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# Teaching Integrated Scope-Cost Methods with Model-based Tools

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**ABSTRACT:** The purpose of this paper is to outline teaching integrated scope-cost methods in a course on fabrication and construction planning using model-based tools. Through project-based active discovery using project documents students create an integrated takeoff, schedule and cost estimate. The goal is to illustrate the processes and interrelation between professions required to effectively obtain the scope, schedule and cost of a proposed project. Students who are provided with a scope-time-cost technology tool in an inquiry-based environment are better able to grasp the core concepts of project planning and control and are less hindered by tedious calculations or look-up tables and manual compilation of project plans and analyses. The goal of teaching integrated scope-cost methods was achieved with the model-based tools. Students performed better on qualitative network analysis, scheduling techniques and planning. It was unexpected that students would not do as well on quantitative process model interpretation and creating a process model manually. The study is limited first by the constraints of course work limitations, second by hardware resources, third by software integratability and last a steep learning curve in integrated model-based systems. The use of model-based tools to complete a scope-time-cost project plan in a project-based learning environment is recommended. The level of effort to create a takeoff, schedule and cost estimate is reduced; the final product is better documented, of higher quality and most likely contains fewer errors.

## 1 INTRODUCTION

*Project planning and control (PPC)* centers around *plans* and *specifications*. The plans are a visual representation of what is to be constructed while specification is a text representation of what is to be constructed. Together these are the *project documents* and provide the basis of what the constructor is responsible for and what they are not. Over time the project documents have evolved to take advantage of technology advancements and the methods of using these documents evolve similarly. In ancient Greece, plans were inscribed in stone to scale so that stonemasons could directly convert plan measurements to field measurement with high accuracy and precision using the only takeoff tool available, the compass (Nova 2008). Tacit knowledge in construction is difficult to gain without field experience, as the 1<sup>st</sup> century B.C. Roman architect Vitruvius writes in Book One of *De Architectura* “economy denotes the proper management of materials and of site, as well as a thrifty balancing of cost and common sense in the construction of works.” Though everyone would agree management and thriftiness importance is true, it is to the reader to understand

what this means in practice. Project documents are evolving to become integrated BIM systems, a combination of drawings, specifications, scope-time-cost models and efficiency analysis tools, providing a technological advancement. As is typical for any innovation that creates a competitive advantage (James et al. 1991) this is catalyzing a change in PPC methods.

## 2 BACKGROUND

The integration of software through BIM [model-based] has enabled an expanded role in efficiency analysis software and resulted in reduced user input. The result is takeoff software functionality to generate takeoff quantities from an information model and then import these quantities to the process model and then with durations import to the cost model software. Model-based systems have facilitated integration of once separate scope-time-cost concepts, as found by Kanoglu in 2002. Interviews published by Laitinen in 1999 reported that a preliminary model-based scope-cost integration tool provided an 80% time saving and that most mechanical errors were avoided. Therefore, through reduced input due to the integration of tools, stu-

dents should be able to discover and investigate more options and alternatives for a holistic viewpoint than would otherwise be possible. In general, applying computers to once manual tasks allows the use of larger problems, investigation of previously ignored problems and illustration of the problem, benefits to education realized as early as 1962 in the University of Michigan Industrial Engineering Program (Wilson 1962). A position of the Michigan Industrial Engineering Experiment with including Computers in the Curriculum (a critical path scheduling problem included) moved the focus from tedious calculations and lookup tables, such as for interest rates, to providing a general solution to the problem. The effect of this was mandating the explicit definition of all the variables rather than omitting steps in the process for time considerations.

Today and tomorrows' tightly scripted process models require actual progress updates to reflect first and foremost weather and then: labor factors, design changes and late arriving materials and equipment (Schwegler et al. 2001). To complete this task, the best matched tools for obtaining project scope, time and cost must be used. The method taught here increases the potential for accuracy, precision and completeness without a change in the labor resources.

### 3 STUDENT DEMOGRAPHIC

Given its location in Silicon Valley and its connection with the Center for Integrated Facility Engineering (CIFE), students of the Construction Engineering and Management (CEM) program and their future employers expect the courses to leverage the best technologies possible. The CEM program instructs some of the construction industries most dedicated undergraduate and graduate students, researchers, academics, practitioners and future industry leaders. The backgrounds represented by the students are diverse, ranging across construction industry segments, such as: self-performed, construction management, owner representatives, design firms, academia and research. Almost any software or subject presented is likely to find someone who has extensive application experience in the field.

