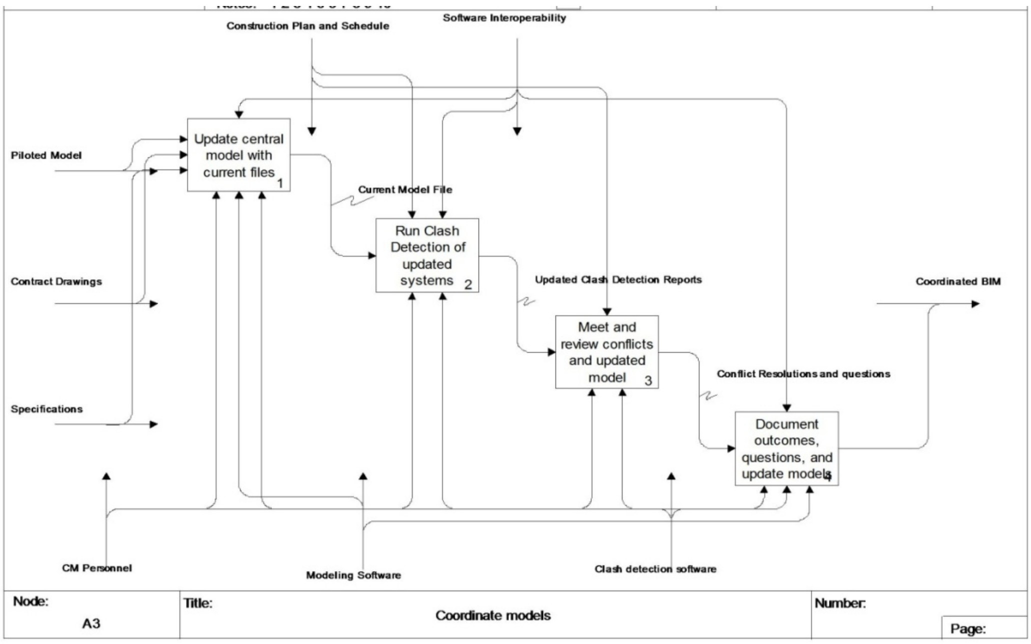

Figure 7: Preparation, procedure, and documentation process for regular coordination meetings using automated clash detection.

Following submission, the files are used to update the central file which is used for running the clash detection. One of the nuances with the chosen software was the need to replace the files linked into the model, rather than deleting the links and loading new files. The clash detection uses identification numbers associated with the model components through the file link. By deleting the link and loading a new file, the clashes which had already been identified and determined to be insignificant would be identified as a new clash for each meeting.

With the new files replacing the files from the previous meeting, the clash detection can be performed. The chosen clash detection software offers options which allow a user to select the specific systems to coordinate, e.g., identifying clashes between mechanical ductwork and sprinklers. Various tolerances can also be added to account for specific conditions, for example a 2 inch tolerance could be added to piping to account for insulation if it is not modeled. The method used for this project was to run the clash detection between any systems which were updated from the last meeting against all other systems modeled in the building. The result is a report of all of the clashes identified, which could be exported and distributed to all of the specialty contractors before the coordination meeting. There were challenges found with the format of the distributed report because the conflicts identified are only portrayed as images and may be ambiguous to interpret, as shown in Figure 8. Often, the central file is needed to navigate to a specific view which allows for the visualization of the objects in conflict. The distributed report does provide an opportunity for the specialty contractors to review and consider the conflicts before arriving to the coordination meeting. It would be beneficial if the software could offer a reference view of the clash either as a marker on a floor plan or as a navigable 3D model with the clashes highlighted, which could be distributed.

