# A CASE STUDY IN STRUCTURAL DRAFTING, ANALYSIS AND DESIGN USING AN INTEGRATED INTELLIGENT MODEL

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## ABSTRACT

One of the promises of Interoperability and Building Information Modeling (BIM) is that information about a building should reside in a central model, and that this model should be used by all members of a design team without duplication of information. While such models have been used for generating 3D models for coordinated designs, the additional use of such models for analysis has been more limited.

Recently software has become available that allows 3D *intelligent* building models to be used for structural analysis. This paper presents a case study – a reinforced concrete laboratory in California – from a structural engineering viewpoint where Autodesk Revit Structure is used to create both a building model for documentation and a building model for export to analysis software. In addition, the structural model was exported in 3D .dwg format for integration with a 3D model of mechanical, electrical, and plumbing (MEP) services. Advantages and disadvantages are discussed with a focus on practical issues of interoperability and implications for the construction industry.

## KEY WORDS

Interoperability, Structural Engineering, Structural Analysis, BIM, CAD.

## INTRODUCTION

### DEFINITION

Building Information Modeling is a term that was coined to describe a 3D object-oriented representation of a building specific to the requirements of Architecture, Engineering, and Construction (AEC). It is intended to highlight the move by the construction industry away from 2D computer-aided drafting (CAD) towards models that collate information about a construction project and associate that information through geometric relationships. To a user, BIM is a collection of data organized hierarchically by objects and most often viewed

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with a graphical user interface (GUI), such that every building piece (a door, a W24x156 beam, a wood panel, etc.) is not just represented as an item in a database, but also as an image (i.e. 3D renderings, plans, elevations, details, symbols, etc).

The information in the building model can thus be extracted to generate documentation in the form of construction drawings, measurements of quantities, and specifications, but also the information can be sent to analysis engines that use the model for structural analysis, computational fluid dynamics analysis, etc. If an accepted language describes the organization of the building information (e.g. using IFC format), the entire design team can potentially use the same *model* (i.e. a single file compiling all the building information).

Recent structural engineering graduates will view the newest BIM software as simply a more complex version of structural analysis input files. In some ways, BIM is more similar to traditional structural analysis software than to traditional drafting software, because structural analysis packages have for years shown 3D views of buildings where each element represents an object in the final building.

## HISTORY

Despite the new name, antecedents to BIM (such as ARC's OXSYS, RUCAPS and GLIDE, as described in Eastman, 1999) appeared as early as the 1970s. These systems were not very flexible and often imposed design constraints. The hardware at the time was both bulky and expensive and until recently, limited further development of these earlier systems.

As a result of this limitation, the computerization of the design process divided into two streams (from a structural engineering perspective): drafting and analysis. Computerized drafting replaced pen, ink and vellum, and computerized analysis replaced the tedious process of analysis based on hand calculations.

In the last few years, computing power has reached a level that allows software to be truly flexible and rich in information, and there are a number of BIM packages available that contain detailed architectural information. However, the integration of structural analysis and drafting has progressed more slowly. Until recently, either analysis packages incorporated and generated construction drawings and schedules, or drafting packages added structural analysis. The latest development combines the processes, so that the building model is both a physical model and an analytical model (for structural analysis), with both sets of information created simultaneously.

## OBJECTIVE

This paper presents a case study of the use of one of this new class of tools – Autodesk Revit Structure – which Arup's San Francisco office has recently used on projects to create structural construction documents as well as structural analysis models to be analyzed using ETABS (from Computers & Structures, Inc.). Thanks to the option to export the building information in 3D .dwg format, additional coordination was carried out with MEP construction documentation created in Autodesk Building Systems. This paper will outline the advantages and challenges encountered when BIM was used to create an analysis model and construction documents for a new university laboratory in California. After a brief description of the project, the paper follows the chronological path of a typical project:

- Creating the Model
- Using the Model for Analysis
- Revising the Model
- Creating Coordinated Documentation

## PROJECT DESCRIPTION

Arup San Francisco is designing structural, mechanical, electrical, and plumbing systems for a 3-story 9,000m² (90,000 sq. ft.) university laboratory in California. Arup and Perkins & Will, the architect, began schematic design (SD) in early 2005 and 100% construction documents will be completed in 2006. Both firms' role in the project continues through construction administration.

The building resists lateral loads with concrete structural walls while flat concrete slabs and concrete columns resist gravity. While the overall geometry of the building is rather simple, the MEP systems are extensive. The straightforward structural design coupled with complex MEP systems presented an excellent opportunity to implement BIM software with expectation of immediate benefits through improved SMEP coordination.