As a core module, construction programs teach scope-cost methods in some form. This paper serves as a course guide. BIM tools knowledge is in demand by industry now, as shown by the 2007 AISC-ACCL eConstruction Roundtable (Hartmann & Fischer 2007), through Center for Integrated Facility Engineering (CIFE) industry surveys (Gilligan & Kunz 2007) and at the 2007 CIFE industry advisory board meeting. Participants repeatedly stress the need for more VDC-capable (Kunz & Fischer 2008) engineers with experience in the use of BIM tools. Engineering best practice requires that we use any tool that provides increased safety to the public;

therefore, we must encourage BIM through education and industry awareness.

### 4 INSTRUCTION METHOD

The Project planning and control course in the Construction Engineering and Management (CEM) program at Stanford University has provided the opportunity to teach Virtual Design and Construction (VDC) students integrated scope-schedule-cost methods using model-based tools. Virtual Design Construction is a method utilizing an integrated system of project planning control and analysis tools (Fischer & Kam 2002). So to provide a lasting impression on students and prepare them for joining a project team, this course utilizes *learning-by-doing*. This is not a new concept, as quoted by Zuckerman (2006), in the 1690s John Locke wrote an essay concerning human understanding, in this he stated "knowledge comes from experience".

Moving forward to the 1960s, from the discovery learning movement, *inquiry-based learning* (inquiry-based learning 2008) was developed as a solution to perceived issues with rote learning. This method is centered on facilitating student teams to define and solve problems in an *open learning* (open learning 2008) environment. In open learning students are provided a goal that does not have a "prescribed target or result which students must achieve" (inquiry-based learning 2008). Students are provided the resources needed and supported as requested to find the path to a solution, gaining knowledge in the process. The *open goal* through scope-time-cost integration is to explore the cost constituent unrecognized in *unit cost* estimating methods. The main advantage BIM offers in this aspect is functioning as the *technology component* of the inquiry-based lesson, therefore allowing students to achieve a more complete solution that otherwise possible given time-constraints.

One of the goals of this course and CIFE in general is to illustrate the interrelation between separate perspectives (Fischer et al. 1999, MediaX) of the designer, scheduler, cost estimator and constructor. Course materials are from recent projects and have been selected for or are given constraints to illustrate key discoveries of scope-time-cost integration, therefore, highlighting the interface between professions. These key discoveries are process model concepts of: Work Breakdown Structure (WBS), planning, takeoff, Location-based Scheduling (LBS), sequence logic, scheduling techniques, network analysis, driving production rates, batching, lay-down space, clash detection, time-variable cost and workflow (Olofsson et al. 2005). In addition to experiencing the separate perspectives, these discoveries illustrate the concepts of hidden cost, also the open goal in the course and the impact of project planning on the level of efficiency. At the same

time, to make these discoveries the students learn the applicable skills of how to complete a take-off, schedule the work process and estimate the resulting cost based on their scheduled solution.

## 5 COURSE MATERIAL

Scope, time, and cost (see figure 4) software tools are introduced as individual tools and then combined into an integrated system. The tools that have been used in the course, while not inclusive of all possible solutions are (last version used listed): Tocoman product suite of iLink 2009, Express (v2.0) and Quantity Manager, Sage-Timberline Estimating Extended v9.6, Sage-Timberline Commercial Knowledgebase, RSMMeans production library, Primavera Project Manager v6.2, Vico Control Location-based Scheduling 2009, Microsoft Project, Common Point 4D, Navisworks Manager 2009, Revit Architecture 2009 and AutoCAD Architecture 2009. In the research lab and another CIFE course several additional combinations of solutions have proved to be suitable solutions.

From three recently constructed projects, product documents are borrowed for the course material; see figures 1, 2 and 3. Through lecture and labs, integrated tools and methods are discussed and practiced. In labs students experienced the frustrations of integration and the discovery of integration efficiency. To support students on this quest a course teaching assistants facilitates discovering software functions and acts as an interface with software vendors.

CIFE member companies provided the project documents for: the Camino Medical Office Building, the Alta Verde Building foundation, and 550 the Moreland steel structure. From these documents the structural product model was selected or in the case of the 550 Moreland, reconstructed.

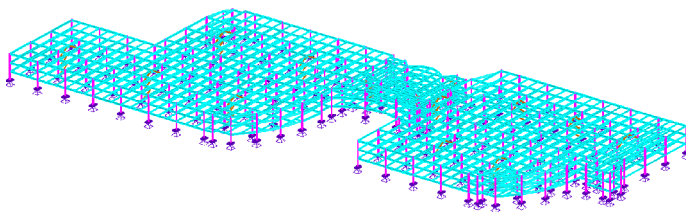


Figure 1 For the autumn 2007 class DPR construction provided an AutoCAD model for a steel framed, three story, 250,000 square foot building project. This model is utilized to introduce scope takeoff. This model was selected due to the various fastener configurations providing the problem of deriving a recipe-formula equation to calculate the implicit quantities from the explicitly modeled beam. A steel frame was used as an introduction due to the limited elements present, therefore reducing the complexity and focusing attention to the software tool functions.