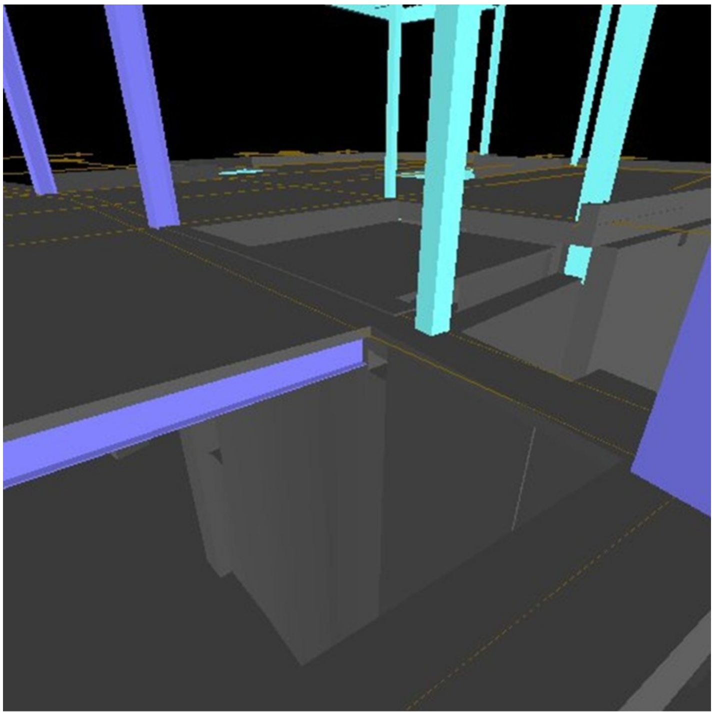

Figure 8: Image from a clash detection report identifying a conflict between the structural steel model and the concrete model.

6.2 Meeting Procedure

The procedure for coordinating the systems was kept to a few steps. The specialty contractors involved, as a group, review each of the identified conflicts in the order in which they are presented in the report. As the group shifts to each conflict, the model is navigated to provide different viewpoints and to identify the systems and components in conflict. The discussion which ensues seeks to determine the necessary course of action. The potential outcomes observed typically fell into three categories, which were:

Table 1: Clashes observed on project classified and related to the remedy typically utilized on the project.

Types of Clashes	**Example**	**Remedy Utilized**
Insufficient Level of Detail	Ductwork penetrating wall, where wall was not required to have such openings	Conflict Report was adjusted to ignore this particular clash if level of detail is deemed unimportant
Coordination Issue	Ductwork and a Pipe directly conflict	Coordinate requirements and potential solutions
Design Issue	Inadequate space for ductwork as designed	Submit as an RFI to design team

While the software offers opportunities for identifying these conflicts, it does not offer a means of reconciling the issues between systems. The task of identifying a solution is still dependent on the knowledge of the project team members.

6.3 Documenting the outcomes

To ensure that the outcomes and identified action items are addressed following the meetings, the meeting results are documented in two forms. First, each clash is documented in the model, including the system and components in conflict along with the location. If the clash found is not a true conflict and required no action, the status of the conflict is changed so it is documented but would not arise as a clash to review in the future. The second form of documentation is meeting minutes documenting the conflicts that were considered noteworthy, either as true coordination conflicts or as design conflicts. At the completion of the meeting, the revised clash detection report with the information about the conflict components and locations, and the meeting minutes documenting the action items are distributed to the project team.

7. PROJECT PERFORMANCE METRICS FOR DESIGN COORDINATION

There were many metrics considered when trying to determine the methods for measuring the impact of implementing 3D design coordination for trades on the project. While cost and schedule growth offer potential insights into the overall change to the project (Thomas et al 2001), these tools are best employed after the project is complete to compare with other completed projects. The DSL project is ongoing, so the metrics chosen, Requests for Information (RFIs) and change orders, are related to cost and schedule growth, but can be analyzed prior to project completion.

7.1 Requests for information

Requests for Information are questions and clarifications from the contractor to the designer related to various project design information. The project currently has 1050 submitted RFIs on record. The submitted RFIs are plotted in Figure 9. The vertical green lines represent the dates of the coordination meetings held. Early in the process there is little correlation between the coordination meetings and the submission of RFIs. One of the likely explanations for this is the small pool of contractors involved at that time. The process began with the structural steel, concrete, and curtain wall trades only, trades which are not usually involved in the detailed design coordination process.