## CREATING THE MODEL

### THE MODEL'S ORIGIN

During SD, the CAD Manager created the 3D building model in Revit Structure. The architect for this project used 2D AutoCAD drawings, so creation of the model began with importing the architect's 2D .dwg floor plans into Revit Structure as shown in Figure 1. Ideally, the architect would provide a 3D architectural model in a compatible format such as ADT or IFC. Architectural gridlines were selected and converted into Revit Structure gridlines; floor plans were assigned to elevations; columns, slabs, and walls were created for the first time as shown in Figure 1. Creating the model took significantly less time than completing similar tasks in AutoCAD.

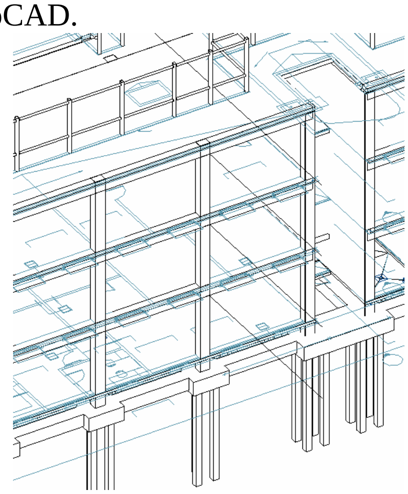


Figure 1: BIM Model with architectural backgrounds

## THE BIM CONCEPT: ONE MODEL, MANY USES

As the drafter creates a building model for documentation, an analytical model is simultaneously and automatically created. Each structural element contains not just geometric properties that allow it to be viewed either 3-dimensionally or in a more traditional 2D environment, but also properties required for analysis, such as material properties, section moduli, and end release conditions. This dual representation allows the potential for the same model to be sent to the printer for documentation while the structural analytical information is also available to external structural analysis software through an Application Programming Interface (API). At present, the structural analysis packages, ETABS, Risa and Robot Millennium have already created routines that read Revit Structure model data and others, such as Arup's Oasys GSA are following suit.

Autodesk created an intuitive graphical interface for displaying the two models (See Figure 2). The analytical model is by default represented by colored lines embedded within the more voluminous 3D representation of the actual structural piece. Beams (orange in Figure 2) and columns (blue in Figure 2) are simple straight lines. Floor slabs (brown in Figure 2) and walls are polygons. Thus, within Revit Structure, the structural engineer can choose to view and adjust the "analytical stick model" just as a structural engineer would traditionally view and adjust an analytical model using a GUI attached to analysis software.