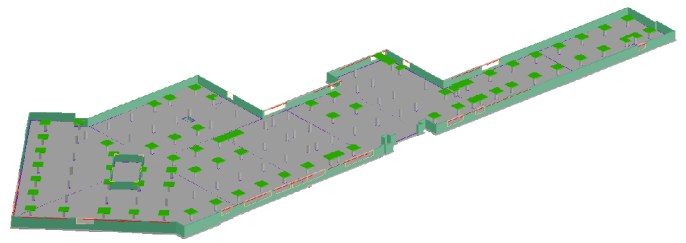


Figure 2 Foundation and podium product model for a multi-story condominium project used autumn 2007 and provided by Accu-crete. This model provided an opportunity to takeoff explicit mass structural components and implicit excavation quantities. The phasing of concrete placement is represented by locations defined in the Autodesk Architectural Desktop (ADT) custom attributes. The location custom attribute allows the taken-off quantities to be defined by location and then both the locations and quantities to be imported to the Control location-based schedule.

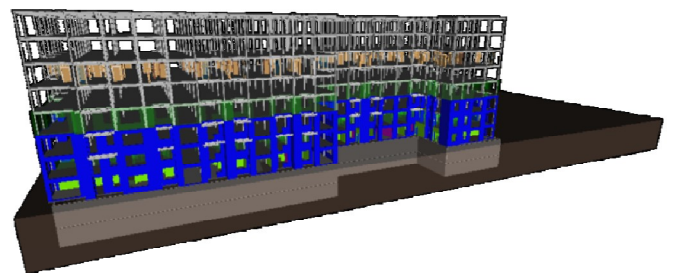


Figure 3 The autumn 2008 class used project documents from the 550 Moreland (Architect: jonwordenarch.com) project supplied by ConXtech ([www.conxtech.com/projects.php](http://www.conxtech.com/projects.php)). An eight story steel structure condominium building set atop a 2 story podium. A simpler model of the same building was used to introduce the software. Graphic is from the lab two report submitted by team Switzerland.

Each project provided a differing aspect for the course concepts to be presented. The product model supplied by ConXtech was modeled in StrucSoft's ProSteel 3D. While this software provides ConXtech what they need for their advanced manufacturing process we were unable to integrate the product with the handful of tools we had available, providing a lesson in adaptability. This model was selected for the existing product model. The Camino Medical Office Building project emphasized the use of Virtual Design Construction (VDC) engineering principles of lean construction (lean construction 2008), a 4D virtual design model and just-in-time (just-in-time 2008) delivery (Khanzode et al. 2006). Lean construction and just-in-time are concepts from the Toyota Production System (TPS) where rather than maintain a large inventory of material, deliveries arrive when the work is scheduled to occur. On this project the use of VDC resulted in: zero conflicts between systems, less than .2% rework, a productivity increase of 30% for the mechanical contractor, field coordination reduced to half an hour per week, two Requests for Information (RFI) related to field issues and no Change Orders (CO) related to field conflict (Collaborative Virtual Building, DPR). This project also provided an MEP

model for the winter 2007 and autumn 2007 classes. The Alta Verde ([altaverdeapts.com](http://altaverdeapts.com)) foundation constructed by Accu-Crete ([www.accu-crete.com](http://www.accu-crete.com)) is a multistory residential building with strip, perimeter and pad footings, formed concrete walls and columns.

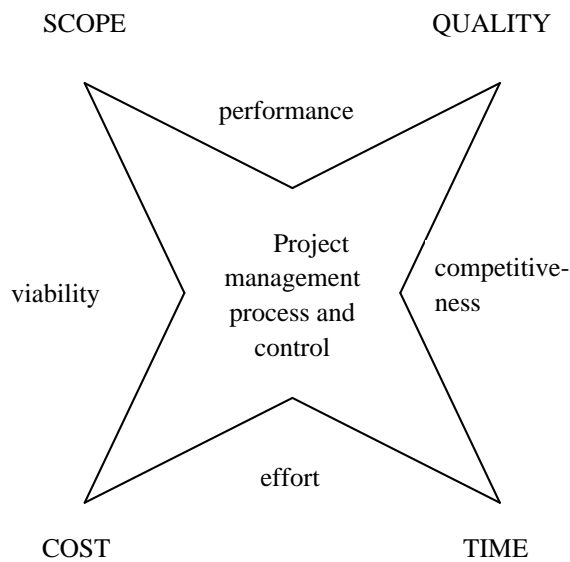


Figure 4 Preliminary project planning and control topics generally touch on the four key aspects of managing scope-time-cost and quality. (© R. Max Wideman [www.maxwideman.com](http://www.maxwideman.com) 2008 reproduced with permission) The graphic is the same as the well known project management, though rather than leave quality implied it is a stated constraint. Integration of scope-time-cost using BIM tools results in a system composed of the product model takeoff, process model schedule and cost model estimate. The process of finding the efficient optimum solution is iterative and results in a circle integration model as proposed by Fischer and Kunz (1993).