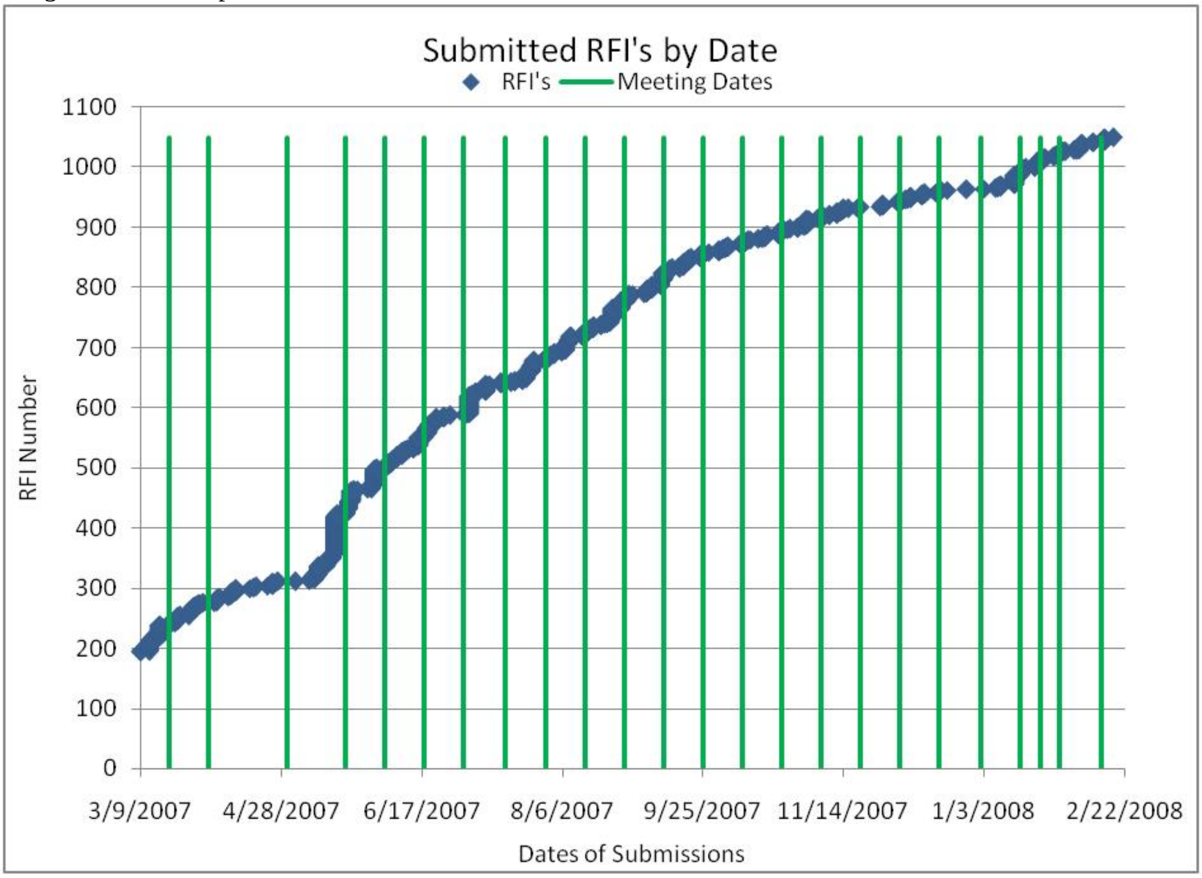

Figure 9: Graph of submitted RFIs by date, shown with the coordination meeting dates.

In May more trades became involved in the project, and the correlation between the coordination meetings and the submitted RFIs started to become evident. In Figure 10 the total RFI submissions can be seen in a more focused view for this time. The highlighted regions indicate the RFIs which correlate most closely with the timing of the coordination meetings. There are two reasons to which this timing may be attributed. First, as the specialty contractors develop their models for the coordination meetings they identify areas which need further clarification. Second, following the meeting the clashes and conflicts identified sometimes require the input of the designers to resolve.

