
AC 2011-96: IMPLEMENTING BUILDING INFORMATION MODELING IN CONSTRUCTION ENGINEERING CURRICULA

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Implementing Building Information Modeling in Construction Engineering Curricula

ABSTRACT

Building Information Modeling (BIM) has been profoundly transforming the architecture, engineering, and construction (AEC) industry and likewise is having a similar impact on construction engineering (ConE) education. Without understanding the limitations of existing BIM software packages, the acceptance and implementation of BIM in ConE education will not take place. This paper presents a study that was conducted to compare the functions of Autodesk Revit products and the Vico Virtual Construction Software Suite, the two most popular BIM solutions, and to determine the feasible BIM-based work flow for fulfilling the Body of Knowledge (BOK) requirements in ConE, such as cost estimating, construction scheduling and control, project administration, and contract documents. This paper describes the procedures for identifying the strengths and weaknesses of each software package, and proposes a protocol of implementing BIM in ConE curricula. Finally, conclusions are made and recommendations for avenues of future research are made.

INTRODUCTION

Today's architecture, engineering, and construction (AEC) professionals are handling energy conservation, sustainability, and environmental compliance of construction projects from inception to disposal. Often time all three of these critical industry issues need to be addressed simultaneously. This significantly intensifies the demand for information exchange and therefore creates an unprecedented challenge for the traditional paper-based management system. In the traditional system, design, construction, and operation information are retrieved and exchanged in isolated silos¹. As a result, productivity continues to suffer and reduction of waste, cost and time from total project delivery is difficult to achieve. The situation is becoming even more exacerbated due to the increasing size, complexity, and aggressive schedule of today's projects.

Building information modeling (BIM) technology effectively addresses this challenge. The concept of BIM is to model a building virtually before it is built physically². A BIM model is a centralized database that contains physical and functional information of a project. In this database, information can be easily captured, stored, searched, and recalled by numerous users throughout the project lifecycle. Using a BIM model, AEC professionals rehearse design, construction, and operation processes, identify potential problems and impacts, and make corresponding adjustments. Consequently, needless rework is eliminated, productivity is dramatically improved, and projects are completed faster and more profitably. Essentially, the evolution of BIM technology has profoundly transformed the process the AEC industry uses to build projects³. In 2009, about 50% of the AEC industry had adopted BIM and another 20% had plans to use BIM within two years⁴. However, it is clear that without the parallel education efforts to assist and promote this transformation, wide-spread adoption of BIM in the AEC industry will not take place.

CURRENT STATUS OF BIM WITHIN THE AEC EDUCATION

Construction engineering (ConE) educators have already joined in providing accessible training. Becerik-Gerber et al. recently conducted a survey study⁵ on the current status of BIM within the AEC education in the U.S. Among 101 respondent programs, 51% were ABET accredited

engineering programs; 44% of these engineering programs offer BIM courses. Other programs that have not adopted BIM believe that they will be incorporating BIM into their curricula with a year (43%) or two (44%).

LITERATURE REVIEW

Recent studies have indicated numerous ways and the corresponding advantages and challenges of incorporating BIM into ConE curricula. Johnson and Genderson⁶ viewed one of the challenges as the complexity of the relatively new software tools. Another research⁷ characterizes BIM as an interactive knowledge repository in which information can easily be accessed, visualized, and simulated, which then create a conducive learning environment. Salazar et al. described how BIM models were developed using Autodesk Revit⁸ and how BIM was integrated into their ConE curriculum⁹. In a recent study¹⁰, Autodesk Revit and Vico software¹¹ each were introduced to students in two different classes for them to use in their final projects. One of the findings was that without guidance, the self taught approach to learn BIM software was challenging. Sabongi¹² surveyed all members of the Associated Schools of Construction plurality and found out that the majority of respondents used Autodesk Revit in BIM education, others used Graphisoft ArchiCAD, Bentley Architecture and VectorWorks Architect. At Brigham Young University, students learned how to use Autodesk Revit Architecture/Structure/MEP, Navisworks and Sketch-up to complete course work. Student feedback was used to design a sustainable building/BIM class¹³. In his study, Woo¹⁴ described the pedagogical challenges of using Autodesk Revit as the BIM solution, including: 1) it was complicated for students to learn the software, 2) there was not enough tutorial materials, and 3) there was not a large enough number of materials and components in the Revit databases.

STATEMENT OF THE PROBLEM

Obviously, similar to what happened in the AEC industry, BIM is transforming ConE education. However, guidance to select appropriate BIM software packages and an understanding of how an individual package can fulfill specific body of knowledge (BOK) for the ConE education is minimal to nonexistent. This is a significant constraint hindering the use and adoption of BIM technology.

The main research questions addressed in this paper are:

1. What are the limitations of most widely used BIM software packages?
2. How to select appropriate BIM software package(s) to fulfill specific body of knowledge (BOK) for the ConE education?