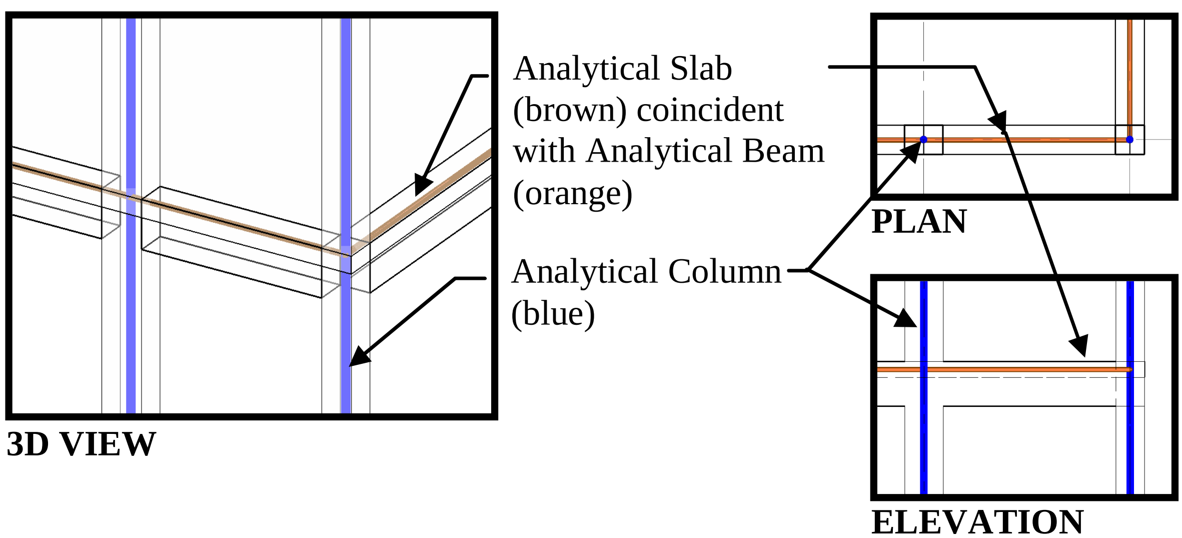



Figure 2: Analytical sticks within model

As expected, creating a multi-use building model requires more coordination between drafter and structural engineer. With more coordination required, design teams often fear that engineers will be required to *draft* more or that more responsibility for design will be placed on the drafter. However, based on Arup's experience, it appears that with increased familiarity, BIM can decrease the amount of time both the engineer and the drafter spend creating the model without altering the traditional responsibilities of drafters and engineers. The roles of the drafter and engineer are discussed in more detail next followed by a more detailed explanation of how the model was used for analysis.

## WHO FIRST CREATES THE MODEL? THE ENGINEER? THE DRAFTER?

As mentioned earlier, the drafter created the first model for this project. This building model proved sufficient for documentation, but could not be used directly for analysis. Initial problems with using the model for analysis included:

- beams did not intersect at single nodes
- columns were not broken up at floors
- walls were not attached to floor slabs

These problems could be reduced in the future by engineers working more closely with the drafters creating the model. However, based on Arup's experience, it seems more likely that engineers will want to first create the model, and for drafters then to work with the model to create documentation.

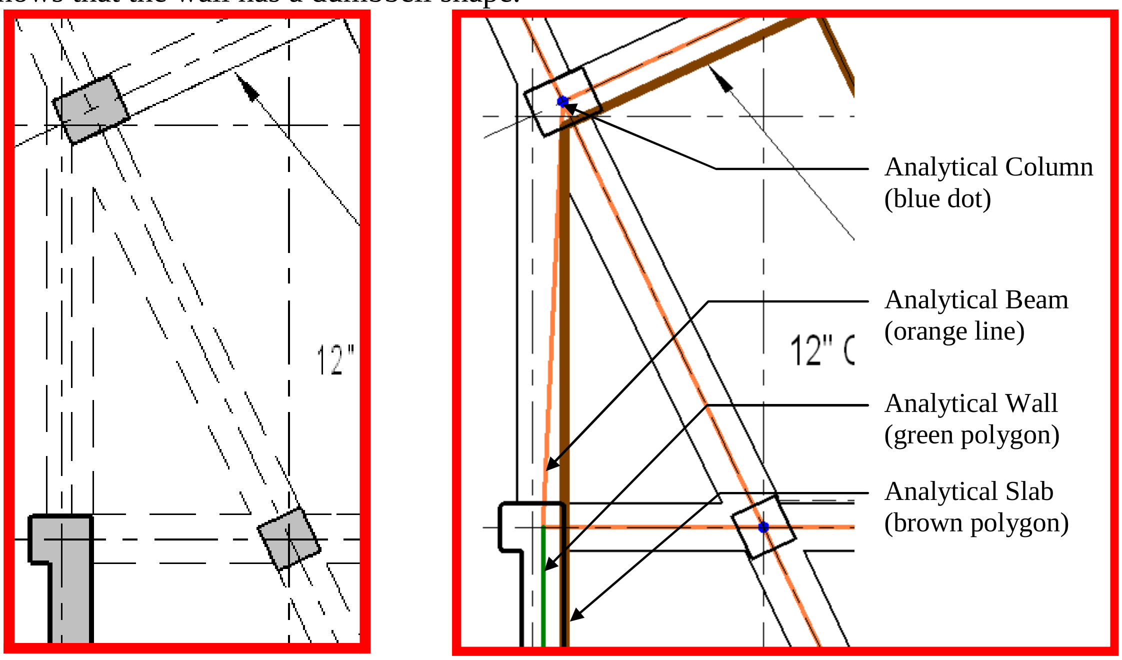
This work flow is preferable, because whereas the creation of effective construction documents relies solely on the appearance of the final documentation, structural analysis models require a certain precision (and sometimes even more importantly approximation) that only engineers are trained to appreciate. That is, to the structural engineer, *how* the model is created may be just as important as the final appearance of the model. This *cultural* difference in how drafters and engineers create models is significant, because it is usually much more time consuming to troubleshoot an analysis model than to create one. Furthermore, in the end the engineer is responsible for the building design, and that design is based in part on the structural analysis of the model.