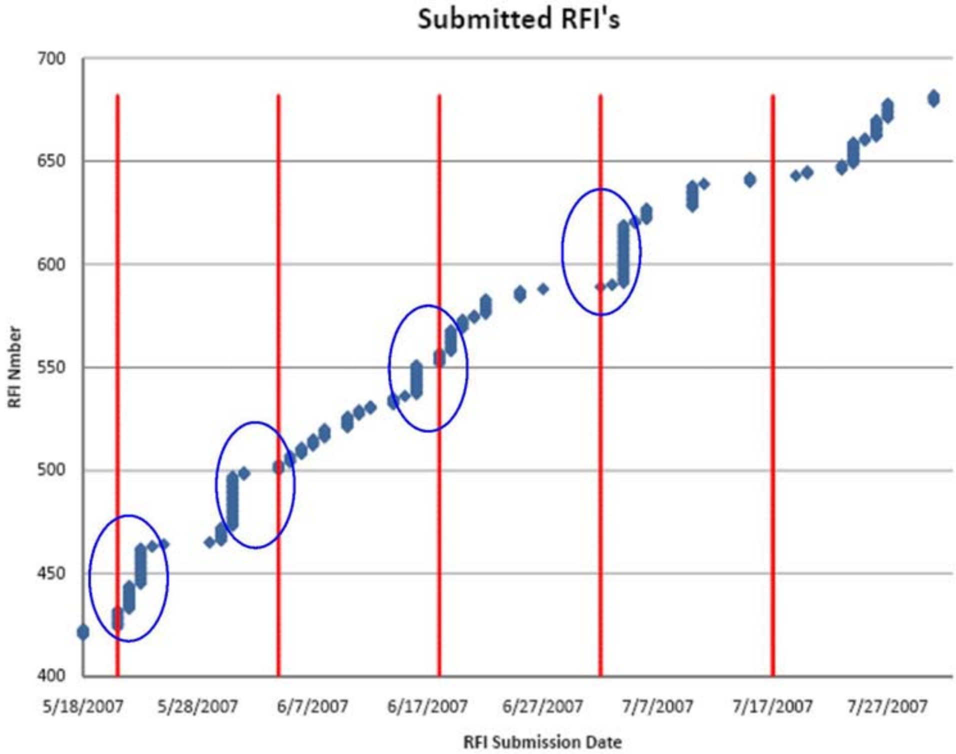

Figure 10: Focused view of submitted RFIs starting in mid-May 2007.

It should be noted that since the 100% complete Construction Documents have not been issued to date, a large number of the RFI's may be associated with design content which had not been fully designed at that point. The intent of the coordination process was to limit the impact of field conflicts. The process may have provided a means of identifying areas of the design which needed further development; while not contributing to the original intent, this is a positive aspect of the coordination process. Due to the overlap of design and construction, these areas would probably have been completely designed before they reached construction, but they may have inadvertently become field conflicts as a result of the timing of the construction. The use of the modeling and clash detection would therefore offer additional value in a delivery process with a higher level of integration than projects with more time to coordinate systems in design.

Along with the overall number of RFIs which were tracked, efforts were made to identify RFIs resulting from actual field conflicts. All of the submitted RFIs were reviewed to identify questions resulting from systems in conflict. Following the preliminary list of potential conflicts, each RFI was reviewed with staff from the CM to verify each was an actual conflict which arose during field installation. While the results are not yet conclusive with the project still under construction, the current status indicates a very low number of field conflicts. Of the 1050 RFIs reviewed, only 6 have resulted from field conflicts.