METHODOLOGY

In this research study, two widely used BIM software packages, namely Autodesk Revit family 2010 and Vico Virtual Construction Suite 2008, were selected and their capacities and limitations were examined by the authors. As a case study, these two packages were used to model a two-story academic building. Finally, conclusions and recommendations are provided.

BIM Solutions

As BIM technology continues to evolve, software vendors have been developing solutions to fill the BIM matrix. A brief introduction of the most developed BIM solutions (presented in alphabetical order) is provided below:

Autodesk Revit (Revise Instantly) family includes Revit Architecture, Revit Structure, and Revit MEP (**M**echanical, **E**lectrical and **P**lumbing). Revit Architecture is one of the best known BIM software in architectural design. Besides the modeling capacity, Revit MEP also provides built-in tools for building systems design and analysis. Revit can interface with other software through DWG, DWF, DXF, IFC, and gbXML files. Revit family is available free of charge for faculty and students to use for 14 months.

Autodesk Navisworks¹⁵ can import modeling file (DWG, DXF, IFC, gbXML, etc.) from numerous BIM software packages, run construction sequencing simulation (4D scheduling simulation) and real-time navigation, perform clash detection, and generate photorealistic visualization. Same as Revit family, Navisworks is available free of charge for faculty and students to use for 14 months.

Bentley System¹⁶ comprises a family of application modules that include Bentley Architecture, Structural Modeler, Bentley Building Mechanical Systems, and Bentley Building Electrical Systems, Bentley Facilities, Bentley PowerCivil (for site planning), and Bentley Generative Components. Its common interfaces include: DWG, DXF, and IFC. The major drawback of the Bentley System is that it is hard to learn and navigate.

Graphisoft's ArchiCAD¹⁷ is the oldest BIM design tool available today. It is the only BIM system that can be used on the Apple Macintosh. Graphisoft has developed a number of construction-oriented applications on the ArchiCAD platform. In 2007, after Graphisoft was acquired by Nemetschek, a German CAD company popular in Europe, the construction applications were developed to Vico Software, which is introduced later in this section. ArchiCAD is free for the academia community for 30 days and then yearly extension of usage is available through an easy request process.

Solibri Model Checker¹⁸ checks for potential clashing building components and verifies whether the model complies with building codes. Other functions include Model visualization, comparison of model versions, and quantity take-off .

Tekla Structures¹⁹ is a modeling, structural design and detailing tool for both steel and concrete construction. It is mainly used by detailers, fabricators, manufacturers, and contractors. It has a construction management module and also has the ability to check clashes and perform 4D simulations.

Vico Software: Vico Virtual Construction Software Suite is the first commercially available 5D (3D plus time and cost) virtual construction system. The suite has six integrated modules: Constructor, Control, Estimator, 5D Presenter, Cost Manager, and Change Manager. *Constructor* creates 3D construction models, *Control* links the construction model to the project

schedule, *Vico 5D Presenter* performs 4D scheduling simulation to allow schedule alternatives to be analyzed and communicated effectively. *Estimator* extracts quantity information from the 3D construction model to produce estimates. *Cost Manager* tracks cost over time to produce cost-loaded schedules for financial analysis. *Vico Change Manager* is a communication platform for project team members and manages document changes. Same as ArchiCAD, Vico is free for the academia community for 30 days and then yearly extension of usage is available upon an easy request process.

Each BIM solution has its advantages and limitations. Results from a recent study showed that when multiple choices were allowed, 67.08% of the respondents were using Revit, 31.69% were using ArchiCAD/Vico, and 14.79% were using Bentley²⁰. One of the authors has had prior experience of using both Revit and Vico. Considering these factors, together with the ease of availability of the two software packages, it was decided to select Revit and Vico as the BIM solutions under study.

The Body of Knowledge (BOK) for ConE Education

Like any other pedagogical techniques, BIM technology should be integrated into ConE curricula to accomplish their BOK requirements.

Hildreth and Gehrig²¹ identified the following four principal knowledge areas and their subsets of knowledge and skills to define the ConE BOK:

- I. The knowledge and skills associated with **cost estimating** include:
 - a. understanding the requirements of the work based on the drawings and specifications;
 - b. estimating work quantities;
 - c. evaluating and selecting appropriate construction means and methods;
 - d. estimating labor and equipment rates;
 - e. designing field operations and estimating rates of production;
 - f. estimating indirect and overhead costs; and
 - g. preparing a bid estimate.
- II. The knowledge and skills associated with **construction scheduling and control** include:
 - a. understanding and preparing various types of construction schedules;
 - b. developing a work breakdown structure and list of schedule activities;
 - c. planning an appropriate sequence activities for a logical project work flow;
 - d. estimating activity durations;
 - e. applying appropriate methods to allocate and level schedule resources; and
 - f. analyzing a project schedule and reporting project status.
- III. The knowledge and skills associated with **project administration** include:
 - a. understanding project delivery processes;
 - b. applying principles of construction law and ethics;
 - c. understanding contractor licensing requirements and procedures;
 - d. understanding lien and labor laws as applied to construction;
 - e. identifying appropriate construction codes and regulations;
 - f. developing quality control programs and plans;
 - g. performing economic analyses and developing cash flow projections; and
 - h. managing risks on a construction project.