## 6 INTEGRATED SYSTEM

Obtaining baseline scope-cost involves multiple software tools, see Table 1. The single most important attribute allowing an integrated solution across software tools that are not necessarily intended to function as one in the work breakdown structure (WBS) as shown in figure 5. With a common WBS classification assigned to objects, activities and operations, both associating these and scaling between levels of detail is possible. A word must be said for the vendor support of this course material. Three vendors, Tocoman, Vico and Sage have provided us with pre-release and Beta software, each time against their will. They have then given us custom solutions midweek in the beta versions. Hopefully the vendors have been as rewarded by this collaboration as we have. Though I am sure Vista users of Navisworks and Primavera will be much happier in 2010 when they can connect to the SQL server. I am also not sure where else anyone attempts to load all this software on Macs running windows virtualizers, not recommended. A mention of the technical support department at Primavera also is warranted.

Company	Project	Location	Sub-location	Building unit / Discipline	Master Schedule Activity	Resource	Object	Operation	Operation Method	workzone
WL0	WL1	WL2	WL3	WL4	WL5	WL6	WL7	WL8	WL9	WL10

Figure 5 Eleven level Work Breakdown Structure. This WBS uses the CSI MasterFormat ([www.csinet.org/s\\_csi/docs/9400/9361.pdf](http://www.csinet.org/s_csi/docs/9400/9361.pdf)) for work levels four through six. The RSMean WBS is represented by levels six through nine. The Revit WBS is represented by levels six and seven. This classification format conforms to the AROW standard, most notably with the inclusion of a work level 10 workzone.

### 6.1 Scope Takeoff

The initial step in scope-cost integration is determining the project scope through a takeoff. Takeoff is a detailed measurement either directly from the product model or inferred from specifications. A typical task is to provide a quantity takeoff of structural objects in a concrete structure. To complete this task, Tocoman's solution is to use a product suite consisting of four separate applications as illustrated, these are *ilink*, *Quantity Manager (QM)*, *Construction Model Server (CMS)* (an extension of the product model) and *Express*. While not unique to this product, the *ilink* tool was chosen because it supports multiple 3D modeling tools, therefore not constraining the user to a single system. *iLink* and *QM* are command line add-ons in the various versions of AutoCAD and are prompted by an icon in Revit and ArchiCAD. With this, the attributes defined in the model are available to filter objects and obtain count, length, area and volume measurements. If a location attribute is available, this can be exploited to filter sub-locations for x and y coordinates as well as z coordinates, i.e., floors. These additional attributes for location are central in Location-based Scheduling (LBS) that is used as part of the integrated solution.

### 6.2 Recipe-Formulas

The takeoff quantities, such as: count, length, area and volume, of model objects are then moved through the quantity manager as mapped links to operations in the construction model server. An *object* constitutes a part of the product (Darwiche et al. 1989). An *assembly* is a collection of objects into an element (Darwiche et al. 1989). It is important to understand that objects represent both objects that exist in the product model and objects implied to exist in the product model, see figure 6. For example a

concrete column *element*, i.e., *assembly*, consists of rebar, formwork and concrete, each a component, though rebar and formwork are likely not included as objects within the product model, see figure 9. To represent implied objects a recipe formula is needed. These formulas can also be utilized to change the level of detail and convert from a measured unit to another unit of measurement, for example, convert cubic yards to weight through multiplication with density. The conversion between levels of detail is an acute issue with greater implications than just the compiling of operations into activities. The issue arises again during feedback of project progress, as described by Teicholz in *Integration of Microcomputer Applications* (1989), budget items are usually at a different level of detail than the accompanying activities items.

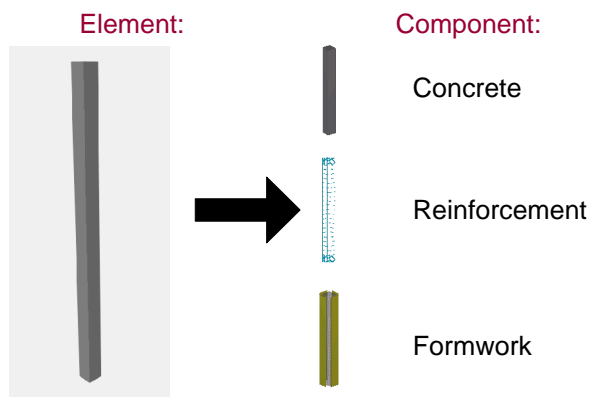


Figure 6 Elements or the objects necessary to construct a product are composed of both explicit and implicit objects. Explicit objects are those represented in the product model and can have implicit un-modeled objects. In this figure, the column concrete is explicitly modeled while the reinforcement and forms are implicit. Adapted from R. See presentation material.

