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Integrated Scope-Cost-Schedule Model System for Civil Works

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Abstract

The purpose of this investigation is to illustrate the potential use of integrated scope-cost-schedule model systems in civil construction. This study is important to help provide an example of how a civil project completed using common methods could have been planned and monitored using an integrated scope-cost-schedule system. Publishing the results of this example will highlight some of the issues with integrated model systems particular to the civil industry. A recent questionnaire survey completed at the Center for Integrated Facility Engineering (CIFE) resulted in 175 responses from all types of construction industry professionals, 50 responses were from the heavy civil construction subdivision. None of the civil contractors reported using an integrated model system though some used components.

Keywords: Integrated System, Scope, Cost, Time, BIM, PIM, civil works

1. Introduction

This study used a system of integrated software tools to construct a civil information model, these are: AutoCAD Civil, Tocoman iLink, Tocoman Express, Tocoman Quantity Manager, Vico Control 2009, Sage-Timberline Estimating 9.5, Sage-Timberline Commercial Knowledgebase, NavisWorks Manage 2009 and the RSMeans production library. As a case example a $200M (US 2002) rail project consisting of mass excavation, concrete retaining walls and structural backfill was used to provide the project scope, object geometry and an operation list. In the questionnaire survey of civil contractors (50), 42% reported using at least one component of an integrated model system, these are: product model 8%, scope software 6%, cost software 19%, schedule software 14%, integration software 6%, no software tools 8%. This compares with the 2008 biannual Construction Financial Management Association (CFMA) questionnaire survey[i]. They found the following from 114 US heavy and highway contractor responses: product model 73%, scope software (NA), cost software 94%, schedule software 75%, integration software 55%, no software tools (NA). These results reinforces that many civil contractors already posses the components needed for an integrated system and only need to add a few select tools to configure into a system.

The following five results are provided. (1) The integrated scope-cost-schedule model system found an approximate error rate of 85% in the 5-week lookahead project schedule durations. (2) The manual take-off contained a double count (3% of total material) and two of the 28 (7%) project locations are missing from the schedule. (3) The recorded level-of-detail was able to be increased from a single project location to 13 locations and two sub-locations. (4) The Location-based scheduling tool provided a resource leveled schedule that defined resources similar to that actually utilized on the project through pull demand. And (5) the importance of a uniform classification method across the system is reinforced.

These results positively show the integrated model system would have provided a benefit to this project. The need to define locations and sublocations to breakdown the quantity takeoff to a level suitable to civil type project controls highlights how these issues are specific with civil projects. It was not expected that applying an integrated model to a civil project would fit so well. Two limitations prevented further exploration. First, compiling the existing 2D paper-based documents into a common format with the integrated system was time consuming and not exact. Second, the 4D model utilization of multi parameters is limited, making the location parameter difficult to exploit.

2. Scope-Cost-Schedule Project Assessment

Construction status assessments are notoriously inaccurate and labor intensive[1]. Many researchers have contributed to the realization that project success is independent of project controls[ii iii iv v vi vii viii ix x xi xii xiii]. An analogy to current project control practice would be an early 20th century doctor during the 1918 influenza pandemic[2]. The only benefit the doctor could hope to provide was to collect as much information and samples possible for future researchers. At that time with the technology available, it was not possible to affect the epidemic or the outcome of an individual. Much in the same way, field engineers today can realistically only be expected to collect project information for future use in the estimating department and not to actively affect project outcome. Additionally what information to collect and in what level of detail are uncertain since the future use is not always foreseen. These uncertainties result in some collected information never providing any use, collected at too low a level of detail to provide a full benefit or only data with no context has been collected. Integrated system tools advance the possibility that one day engineers will be capable of affecting the outcome of a project after the planning, design and fabrication stages.

1 Tocoman PowerPoint presentation

2 Human Virology at Stanford "The Influenza Pandemic of 1918" updated February 2005 http://virus.stanford.edu/uda/

With an integrated system the changed quantity is passed to the process and the cost models. Any change in the cost model also results in a revised process model and any change in the process model results in a revised cost model. In this process rework and errors are avoided. Optimization algorithms requiring accurate and precise up to date information, such as that proposed by Märki[xiv] and described by Leu[xv] are reliant on these integrated system tools. Current project planning and monitoring requires knowledge of the quantities' sources[xvi]. A common method is Earned Value Management; reference the *Project Management Body of Knowledge*[xvii] for a through review of this method. Note that many of the details in how to implement the method are left to the reader, indicative of the difficulty in achieving such a method.