Thus, in future Arup projects, the structural engineer will create the first model, and then, the drafter will make necessary adjustments for proper documentation. At first it may seem that this process requires more of the engineer's time, but really, the engineer creates analysis models anyways, and it is much more efficient to create an analysis model in Revit Structure than using traditional model creating techniques (2D CAD or structural analysis software). Thus, from the beginning the engineer saves time creating the analysis model and the drafter saves time by starting with a model, and then, simply adjusting it to create construction documents.

## USING THE MODEL FOR ANALYSIS

By means of Revit Structure's API, structural analysis programs are able to extract the relevant structural elements and properties (the analytical sticks shown in Figure 2). Within Revit Structure, beam, column, wall, and slab sizes are automatically defined and exported to ETABS based on the building model. Grid lines and floor levels are also automatically transferred into ETABS, though some further adjustment may be necessary (either in Revit Structure or ETABS) to ensure that columns, beams, walls, and slabs all lie on the same analytical plane, so they connect at single nodes. Loads can be defined within the building model, but there is currently no distinct advantage to applying loads within Revit Structure, especially since during analysis most programs including ETABS offers several code-based tools for applying seismic and wind loads that will not translate back to Revit Structure. Geometry transferred exactly into ETABS and with careful preparation nodes were always coincident.

The advantages of flexible BIM software are demonstrated in Figure 3. Here, the engineer wants the building to be constructed according to Figure 3 a.). Note that Figure 3 a.) is a 2D view of a 3D model that appears identical to documentation that would traditionally be created in a 2D AutoCAD drawing. When an analytical view is selected, the same model appears as shown in Figure 3 b.). Revit Structure allows the analytical beam to be slightly angled to allow it to connect to a single node on the column even though the physical beam runs directly north-south. Furthermore, the physical wall can be represented as a rectangular 2D element (shown as a single line in the 2D view); even though the documentation view shows that the wall has a dumbbell shape.




a.) Plan view for documentation

b.) Analytical view to show elements to be exported to ETABS

Figure 3: Plan view that demonstrates model flexibility

This flexibility makes BIM software an effective and efficient tool for creating models that are then read by analysis software packages. It is eventually intended that changes made in the analytical model would then be fed back to the original Revit Structure model. By improving and understanding finite element meshes, load applications, the importance of rigid offsets, restraints, element and material property modification factors, and many other structural model related issues currently available in analysis software, Autodesk and analysis software companies will eventually create a model that can truly move between analysis packages and Revit Structure multiple times. At the time of writing this process has not been fully implemented, but this close relationship between analysis and documentation will certainly increase efficiency even further. Even without this process, the implementation of design changes using BIM offers much improved efficiency as discussed next.

## REVISING THE MODEL

### WITHIN REVIT

Computerization has brought significant advantages with regard to making changes to drawings. Before CAD, moving a gridline some distance to the north required redrawing every sheet that had a plan view of the columns on that grid. CAD saved time, because with CAD every plan sheet could be opened and one half of the building could simply be cut and pasted into the new position. Of course, moving the columns required adjusting the beams, the elevations, perhaps even some details, and it was easy to forget to tie everything back together again or to miss that an associated section or detail had now been changed. If there were multiple stories, simply opening every drawing required a significant amount of time. With a parametric relational modeler present in the BIM software, the relationship of the columns to the grids can be locked, at which point, when the grids are moved, all linked elements are automatically extended. Sections and the outline of details are automatically updated, because they are merely views of the 3D building model.

This parametric relationship between building objects potentially offers significant time savings, although it should be noted that human nature dictates that the easier it is to make changes, the more changes will be demanded (closer to deadlines!) by the rest of the design team. As BIM becomes more prevalent, it may become even more important to regulate and limit project changes. Just because changing the model is easy, does not mean changes should be frequent, as engineers still must perform design calculations for every iteration, as highlighted in the next section.

### WITHIN ETABS

While it is no doubt intended that models exported from Revit should be ready for analysis, it is likely that in many cases some level of adjustment within the analysis program will be necessary. For this project, with the current levels of integration, it was necessary to define offsets, loads, meshes, load combinations, restraints, etc. after the initial import. As a result, the analysis model became independent of the main building model. Revisions were carried out in parallel somewhat defeating the objectives of a single model.

It should be noted, however, that Revit does allow areas of a building to be selected for export, so if changes are restricted to a particular area, updating the ETABS model is feasible. The university laboratory for example had an office wing with a constantly changing geometry. While the core ETABS model never changed throughout the project, the office wing could be deleted from the ETABS model and then, just the new office wing geometry could be reimported into the old model.