7.2 Change orders

The DSL project is scheduled to be under construction through the end of November in 2008. The overall value of the project change orders will not be certain until project completion. To provide some feedback about the current status, the current value of changes and specifically those related to field challenges and conflicts has been tracked. To date, there are no change orders originating from field conflicts. The current value of change orders is approximately 10% of the original contract value. The majority of these changes resulted from the further development of the design and additions to scope after trades had been procured. There have been a few minor field changes which have been handled through allowances. With the project more than 1 year into construction, the value of these allowances for field issues is less than $10,000. With the original contract value of $60 Million, this means that costs for field changes are less than 0.01% of the original contract value.

8. LESSONS LEARNED

When entering into an exploratory study, the most valuable outcome may not necessarily be the money saved or the field conflicts which are avoided, but the clearer understanding of the process needed. In pursuing the use of BIM on the DSL project, the CM tried a variety of implementation concepts to identify what worked well, what did not work, and what potential future opportunities existed.

8.1 Project Successes to Date

One of the areas found to be of the most value, in an intangible fashion, was the planning and transparency of the process. When trying to define the process and requirements, it was often necessary to garner comments and feedback from the specialty contractors, the owner, and the design team. By keeping all of the team members informed of the process and planning for the next steps, the CM avoided many potential pitfalls, such as requiring too much detail for the models. The planning was pursued with the purpose of the models clearly in mind, and the planning concepts reflected that purpose. The outcome was that the requirements aligned with the model use, and therefore avoided unnecessary detail or missing detail. For example, defining the level of detail for each system by outlining the components kept the requirements clear for each work package, while still offering a consistent and systematic approach which would be simple to transfer to another project.

The issue of file interoperability could have presented a severe challenge to the project, due to the array of authoring software available and the current limitation of file exchange within the industry. By defining the software by the performance with the given clash detection software, the CM diffused the situation for 3D geometry and still allowed a wide variety of solutions available to the specialty contractors when choosing their modeling software. This limited the potential impact to the specialty contractors and allowed them to minimize their costs for developing the models. As software becomes more interoperable in the future, this may become less important, but for this project it was a significant concern.

8.2 Project Challenges

While the overall process was clear to all involved, there are still opportunities to improve that process by analyzing the challenges encountered. The process of defining the requirements was well planned and thorough. That does not mean, however, that all of the requirements fit exactly to the needs of the project. The exploratory nature of the use of 3D and BIM on the project encouraged the use of requirements beyond the current needs and skills of the current state of the specialty contractors involved. The encouragement and awareness created by this are of potential benefit, but the outcome for the DSL project posed some challenges to the team. It was found that some of the specialty contractors involved had experience with 3D modeling before the DSL project, and its requirement was not an extra burden, e.g., the steel fabricator and the curtain wall contractor. However, in cases of specialty contractors with only 2D shop drawing experience, the requirements for 3D and the submission of a model with intelligent objects added new responsibilities and in some cases the manner of meeting these new requirements created extra work and costs. For example, several of the specialty contractors performed the 2D shop drawing submittals in the traditional 2D fashion, and had a separate modeler or 3rd party firm develop the 3D model or BIM to meet the additional requirements. The separation of the modeling from the shop drawings created inefficiencies and extra work, whereas if the shop drawings were developed as a 2D view of the 3D Model, the 3D model submission would simply be a extension of the same effort.

There are several reasons causing the challenges seen on the DSL project which should be considered before determining these requirements for the next project. First, some of the trades had limited experience in 3D modeling, and almost none had experience with the additional attribute data and information required of the BIM submissions. While this should not eliminate the use of such requirements, it suggests that these capabilities should be considered when determining which trades should submit 3D models or BIM for coordination. Second, there are more trades involved in the coordination process on DSL than are typically involved in this process. The mechanical, electrical, plumbing, and fire protection trades are the most common to participate in the traditional coordination process, mainly because they have the most to gain from the process (Riley and Horman, 2001). On the DSL project, almost every specialty contractor is required to submit a model and to participate in the coordination process. While this allows for identification of clashes between all of the building systems, it requires a substantially larger cost savings to justify the added modeling costs to the project. Third, all of the models were developed from 2D paper drawings since the original design was not developed using BIM tools. If the design was developed using BIM and the files were shared with the construction team, the cost of performing the design coordination and clash detection could be significantly lower. In fact, many of the design coordination tasks could be moved into the design process, thereby limiting the information requests and revisions required in later trade design coordination. This assumes that the design team authored and performed some coordination using BIM software, and that the specialty contractors are able to use the design model to develop their detailed shop model.