3. Technological & Professional Context

Professor John Fondahl helped introduce the Critical Path Method (CPM) to the construction industry in 1961[xviii]. Not developed for construction specifically, CPM was adapted from the 1950's Program Evaluation Research Task (PERT) analysis used in the ballistic missile industry and the Project Planning and Scheduling System used by the US Navy on submarine projects[xix]. Like construction projects, missiles are a large, complex, [short] production product. As such, the transferability of project management methods is straightforward due to the shared terminology and concepts as a sub-domain of the industrial engineering field. Since 1961, through incremental innovation of analysis methods such as CPM, construction project management is increasingly integrating points of the project management scope-cost-time triangle into integrated systems. Integration of the product model and process model resulted in a new tool called a 4D model[xx]. The adoption in the building industry of information models, specifically termed as Building Information Model (BIM), provides a new source of information. Used as a database, information models facilitate greater integration of information across the various efficiency analysis and graphical information representation tools.

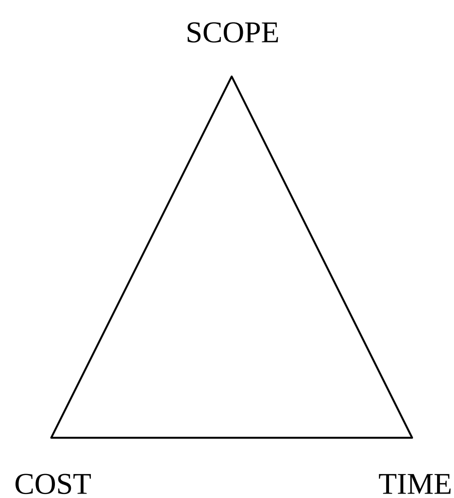

Figure 1 Integration of scope-cost-time results in an integrated system composed of the product, process and cost models. The process of finding the efficient optimum solution is iterative and results in a circle integration model as proposed by Fischer and Kunz 1989.

Scope-cost, scope-time and cost-time are the triad sides of the project management triangle. Properly determining these sides is often the task of separate professions such as: estimators, schedulers, and financiers.

These professions rely on scattered information sources such as: product, cost, process and quality models, efficiency analysis tools and object, operation, production, cost and direct and indirect specifications databases. Examples of what these sources can manifest as: RSMeans, AutoCAD model, Field Engineers Manual, company knowledge-base, project specifications, CalTrans standard specifications, quarry material properties, and government dept of labor statistics. Integration through an information model allows pulling these scattered resources together and provides a more precise and accurate model of the resources necessary to construct a product. Integrating scope, cost and time as the takeoff, schedule and estimate, with the geometric product model as a 4D model, provides a check of plans in a human digestible format. In higher level of detail parametric estimating production rates drive the process and the cost models. To obtain a production rate, recognition of constraints such as: climate, learning curve, conditions and resource leveling[xxi], as well as object, laydown and work space clashes[xxii] [xxiii] [xxiv] [xxv] across the process model is necessary. It is well known the importance of leveling resources to reflect the physical limits of local resources, avoid fluctuations of resource demand and to maintain an even pace of application of resources[xxvi]. Less well known is that once resources have been leveled the durations of activities change, resulting in adjusted time-dependant costs, therefore providing a different cost than simply multiplying quantity by unit cost[xxvii]. Even less commonly practiced is adjusting production based on the other three constraints and the various clash conditions, though they have an effect on cost. The increased work necessary to account for additional factors such as climate and work zone congestion is mitigated through the use of integrated model-based systems, therefore providing a more precise representation of the project management triangle tradeoffs.

Proficiency in preparing scope-time models[3] (schedule) and scope-cost models (estimate) is difficult; many steps are repetitive and time consuming. A careful analysis of these steps provides a metric to measure performance against and provides a current performance measurement relatable to information model-based methods, see table 1. When placed in general categories, these break down into: project planning and setup, takeoff project scope also termed a *quantity survey* in the U.K., schedule process model, create 4Dmodel so to detect time-space and laydown space conflicts[xxviii] [xxix], estimate cost model, and optimize for efficiency for the preferred characteristic, such as: cost, time, material, impact. An analysis and quantification of the steps shows that of the 32 steps, 13 (41%) have software tools available now, 29 (91%) are repetitive, 16 (50%) are manual and nine (28%) have potential software tools or are included in some software tools. Assuming increases in software maturity will address the potential applications in the next few years then the number of tasks with software tools increases from 13 (41%) to 22 (69%). Four examples of potential software tools are: Automated adjustment of production rates based on expected climate conditions as researched by Akinci[xxx]. Automated linking of object to activity in

3Two examples are Program Evaluation and Review Technique (PERT) which calculates start and finish dates and Critical Path Method (CPM) which calculates free float then finds shortest free float path through process model.