## CREATING COORDINATED DOCUMENTATION

Even without consideration of the analytical uses of the model, BIM still offers numerous advantages over traditional CAD as discussed below.

### MANY VIEWS, ONE MODEL

Once a 3D model exists, elevations, section cuts, and details can be created with just a few mouse clicks. After extents of the view are defined, each view can be simply dragged into a drawing sheet, and detail numbering is automatically updated in every view (See Figure 4) Whereas before, the engineer would sketch elevations and then pass them to the drafter to be drafted from scratch; now, views are created instantly, and they are automatically accurate and to scale.

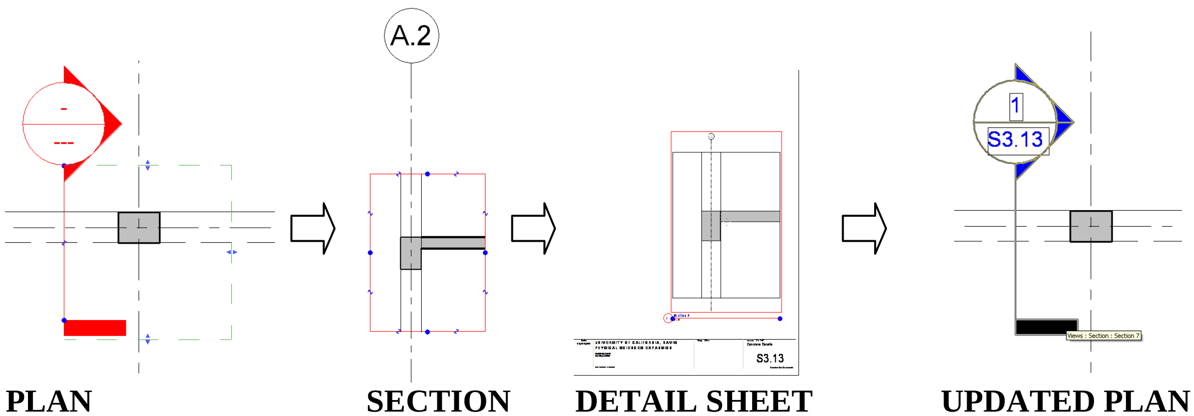



Figure 4: Creating a detail

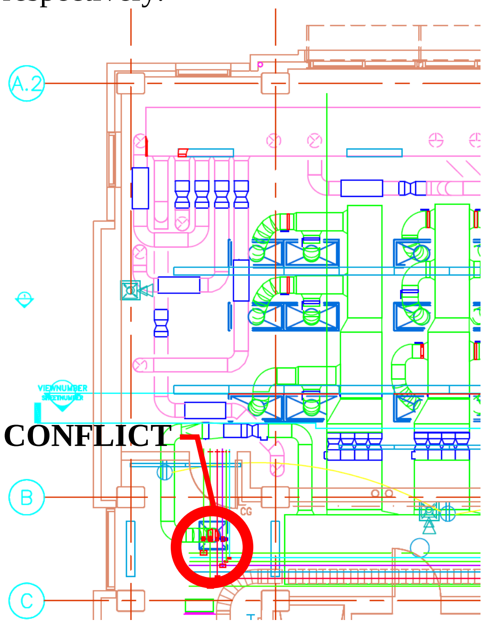
### THE END TO CONTRADICTING DRAWINGS

Since all drawing sheets are based on the same 3D model, it is simply impossible for one view of the building to conflict with another view. As soon as a beam size is updated, every single view that shows that particular beam is also updated. If a detail number changes, all references to that detail automatically change. Traditionally, a single dimension is shown only once; a beam size is shown only once; an elevation is preferably shown only once. Design team members would flip through numerous pages to gather the evidence to understand a single structural element. This tradition of showing data only once is now obsolete, because there is no risk of updating one dimension and forgetting to update another dimension on another sheet. Now, every individual view of the building can give the team member a complete understanding of the design intent.