In addition to challenges with the team, there were technical challenges to overcome as well. The clash detection software proved very useful for identifying when two systems came into conflict. However, it was discovered that there were times when the systems did not identify a conflict, yet there were coordination issues. For example, when the elevations of the column base plates were being coordinated with the top elevations of the spread footings, the elevations were to have a two inch gap for the placement of non-shrink grout. If the elevations were modeled with too large of a gap, the clash detection system did not identify a problem, because there was no geometric conflict to find. The software allows for the measuring of distances in the model, so the gap can be measured, but it does not offer any way to easily automate the identification of such problems, unless geometry is specifically modeled so it should clash and the absence would prove an indication of a problem. So for the given example, a piece of geometry could be modeled within the two inch gap, with a thickness of slightly more than two inches. If the geometry identifies a conflict, the distance of the conflict will quickly determine if the conflict is different than the overlap built into the model. If no conflict is found for a column, then the gap is too large and needs to be revised. So along with the modeling of the geometry, other coordination challenges needed to be considered that could not be automatically coordinated using the software.

A better method for addressing this issue would be to develop automated rule checking for coordination issues such as the column footing and base plate elevation. This could be performed in model checking software if all the information regarding the objects were accurately reflected in the models. This was not feasible on this project since the trade models were primarily 3D geometry for coordination, and did not always carry object attribute data.

9. CONCLUSIONS

The process used for developing and coordinating specialty contractor work packages on the DSL project was documented and presented. Along with this process, feedback and project data was presented to demonstrate the changes which took place on the DSL project. The process was found to have a few unique and important steps:

- Defining the 3D and embedded information requirements;
- Providing reference information and a template model for alignment of the shop models; and,
- Piloting the initial linking process and troubleshooting the problems.

These steps were designed mainly to alleviate concerns with the level of detail required for the models and the interoperability challenges. The interest in the process from the specialty contractors was clear. While only the MEP trades were required to submit BIM files, there were several other trades that developed their models using BIM authoring software and submitted files containing intelligent objects. The use of this software when it was not required is a strong sign that the interest in 3D modeling and BIM is growing in the industry.

The process also demonstrated value in the form of the submitted RFIs, which show a correlation between the coordination meetings and the RFI submission dates. While the project has a substantial number of RFIs for its current status in the construction process, the number of RFIs resulting from field conflicts was 6. Beyond the measured benefits taken from the clashes found by the software and the shift in efforts to develop the 3D or BIM models, the process created a more transparent environment on the project. The value derived from this sharing of information, visualization, and understanding of systems between different trades is not clearly measurable.

While the project had several positive outcomes for the use of modeling and BIM analysis tools, there were some outcomes which showed the requirements for BIM should be planned based on the purpose of the tasks being performed. Despite the interest shown by the specialty contractors, the use of embedded information showed no added value for the design coordination process, beyond the use of the 3D geometric data. It is possible that information could be valuable in the future for shop drawing review or code-checking, and it may still prove useful with the transmission of the as-built model to the owner. It was also found that the level of modeling experience was an important factor to consider when determining modeling requirements. And while the automated clash detection identified a multitude of system conflicts, there were some coordination issues which could not be identified by the 3D geometric cash detection software since they were not geometric clashes.

Thus far, the process has been found to be a positive experience for the team members involved and for the project environment. The project team plans to continue to utilize the process for the duration of the project.