- IV. The knowledge and skills associated with **contract documents** include:
- a. understanding the elements of a construction contract;
 - b. understanding payment, performance, and bid bonds;
 - c. preparing construction contract documents;
 - d. developing safety programs and plans; and
 - e. developing procurement documents for construction materials and services.

Different ways the chosen software packages can meet these BOK requirements and particular software function limitations are described in the Methodology section.

The Case Study Building

The building selected for this research is a 52,000 S.F., 2-story academic classroom building located in North Carolina. Figures 1 and 2 show the first and the second floor plans of the building. Revit and Vico were used to develop BIM models of this building. Then software capacities and limitations were studied.

BIM SOFTWARE CAPACITY COMPARISON

3D Modeling Capacity

Autodesk Revit family: Three Revit packages were used to develop a 3D model of the case study building following the steps below:

1. Revit Architecture was used to model the building form, including walls, floors, roof, ceilings, doors, and windows, the work was saved as Model A;
2. Model A was opened in Revit Structure to add wall and column footings, slab on grade (SOG), structural beams and columns, and reinforcement, the newly added structural work was saved as Model B;
3. Model A was opened in Revit MEP to add mechanical, electrical, and plumbing components, the newly added MEP work was save as Model C;
4. Site components were added to Model A; and
5. Models A, B, and C were combined together to create Model D, which was the final 3D model.

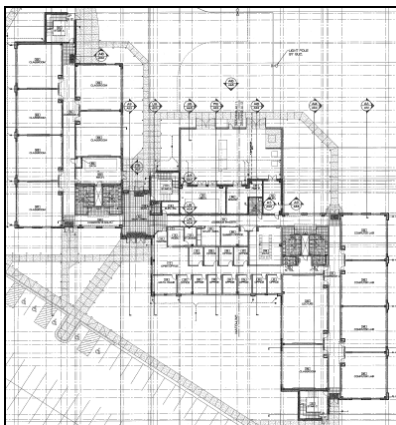


Figure 1. First Floor Plan

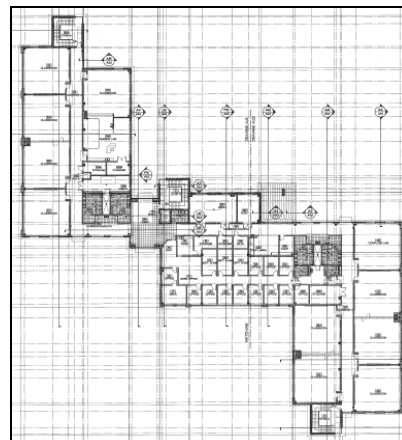


Figure 2. Second Floor Plan

Figure 3 shows the main functional tools residing in these three packages.

This workflow is close to real-world practice where modeling work is typically split by discipline. For a classroom setting, this workflow is more efficient because as long as Model A is created, steps 2, 3, and 4 can be worked on by individual students simultaneously. This shortens time to complete a 3D model.

One limitation was that when a project involves more than one Revit package, the same software version must be used. For example, Revit Architecture 2010 only works with Revit Structure 2010 and Revit MEP 2010. This may be problematic when students install different versions of Revit on their personal computers, and eventually find out that individual models cannot be combined.

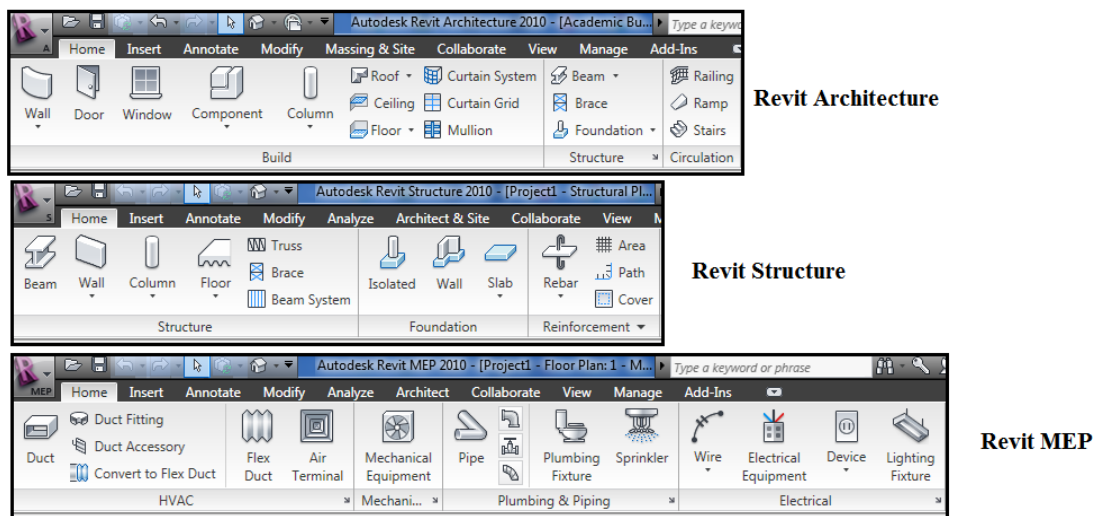


Figure 3. Revit Architecture/Structure/MEP main functional tools.