These recipe formulas are facilitated in the construction model server. Here operations (having a unit of measure) that are imported from the cost estimate are often implicit in nature are associated with the explicit model objects through recipe formulas. The construction model server (CMS) also provides for defining the location breakdown. In quantity manager while mapping objects to operations, the appropriate location is specified, often based on some object attribute such as floor.

### 6.3 Time Process Model

The operations in the CMS are a project specific operation library, selected from a project independent library such as RSMMeans, or created as needed. Sage-Timberline estimating is used to derive the operation list, usually prior to the take off but just as easily could be completed after or during the take-off. Next, the location-based software *Control* provided by Vico ([www.vicosoftware.com](http://www.vicosoftware.com)) was used. Tocoman provides an export function to Control making this step uncomplicated. The operations,

any identifying descriptions and code, unit of measure and the quantities are opened in Control. The production rates, an essential component of a schedule are not provided for in the CMS and so must be imported to Control through an excel transfer from Sage-Timberline estimating to Vico Control.

Once in control the operations need to be compiled into activities based on driving production rates. The work breakdown structure levels one through four serve as the process model location breakdown structure, reference figure 5. Work levels five through seven are the basis of the process model activities descriptions. The task of compiling, naming and defining the production rates of activities from operations is not an easy task.

In Control, the flowline display illustrates the line of balance activity sequencing, prominent for sequencing work to maintain the same successor crews (Andersson & Christensen 2007). Once an optimized solution is found, meeting the constraints for resource leveling, time, and efficiency of workforce access (Sappanen & Kenley 2005), the resulting start and finish dates are transferred to a 4D model check. Control and Navisworks do not have a link provided by the vendor but they both do have MS Project and Primavera links. The Primavera link is through an SQL database, therefore allowing schedule updates with a refresh rather than the MSProject need to make a new export file (clever file naming neglignates the need to relink objects to activities in Navisworks). In Navisworks the objects are linked to the activity, and a visual inspection is conducted for errors of various types. With the 4D check complete and any necessary correction made to the 3D model and/or schedule, the takeoff and time-variable quantities can be pushed to the cost estimate.

### 6.4 Cost Estimate

We used the Sage-Timberline estimating software and the RSMMeans production library for the cost estimate. The production library is organized using the CSI 2004 MasterFormat, providing a classification for identifying each operation also adaptable to the 3D objects and activities. To create the initial operations list, those operations necessary for the project scope, quality and time are selected from the RSMMeans library. Sage-Timberline provided their estimating Commercial Knowledgebase (Sage-Timberline), this as a library of operations and their association with a more easily quantifiable operation. To complete the estimate the quantities are transferred from the schedule to the construction model server and then through another Tocoman product called Express to the estimate. Express is

much like ilink and provides a wrapper type interface to multiple software tools.

Table 1 This table of software tools is not intended to be comprehensive, only a representation of what are available. The pro and con notes are a combination of others impressions, demonstrations observed and actual software use.

Software Tool	Type	Pro	Con	Tested
CommonPoint	4D	user interface	not dwg interoperable	tested in class
Navisworks	4D	clash detection	limited rules mapping	tested in class
Sage-Timberline	cost	assemblies, print to csv	limited integration	tested in class
MC2 - ICE	cost	assemblies	N/A	N/A
HCSSS - HeavyBid	cost	crew-based estimating	limited integration	tested in lab
Tocoman system	integration	recipe formulas, wrapper	no production or resource fields	tested in class
Innovaya Visual Simulation	integration	automated linking function	limited schedule integration	tested in lab
Syncro	integration	line of balance, integrations options	no clash detection	tested in lab
IFC	open-source	widespread support	varying levels of support	tested in class
Revit	scope	integrated CSI, definable attributes	IFC object errors, integration with ETABS	tested in class
Bentley Microstation	scope	engineer functions, bill of material	N/A	presentation
Tekla	scope	integration with ETABS	N/A	tested in class
Primavera	time	established software with many trained users	production and crew functions	tested in class
Vico Control	time	location-based	data intensive setup	tested in class
Building Explorer	system	automated process model & cost	not bi-directional & inclination towards RSmeans database	presentation
Oracle System	system	N/A	N/A	N/A
AutoDesk System	system	N/A	N/A	N/A
Catia 3D System	system	N/A	N/A	presentation
Vico 5D System	system	single vendor support	no clash detection	tested in lab
Bentley system	system	N/A	N/A	N/A

The one quantity that is not exported from the schedule is the time-variable quantity. Any operations with a unit of measure of time, such as, days, weeks, months, must be manually entered from the schedule to the construction model server. Then the completed list of operations, with quantities is transferred to the cost estimate. Sage-Timberline demonstrated an IFC based scheduling tool in 2000, though they have no commercial product available (Froese

& Yue 2001). There are other software tools which perform a similar function as express for Sage-Timberline and other cost estimating tools, such as MC2 ICE.