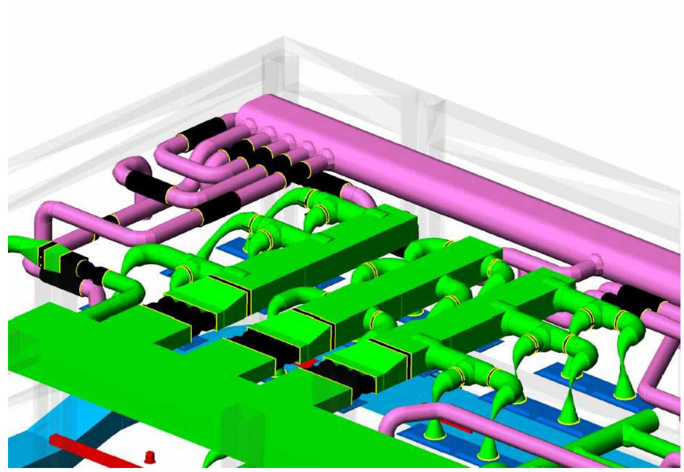
### AVOIDING SMEP CONFLICTS

BIM does not just help to coordinate drawings within a single discipline. Perhaps the greatest advantage comes from interdisciplinary coordination and communication. By resolving conflicts early in the design process, developing solutions during construction can be avoided. Furthermore, with all the building information in one file, communication between the design team can facilitate better designs.

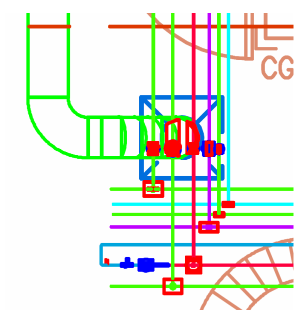
For this project, the Revit Structure model was imported via 3D .dwg format into Autodesk Building Systems. Coordination between MEP systems and the structure was performed visually. A few conflicts among M, E, and P systems were identified automatically using Autodesk Building Systems, and these conflicts were resolved during design, avoiding potential delays during construction while the contractor requests clarification. Figure 5 a.) shows a 2D representation of the MEP systems shown in Figure 5 c.). In this case, the software automatically finds a conflict in the MEP systems and highlights the area in red. Figure 5 c.) and d.) show a 2D and 3D view of the conflict area, respectively.



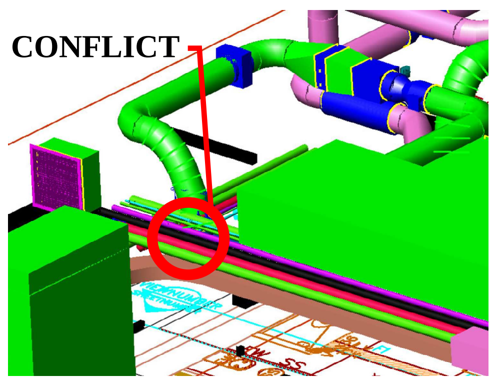

a.) 2D View of Overlaid SMEP & Arch. Plans



b.) 3D View of SMEP




c.) Area of MEP conflict




d.) 3D view of MEP conflict

Figure 5: MEP systems with structural and architectural backgrounds

## DOCUMENTATION CHALLENGES

Fittingly, CAD's greatest strength is at least for now, BIM's greatest challenge: lines. CAD offers complete control over line weights and line styles (hidden, invisible, center-line, solid, etc.), and so lines always appear exactly the way the designer intended. It is critical that BIM software have the intelligence to recognize how engineers use line types to communicate via 2D documentation. Otherwise, drafters will still need to draw lines on top of a 3D model or edit lines already present in the building model, defeating the purpose of BIM. The Plan and Elevation in Figure 2 present an example of this challenge. Here the Plan should show the beam edge under the slab as a hidden line (it is solid in the figure), and the Elevation should show the slab edge beyond the beam as a hidden line (it is hidden only after adjustment by the user). While this is a relatively simple problem for drafters and engineers, it may well be more difficult to implement in programming code, but we can expect to see these issues cleared up in the future.

## CONCLUSIONS

The process of generating documentation from a 3D parametric model is a step forward for the construction industry, with the potential for significant savings[4]. This process is already underway in the industry and major players are encouraging it. Based on the experience in this project, time can be saved through building one integrated model instead of two separate representations for analysis and documentation, even where additional manipulation is required.

On this project, integration with mechanical and electrical systems was preliminary, but even here there is the opportunity for added efficiency through identification of lack of fit at an early design stage, instead of on site. Intelligent building models constructed in this way will also become the starting point for other forms of spatially-based analysis - acoustic, CFD etc, leading to better design through greater and earlier coordination among the construction industry.

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ETABS, Nonlinear Version 9.0.2, Copyright © 1984-2005, Computers and Structures, Inc.

[4] NIST report NIST GCR 04-867 (2004) came to the conclusion that, as a conservative estimate, \$15.8 billion is lost annually by the U.S. capital facilities industry resulting from inadequate interoperability.