One drawback lies in the way in which Revit models footings. In Revit, walls must be created first, and then wall footings are attached beneath. The same procedure applies to placement of columns and column footings. Obviously, the opposite order is used in real-world construction practices. This drawback should be explained to students because they are expected to use BIM technology to simulate construction sequences correctly.

Revit's built-in libraries contain a large number of pre-defined elements, such as walls, floors, ceilings, doors, windows, and columns. If specifically designed elements cannot be found in these libraries, Revit provides users the ability to design new elements (Figure 4). This design flexibility alleviates complexity constraints on projects so that more projects can be assigned to students.

Building components, such as site accessories and logistics, can be found in an online library: Autodesk Seek². This resource provides thousands of ready-to-use objects to assist in the development of site plans for students' projects.

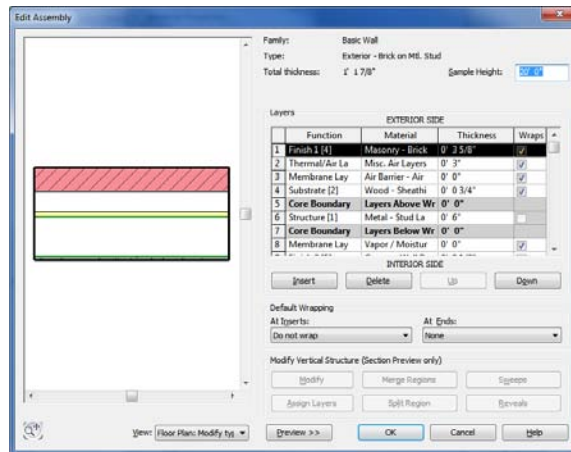


Figure 4. Design of a new type of exterior wall in Revit

When modifying an element, e.g., an exterior wall, users are able to add as many custom parameters as are needed. Consequently, each element in Revit can not only carry its physical information, but also its functional information. The advantage of this design flexibility is twofold: 1) students can use these parameters as filtering criteria to generate quantity schedules, for example, the surface area and volume of exterior walls whose R value is 4; and 2) these parameters can be exported to third party software tools for structural analysis, construction scheduling, cost estimate, and even energy analysis.

Figure 5 shows thermal resistance R was added to an exterior wall.

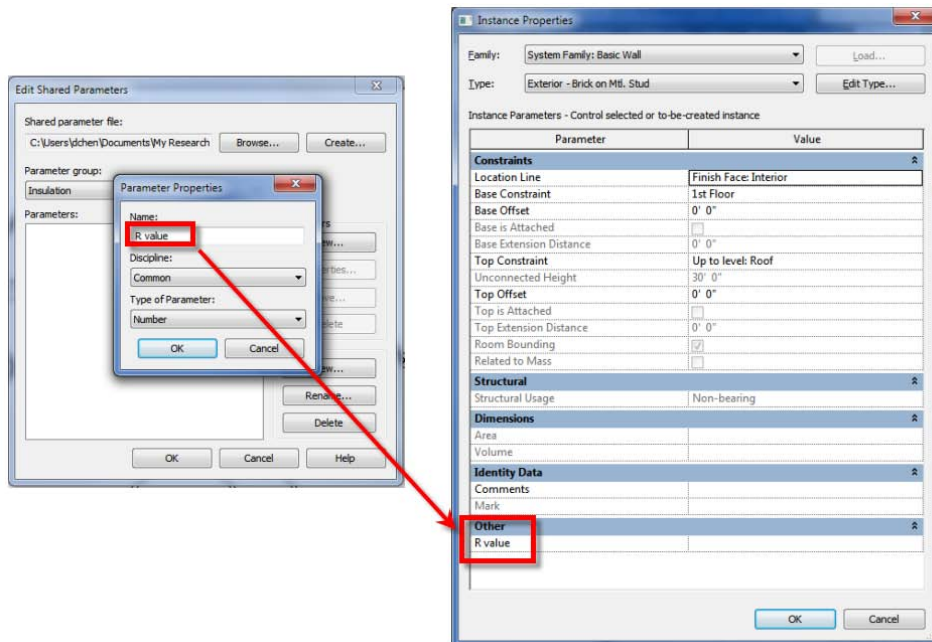


Figure 5. Addition of a new custom parameter

Vico Virtual Construction Software Suite : All architectural, structural, and MEP elements were modeled using Vico Constructor. One disadvantage of this modeling method is that at any point

of time only one model file can be operated. Compared to the Revit workflow, it took a longer time to complete the same 3D model. Figure 6 shows the functional tools in Vico Constructor.