10. FUTURE RESEARCH

The tracking of this case study will continue through the completion of construction, commissioning, and turnover to the owner. The research into the impact of 3D and BIM on the project will continue, with research into the value of the As-Built BIM to the owner, and the final cost and schedule impacts for the project at completion. The model will also be employed to determine other potential uses for project planning, including the impact of visualization and collaboration, the use of virtual mockups focusing on a mock courtroom in the building, and possibly the planning of the Law School's Virtual Classroom setup.

11. ACKNOWLEDGEMENTS

We would like to acknowledge The Pennsylvania State University's Office of Physical Plant and the Dickinson School of Law for allowing us to use this project as a case study. We would also like to thank the project team for their help and support in the performance of this research with a special thanks to the interviewees. We also thank the National Science Foundation for their support of this research (Grant No. 0348457). Any opinions, findings, conclusions, or recommendations are those of the authors and do not reflect those of the National Science Foundation or the project participants.

12. REFERENCES

AGC (2006). Contractors guide to BIM, The Associated General Contractors of America, The Associated General Contractors of America, Alexandria, VA.

Bazjanac, V. (2003). Virtual building environments (VBE) - applying information modeling to buildings, Lawrence Berkeley National Laboratory, University of CA, Berkeley**:** 8.

Dickinson School of Law, P. S. U. (2007). Penn State trustees approve university park building plans. http://www.dsl.psu.edu/news/buildingapproved.cfm. Accessed: 24 July 2007.

East E.W. and Kirby J.G. (2006). Evolving a building information model, presentation to National Building Information Modeling Standards Committee, NIBS, Washingtion, DC, 10 July 2006.

Gallaher, M. P., O'Connor, A. C., Dettbarn, J. L. and Gilday, L. T. (2004) "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry", GCR 04-867, NIST

Gopinath, R. (2004). "Immersive virtual facility prototyping for design and construction process visualization." M. S. Thesis, The Pennsylvania State University, University Park, PA.

Hartmann, T., Gao, J., and Fischer, M. (2006). *An analytical model to evaluation and compare 3D modeling productivity on construction projects.* Joint international conference on computing and decision making in civil and building engineering. June 14-16, 2006. Montreal, Canada.

Kiviniemi A., Fischer M., and Bazjanc V. (2005). Integration of multiple product models: IFC model servers as a potential solution, in Scherer R.J., Katranuschkov P., and Schapke S.-E. (eds) *22nd Conference on Information Technology in Construction*, Institute for Informatics, Technische Universitat, Dresden, Germany.

Knowledge Based System Inc. (1992), *IDEF0 Function Modelling Method Overview,* KBSI, College Station, TX.

Leicht, R. and Messner, J. (2007). *Comparing traditional schematic design documentation to a schematic building information model.* Conference Proceedings from CIB w78, IT in Construction. June 26-29, 2007. Maribor, Slovenia.

McDuffie, H. T. (2006). "BIM: transforming a traditional practice model into technology-enabled integrated practice model." The Cornerstone, AIA. 2006.

Morrissey, E., O'Donnell, J., Keane, M., and Bazjanac, V. (2004). LBNL paper 906.

Neggers and Mulert (1993). Interference detection with 3D computer models, *Proceedings, ASCE Computing in Civil Engineering* Anaheim, CA, pp. 1279-1282

Pietroforte, R. (1997). Communication and governance in the building process. Construction Management and Economics, Volume 15, Issue. 1 January 1997, pages 71 – 82.

Riley, D. and Horman, M. (2001). *The effects of design coordination on project uncertainty*. Proceedings, Annual conference of international group for lean construction, 9. Singapore, 2001.

Thomas, S. R., Macken, C. L., and Lee, S. H. (2001) "Impacts of Design/Information Technology on Building and Industrial Projects", GCR 01-828, NIST

SofTech (1981). Integrated computer aided manufacturing (ICAM), Function Modeling Manual, Prepared for Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Ohio, USA.

Steinberg, J. (1997). "On campus; Penn State merges with Dickinson School of Law." New York Times, Section B, Page 7, Column 3. 22 January 1997.