Sage-timberline automatically calculates the cost once quantities are present and a cost report can then be generated for further analysis and bid review. Modifications to cost can then be accomplished by adjusting product scope, construction operation methods, schedule sequencing and resource utilization. After test modifications a new pass is made through the system and continues iteratively until acceptable results are achieved.

## 7 TEACHING PROCESS

Scope-cost concepts and the software tools used with the product models are introduced through a series of lectures. These lectures focused less on the specific software and more on general principles of integrated scope, time and cost. Professor Martin Fischer's class lectures are supplemented with guest lectures by Ollie Seppanen of Vico Software, Richard See of Digital Alchemy, an IT services company ([www.digitalalchemyinc.com](http://www.digitalalchemyinc.com)), Mark Jenkins of DPR and other alternative speakers with knowledge about some aspect of the course material. Guest lectures are important since they provide students the opportunity to question the professionals involved in developing integrated systems, places a human connection with the software tools they are using as well as provides the opportunity to ask advanced software functional questions that have escaped the collective groups ability to overcome.

In addition to the usual project planning and control topics of scope-time-cost, refer back to figure 4: the critical path method (CPM), 4D process modeling, production management, ensuring feasibility/constructability and risk mitigation, all concepts particularly relevant to integrated model systems are introduced. Specifically the work breakdown structure classification and recipe-formula equations are introduced early in the course. These two topics are possible to overlook completely in some scheduling and cost estimating courses but are critical to understand when using an integrated system.

The lectures are accompanied by lab sections and open lab hours. The first lab is essentially the scope-time-cost process as it most commonly manifests within the construction industry today. Students complete a manual quantities takeoff from the product model dimensions. They then generate a cost estimate in excel using the lookup tables in the RSMMeans cost books. They then create a CPM schedule in Primavera. Last a 4D process model is created from the schedule and product model. In the second lab students take the skills they developed in the first lab and integrate them into a system.

For labs, students form teams of two or three and are encouraged to collaborate between teams. Prior to the first lecture, students installed the necessary software on their personal laptops and the lab computers are prepared. Be aware the combined simultaneous use of software tools may exceed the capabilities of some laptops. The labs have shown that each student needs access to a computer, either a personal laptop or a lab machine.

Some process by which students can exchange files is an important component of the integrated system; the product model can be over 50 MB so email is not the best solution. The software installation files are provided in a mix of sources, some are physical CDs and others are downloaded from the website. It has proved helpful to place the course material and software installation files on an openly accessible server. The Kerberos ([web.mit.edu/Kerberos](http://web.mit.edu/Kerberos)) and Andrew File System (AFS) ([www.openafs.org](http://www.openafs.org)) has provided this solution for the past three quarters.

In the lab, to facilitate student learning, it seemed helpful for the Teaching Assistant (TA) to understand *interactive learning* (Center for Teaching and Learning). Some scope-cost steps are not necessarily critical to and interfere with learning. It helped to work through the assignments to find what, in this case, publishing quantities to the online server and creating recipe formulas for implicit objects, will unnecessarily confront students. Contrasting implications of various scope-cost concepts of maximizing productivity, minimizing risk, and ensuring feasibility and providing process control concepts from industrial engineering (process control 2008) assisted students grasp why process model updates are important and how this relates to the product and cost models.

## 8 FINDINGS AND ASSESMENT

### 8.1 Lab Findings

With the BIM tool, the labor resources necessary to complete a scope takeoff from the product model, and then create a process model and cost model is reduced [by how much, baseline =  $n$  (3-4 weeks), system = 18 hr]. The final product is better documented [example of 6 files, takeoff, estimate, recipe-formula, schedule, 4d, 3d model], of higher quality [quality metrics] and most likely contains fewer errors [how is this measured]. During the course, we found through BIM software tools that preparing scope-time-cost project planning and control (PPC) is less monotonous to complete. This is important because the repetition required to manually derive and calculate scope-time-cost lends itself to shortcuts and assumptions, possibly resulting in incorrect quantities, production rates, and missing line items. With the BIM takeoff, integrated production library,

process model and cost model there is less incentive to take shortcuts [because].