However, one Vico's technology, namely Virtual Trace (VT), greatly expedites the process to create a 3D model. Similar to the concept of an architect's trace paper, VT allows an external drawing to be overlaid on top of any plan views. Users can trace building elements from this virtual trace paper. If the external drawing file format is DWF, DXF, DWG, or DGN, all objects on the external drawing are snapable. This significantly improves accuracy. Most of today's plans are in PDF format. Although PDF files can be traced, they are not snapable and it is difficult to change scale. The solution is to use a third-party solution to convert the PDF files to DWG or DXF files and then trace them. However, only high resolution PDF files can generate acceptable DWG or DXF files. Figure 7 shows how VT was used on the case study building.

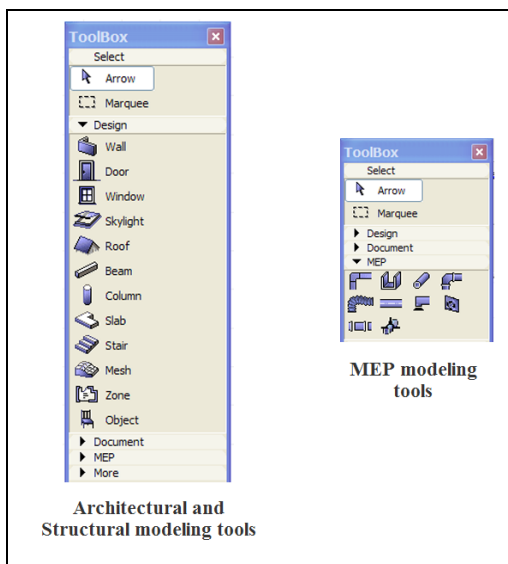


Figure 6. Vico Constructor functional tools

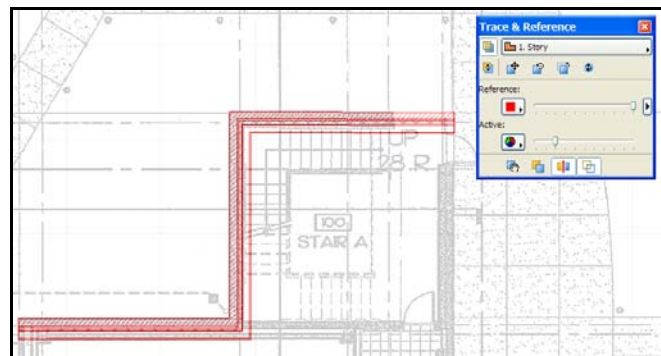


Figure 7. Vico Virtual Trace function

Similar to Revit's built-in library, Vico Constructor's built-in library contains a large number of pre-defined elements. Similarly, Vico allows users to create new elements if they are not in the library (Figure 8). However, no custom parameters can be added to the new elements.

Vico's built-in library also contains a number of building components, but unlike Revit, Vico does not have an online resource to provide additional components.

A 3D model of the case study building created by Revit is shown in Figure 9.

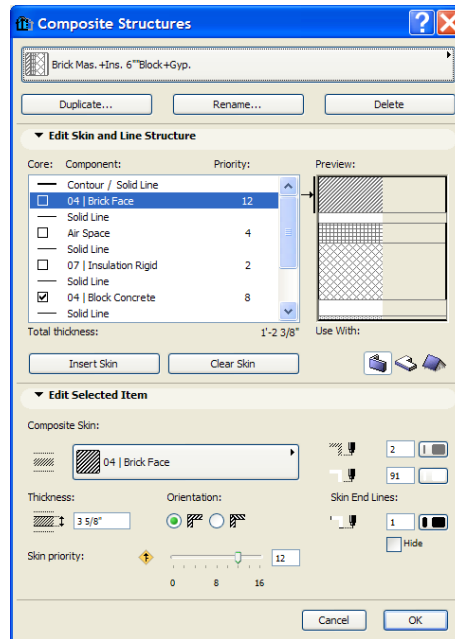


Figure 8. Design of a new type of exterior wall in Vico

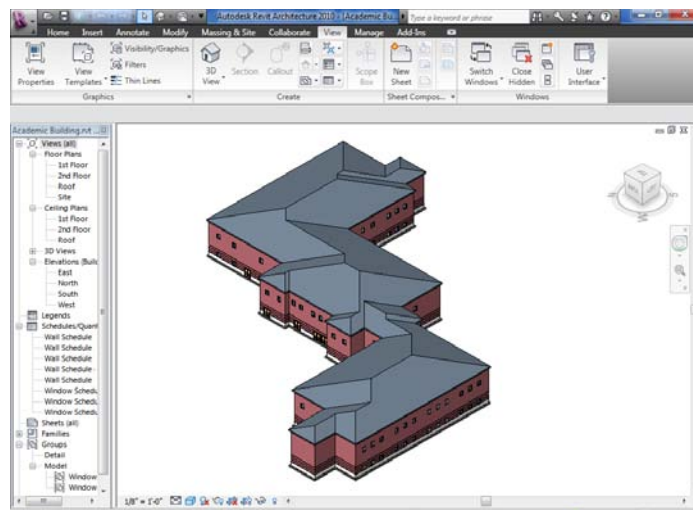


Figure 9. 3D model of the case study building created by Revit

4D (3D plus Construction Scheduling) Construction Sequencing Simulation Capacity

Autodesk Revit family: Revit software packages are essentially 3D modeling solutions. Therefore, Revit alone cannot perform 4D construction sequencing simulation. The alternative method is described below:

1. The 3D Revit model of the case study building was exported to an IFC file;
2. This IFC file was imported into Autodesk Navisworks;
3. A construction schedule was developed using Microsoft Project;

4. A link was established in Navisworks Timeliner between the construction schedule file and the 3D model;
5. Tasks in the construction schedule were matched with building elements in the 3D model; and
6. A 4D simulation was generated.

Figure 10 demonstrates the procedures to create a 4D simulation.

Vico Virtual Construction Software Suite : 4D simulations can be performed through interactions among Vico Constructor, Control, and 5D Presenter. The 3D model was first imported into Control from Constructor, then the construction schedule was attached to the model, then this updated model was transferred back to Constructor where tasks and their associated durations were checked, finally the model was imported into 5D Presenter to generate a 4D simulation. Figure 11 shows the 4D simulation process within the Vico Suite .

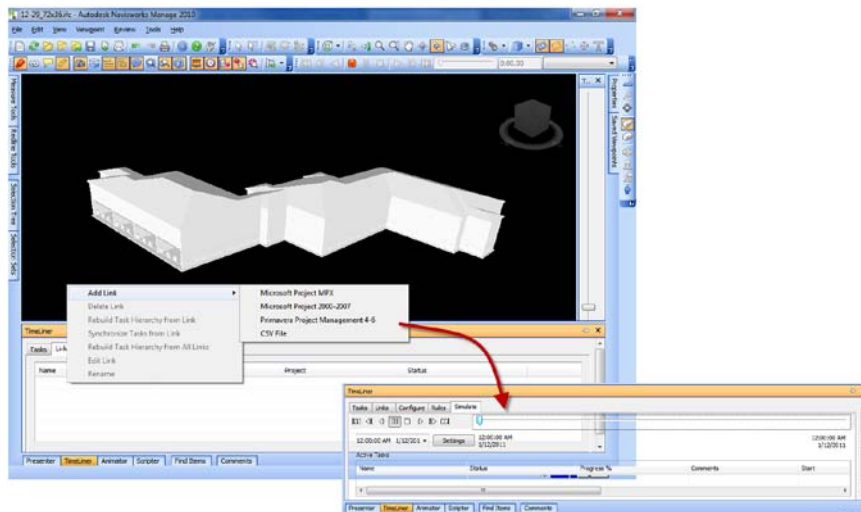


Figure 10. Generating a 4D simulation using Autodesk Navisworks

Even though Revit requires two third-party software tools, Microsoft Project or Primavera to generate a construction schedule, and Navisworks to link the 3D model with the construction schedule, to help create 4D simulations, the entire process is relatively straightforward. With Vico, although no other software tools are needed besides its own three modules, the process is difficult to grasp because 1) the 3D model needs to be cost loaded first, and 2) import and export procedures involve numerous steps and thus beginners can easily be confused.

5D Cost Simulation and Financial Management Capacity

Autodesk Revit family: Revit cannot conduct 5D cost simulation and project level financial management directly. Quantities of elements can be exported to third-party software tools, such as Timberline, to complete these tasks.