In the labs, we found four main issues, these were: conceptual, functional and formatting issues. First, the concept that six or more software tools are going to be used as one single system is a hurdle to overcome. Second, we found limitations due to the market focus of the software. The construction industry is sufficiently segmented that tools are not universal. This is verified in the 2008 CFMA survey showing that the industry segments prefer different software tools. For example, Control, the scheduling tool used, is specifically developed for project planning and control of self-performing contractors by general contractors. The level of detail of the software appears to stop short of allowing a self-performing contractor to plan and control their work as their own general contractor. Obviously the functionality must be there but forces the user to plan their crews work as though they were separate sub-contractors. This is a small distinction seemingly easy to correct from the vendors perspective. Third, we do not have time in the course to use all the software's functions. Several students found that Control has statistical analysis and simulation functions and thought they were helpful in optimizing the efficiency of their process model and would like to have explored these tools more. Fourth, if the constructor participates in the development of the product information model, i.e., BIM, then a WBS could be added as an attribute to objects. With a universal classification system, for objects in the product model, activities in the schedule and operations in the production library, associating an item across the three models is facilitated or even automated. This begs the question, why don't information models contain an exportable Work Breakdown Structure (WBS). We were provided models in the first course so were not able to attempt leveraging the object identifiers. In the second quarter we did develop our own model and made the extra effort to define objects with MasterFormat attributes. MasterFormat is a work breakdown structure standard published by the Construction Specification Institute at [csinet.org](http://csinet.org). We found the systems weakest link then moved to linking in the 4D model. Previously the most difficult tasks seemed to be linking the object to operation and compiling the operations into activities.

A couple expected benefits of a universal classification code:

- 1) The list of explicit objects contained in the product model may be exportable to the operation library, eliminating the need to define operations. Once the operations are exported then identifying implicit objects in the product model remains.
- 2) These implicit objects could then be quantified from explicit objects through predefined recipe



formulas, assemblies or both, associated by the classification code.

As an example of the benefits of a shared classification system, the Rocky Flats decommissioning project reports that they used the same classification WBS for both the cost model and process model, resulting in “easy interaction with and understanding by the craft supervisors, and a reduced learning curve... [and] an improved link with the site’s [process model] software” (Stevens et al. 2002). This provides an example of benefits from standardizing the classification across project models, resulting in improved integration and learning curve.

## 8.2 *Scope-Time-Cost integrated System Findings*

For course instruction purposes the integration of software in addition to user experiences are important. Providing the students with the course material at a suitable level of preparation is a balance between providing a learning experience with-in the allocated time and reducing the material to an overly orchestrated process. In the course material for the first quarter, Tocoman provided a list of operations already imported into the Construction Model Server. If students wanted to modify this list of operations or create an entirely new project operation list, they had not learned this step. In the second quarter we began the process at a much more root level and began with the basic elements of the process. The only prepared material given to the students was a product model with location and classification attributed. These would likely not be provided in other product models from a project.

Again in the first quarter, several students attempted to go beyond the assignment scope and figure out how to designate additional locations within Autodesk ADT using Tocoman but they found this step non-intuitive. In the second quarter after discussing this with Tocoman we were provided with a Revit solution that allowed students to select an attribute as the location designation. This issue is becoming mute as the transition from 3D CAD to information models progresses and the list of available attributes but standard and custom is expanded.

We are finding that a non-vendor specific integrated system provides a more adaptable and robust base to build a scope-time-cost plan than a vendor specific system. The number of iterations possible with the few software tools we have used to date reaches into the hundreds. We continually find new combinations that work. Obviously of these combinations many are minor, such as swapping MSPProject for Primavera, though this solution did save us in the autumn 2008 when an issue with Navisworks reading Primavera activity classification attributes appeared. The main point is that the option to rotate any software tool out of the system and swap in a replacement provides for a system able to evolve

with changes in versions and functions over multiple software versions.

Expanding on the previous point of software adaptability is that we have experienced version conflicts with each year’s software system. The first to occur was in the autumn of 2007 when Sage-Timberline changed from version 9.4 to 9.4.3. Due to the TAs inexperience in recognizing the issue, this proved to limit the use of the estimating software. In autumn 2009, the change from MasterFormat 16 divisions to MasterFormat 50 divisions was mitigated by proactive software version updates. Then an expected release from Vico materialized a bit slower than anticipated which forced an MSPProject patch to Navisworks rather than the preferred SQL connection with Primavera. More recently a fleeting lapse was noticed between Tocoman CMS and Vico Control as the later switched to an XML integration interface rather than a dedicated Tocoman function. Last, we noticed that Revit 2008 and Revit 2009 do not talk well with each other and that 2009 Revit has lost the integration with ETABS it had in 2008. The issue here is being aware of version changes. The same is true for new versions with functions that allow greater integration.

Students are able to run more complete scenarios using an integrated solution. One particular tool aids in this process, it is Location-based Scheduling (LBS). This method has specific peculiarities to scheduling. The most prominent of these is the need to only link activities for the work sequence once rather than repeatedly link the same type of activity for each location. This means that a project with ten locations requires 1/10<sup>th</sup> the work to: create the baseline process model, update the process model to design changes, change activity sequence, or make mid-project adjustments to process model level of detail.

## 8.3 *Exam Findings:*

In the winter of 2007 the course was taught without an integrated system, in the autumn of 2007 and 2008 an integrated solution was used in the course. A comparison of final exam scores for specific questions from winter 2007, autumn 2007 and autumn 2008 provides a benchmark of change.

It appears that students performed better in the autumn 2007 and 2008, i.e., with an integrated system, on qualitative network analysis (i.e., defining where critical activities, activity float and total float reside), scheduling techniques (best practices) and planning (sequencing, accessibility, duration impacts, crewing, minimized mobilizations, risk buffer and feasibility/constructability). Students did worse on quantitative process model interpretation (i.e., calculate: float, start-finish and delay risk). Some of this may be explained by the course labs being software-based while the exam is given on paper, test scores may be reflecting this. In practice, no student

is likely to construct a process model and cost model manually beyond sub-process modules constructed mentally or on scratch paper. Though be aware that about 10% of contractors responding to both a CIFE (Peterson & Fischer 2009) and the CFMA 2008 surveys claim they do just this.

For purposes of comparing exams a review of questions provided those that are similar. A cost model question on finding the driving production rate and recognizing *time variable indirect cost* was about the median question in difficulty for both terms. Time variable indirect costs are those costs that vary with project or activity duration. The most obvious time variable cost is the office trailer and office staff, though there is a large number of smaller expenses that summed can erode project margin. This question on time variable indirect cost, set equal in score for both exams, served as a calibration point. For test questions with no corresponding equivalent in the previous term, students did well. These questions were more specific to the instruction given in integrated scope-time-cost and location-based scheduling (LBS), such as: questions on the Work Breakdown Structure (WBS), creating a LBS on paper, completing a takeoff and drawing a map of the integrated system, see figure 7, the autumn 2008 solution.

The qualitative network analysis questions, scheduling techniques and planning relate to conceptual issues highlighted by the software. In general these concepts are maximizing productivity, minimizing risk and ensuring feasibility. Process and cost model interpretation and creating a process and cost model requires manual calculations automatically performed by process model and cost model software tools. From this, it appears that students did better on conceptual questions and worse on repetitive process questions, i.e., they understand a process or cost model report but would have difficulty creating a process or cost model on a whiteboard. This relative balance in skills existed in both course terms but was more pronounced in the course taught using an integrated system.

## 9 RECOMMENDATIONS FOR TEACHING, RESEARCH AND PRACTICE:

In teaching, the use of BIM tools to complete a scope-time-cost project plan in a project-based learning environment is recommended. In practice, the adoption of BIM tools on design-build projects will allow closer integration of design and construction functions within project staff. VDC enabled engineering staff with the ability to design and construct will prove advantageous through reduced risk.

In research, guidelines defining those BIM objects always explicit and those objects always implicit, and then creating associated recipe formulas will facilitate the reliable implementation of these

tools in field use. Additional research on providing a feedback loop of the process state is needed to further integrate project planning of scope-time-cost into project control. Research on automating tasks completed manually will reduce the risk of tasks being skipped or unreliably completed.

Innovations in practical field use will mold these tools into a final form. The task of converting cost model operations to a process model activity is still manual but is much more organized and provides a record of what operations are included in any given activity, this process could benefit from a database of assemblies associations between activities and operations.

## 10 CONCLUSION

Obviously the integrated system outlined here could be applied to non-building projects such as civil, marine and industrial. These innovative software tools open the need for further standardizing of common scheduling tasks. Identifying those product model objects that are always explicit and establishing a naming or coding method to apply across software are identified in this paper.

It has been observed in the course that Building information modelers in addition to being consistent must coordinate with the other disciplines of takeoff, scheduling and cost estimating. It must be ensured that those inputs needed for process and cost modeling, are represented in the product model.

Student feedback and exam scores indicated that the integrated scope-time-cost system successfully introduced and solidified concepts of project planning and control. The main properties of the system that facilitates this are precision, repeatability, work breakdown structure and recipe formulas. The integrated system facilitated and illustrated the following to the point they seemed intuitive: maximizing productivity, minimizing risk and ensuring feasibility, core concepts of scope takeoff, process scheduling and cost estimating. In previous assignments completed without an integrated solution, some students appeared content merely to be done with the cumbersome process of looking up tables of production rates, manipulating spreadsheets of calculations and then transposing these into the process model.

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