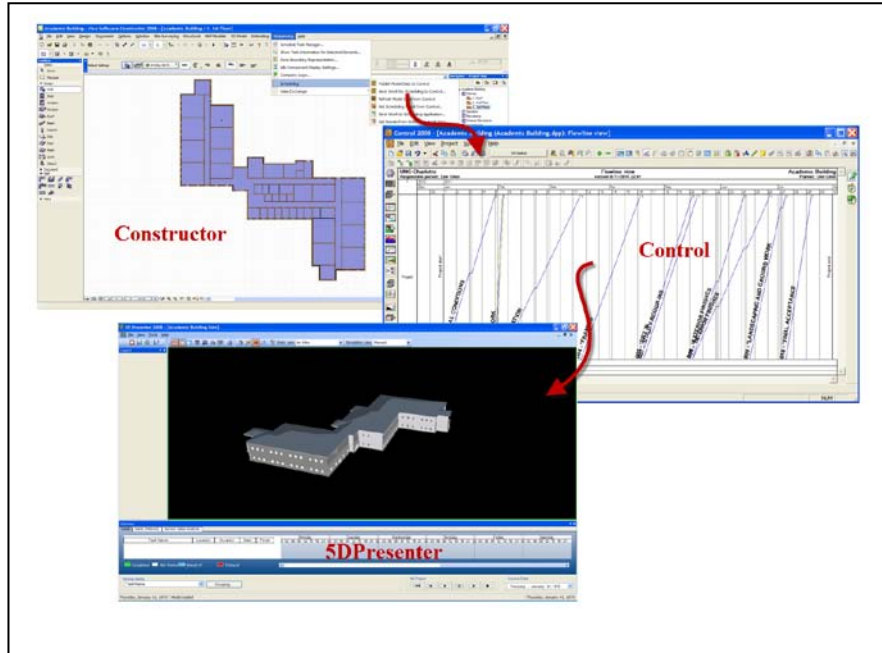


Figure 11. Generating a 4D simulation using Vico

Vico Virtual Construction Software Suite : Vico’s Estimator was used to take quantity information from the 3D model, match quantities to recipes, and generate a bid package. In Vico, a recipe is a data package that contains all information needed for estimating, scheduling, and controlling. The recipes (Figure 12) were then exported to Cost Manager where budgets can be compared, changes identified, and reports generated. The results can be exported to 5D Presenter in which cost and schedule information can be simulated, and cash flow analysis can be conducted (Figure 13). In this research, cash flow analysis was not performed because necessary cost data was not available.

For student projects that require cost simulation and financial management, Vico is clearly the choice.

Clash Detection Capacity

Neither Revit nor Vico can perform clash detection directly. The generated 3D models were exported as IFC_2x3 files and then imported into Navisworks to detect potential clashes.

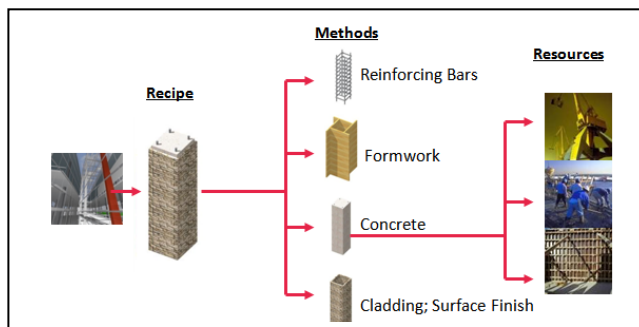


Figure 12. Definition of Recipe (picture courtesy of Vico Software)



Figure 13. Cash Flow Analysis in Vico 5D Presenter (picture courtesy of Vico Software)

BOK Requirements

Based on the findings from the previous section, the software package(s) that can be used to fulfill the ConE BOK are listed in the matrix below (Table 1). It can be observed that:

- Both packages can perform quantity take-offs; whereas only Vico can prepare a bid estimate.
- With help from Microsoft Project or Primavera, Revit can generate and analyze construction schedules. Although Vico can complete the same scheduling and control tasks, the process is difficult to grasp for beginners.
- One shortcoming that Revit has is that it cannot perform cost analyses and financial management. On the other hand, Vico is very sufficient in handling these tasks.
- Both packages can generate construction documents.

SUGGESTED WORKFLOW FOR A BIM COURSE

As an attempt to synthesize past research and this study, a suggested workflow for a BIM course is proposed (Figure 14). Ideally, this BIM course is a senior level course, and all students in this course should have completed their basic ConE courses such as estimating, scheduling, and project management. Even though it is unlikely that two BIM software packages will be used at the same time in a construction company, this workflow is still recommended for an academic setting because: 1) both software packages are free to use for student projects, 2) trained students can easily move from Revit to Vico, or vice versa, because of the steep learning curve, and 3) during the time the new generation are skillfully wielded with BIM technology, the AEC software industry also evolves, and a versatile solution is very likely to be developed to perform BOK tasks that used to be handled by several software solutions.

Table 1. BOK Requirements

Principal BOK Area	BOK Subset		Revit	Vico
Cost Estimating	I (b)	Estimate quantities	Architecture, Structure, MEP	Constructor
	I (g)	Prepare bids	N/A	Estimator
Scheduling & Control	II (a)	Develop construction schedule	N/A	Control
	II (b)	Develop WBS	N/A	Control
	II (c)	Plan construction sequencing	N/A	Constructor, Control, 5D Presenter
	II (d)	Estimate durations	N/A	Estimator
	II (f)	Analyze construction schedule	with help from MS Project and Navisworks	5D Presenter
Project Administration	III (g)	Perform cost & cash flow analyses	N/A	Cost Manager, 5D Presenter
	III (h)	Manage risks	with help from Navisworks	with help from Navisworks
Contract Documents	IV (e)	Develop construction documents	Architecture, Structure, MEP	Constructor

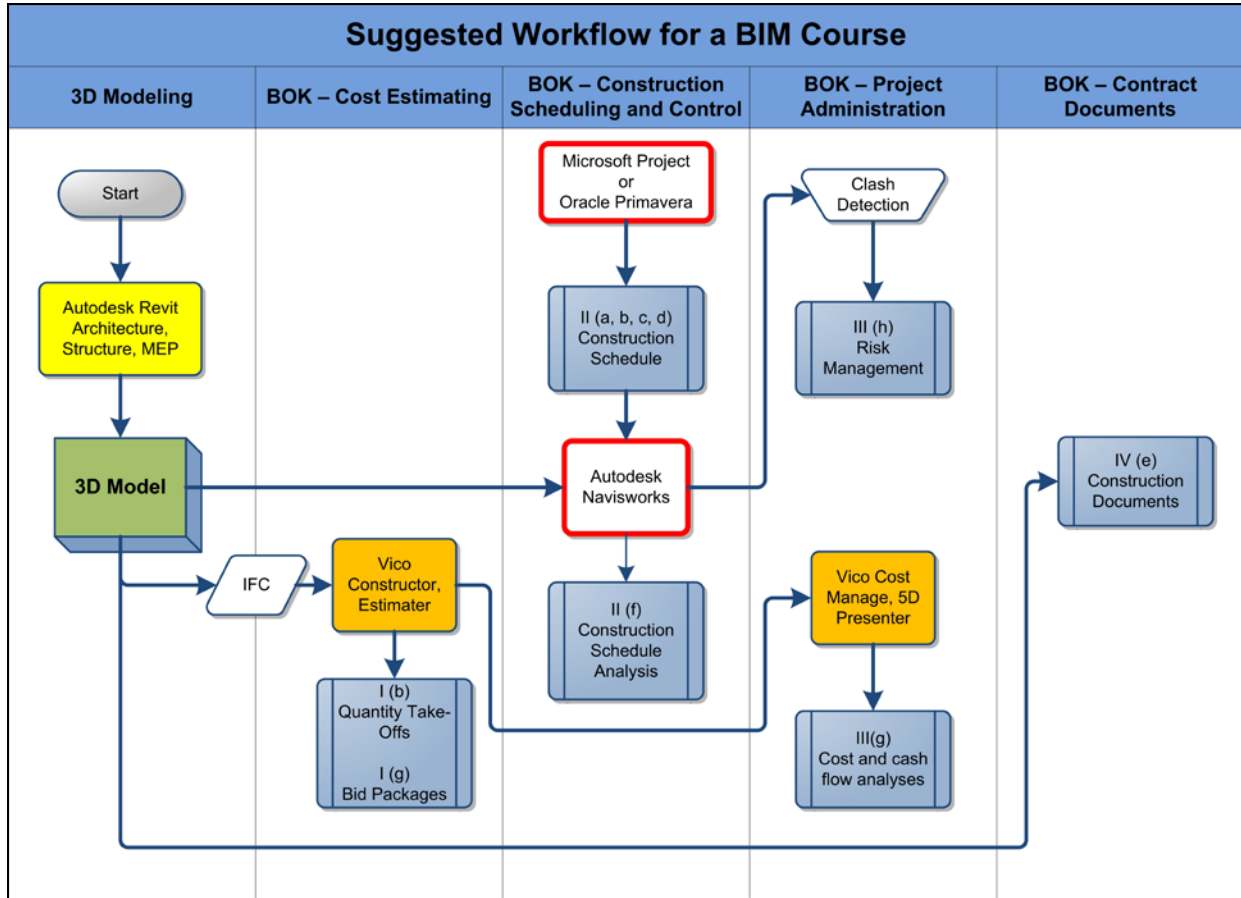


Figure 14. Proposed Workflow for a BIM Course

CONCLUSIONS AND RECOMMENDATIONS

The AEC industry has been profoundly transformed by BIM technology. However, lack of adequately trained engineers has significantly hindered this transformation. This has called for a change in ConE education; consequently BIM has been integrated into ConE curricula at numerous institutes. A number of anecdotal evidence has described what BIM software solutions were used in classroom settings; however detailed studies on limitations of BIM software solutions and how to appropriately select and use them to fulfill the ConE BOK requirements are sparse to nonexistent. This research was conducted to address this issue. Through a case study, functionalities of the two most popular BIM solutions, namely Autodesk Revit and Vico, were compared and their limitations were identified. The major findings are:

- Revit is superior in developing 3D models;
- Both solutions are able to efficiently generate construction documents;
- With the help from Microsoft Project or Oracle Primavera and Autodesk Navisworks, Revit handles construction schedule analysis better;
- Vico's strengths lie in preparing bid packages, performing cost and cash flow analyses; and
- Neither solution is able to detect potential clashes. However, both solutions can collaborate with Navisworks seamlessly to perform this task. This function can play a very important role in construction risk management.

Drawing on findings from previous research and this study, a workflow for a BIM course is proposed. Designed for the wide-accepted BOK for ConE education and the most commonly used BIM solutions, this workflow can be easily adopted throughout the ConE academic community and should help to remove the associative barriers that hinder the rapid transformation.

The BIM software packages that were studied are Autodesk Revit family 2010 and Vico Virtual Construction Software Suite 2008. The newer versions of the both packages, Revit 2011 and Vico Office Suite, are currently available. Even though the main functions and operation procedures are the same, it is recommended that future research be conducted to identify the functionality differences between the new and the old versions, on how these two solutions can better interoperate with each other, and on how they can more efficiently accomplish the ConE BOK requirements.

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