4D, Navisworks and CommonPoint Project 4D[4] both have an auto-link function if the classification code is the same (1,2,3 != 1.2.3). Automated schedule generation, Building Explorer[5] provides automated Primavera Project Manager CPM schedule with all logic links complete and Sage-Timberline Estimating Extended and HCSS HeavyBid both produce a Primavera P3 schedule without logic links. Last, assemblies or bundles of operations likely connected, RSMeans Commercial Knowledgebase (CK) provides operation assemblies linked by formulas, Sage-Timberline provided the ability to create custom assemblies and new versions of Tocoman provides an assembly takeoff function to provide recipe formulas for often implicit objects. None of these automation functions are universal to project management software, each has limitations and likely no one software tool contains them all.

Table 1 Tasks necessary to create integrated scope-cost-time model

Integrated Scope-Cost-Time tasks:
project planning and setup
1. ▲develop project strategy
2. ▲■define what object are explicit in the product model [assembly implicit object-component]
3. ▲■determine Work Location Breakdown, project, location, sub-location and work-zone

product model takeoff (scope)
4. ■define operations & associated objects [assembly operations]
5. ▲■define implicit objects from explicit objects [assembly implicit object]
6. ▲■create recipe formulas for implicit objects [assembly object recipe formula, type template & specific]
7. ■map objects to operations [assembly operations]
8. ●■calculate quantity takeoff from object dimensions using recipe formula

process model (time)
9. ●■lookup operation production rates
10. ■&/or derive production rate from process analysis
11. ■create activities from single or multiple operations
12. ▲■determine driving production rate for activity
13. ▲apply locations from project planning
14. ●■assign sequence logic [assembly operation]
15. ●■assign resources to activities [assembly operation]

4D model (scope-time)
16. ●■map activities to 3D model [code match]

cost model (estimate)
17. ●■look up and assign unit cost
18. ■adjust unit cost for current conditions [contextual library]
19. ▲■&/or derive unit cost from labor, equipment, material, haul, & subcontractor

optimize for efficiency (recognize risk efficiency not met)
20. ●■calculate durations
21. ▲■adjust locations for production (20)
22. ●▲■level resources & workflow (20)
23. ●▲■laydown & workspace detection (20)
24. ▲■recheck driving production rate
25. ●■forward pass (ES, EF)
26. ●■back pass (LF, LS), free float
27. ●■determine critical path & total float
28. ▲■adjust production for climate & conditions [auto] (20)
29. ●■calculate cost (OT, time variable, marginal cost)
30. ▲■adjust location sequence (20)
31. ▲■optimize process model logic for efficiency - local optimum (20)
32. ▲create alternative project plan - global optimum, iterate from develop project strategy

● software tool ▲ manual conceptual task ■ repetitive task [ ] potential software tool

[4] http://www.commonpointinc.com/products/project4d/project4d.asp
[5] http://www.buildingexplorer.com/

Prior to integrated tools, a complete scope-cost-time project plan contained about five reentries for each of three applications, resulting in manually keying each entry 15 times for every operation or activity. A typical project schedule prior to adding five week look-ahead activities can have around 1000 activities. If thoroughly completed, this indicates 15,000 items are keyed during project planning. Each iteration of change results in further keying, assuming a 50% change in planning material results in over 20,000 items keyed. Humans can have 1:300 to 3:600 error rates. This rate results in less than 100 errors or ½ % error in the above assumed project planning material. If the error rate or changes in project material during planning are higher then this is conservative. This seems a small error, equaling about $3,000 to $5,000 per $1M of project scope. On a medium size ($250M 2009US) civil project this error could result in over a million dollars in misplaced resources. This analysis is assuming the use of electronic CPM process model, cost model and onscreen takeoff software tools. A paper-based scope-cost-time plan results in more keying or the use of paper tables/chalk boards for each software tool not used. Where and when in the project planning material these errors occur is also tasks are classified as one of six categories generally divided by software tool and project management process and control class. Human error ranges from 1:300 to 6:100, automation errors range from 1:394,000 to 1:5,400,000[xxxi xxxii]. Some potential software tools counted for product model takeoff, process model, 4D model and cost model, either exist in an existing software tool or have had substantial research completed. These are included since they are not generally included in similar software tools. Repetitive tasks include all except developing project strategy, apply location breakdown, and create alternative project plan. Repetitive tasks are those requiring repeating the same task for each activity or component-operation. The greatest gains are from common classifications so to allow assembly use in applications other than estimating.

Table 2 Analysis of tasks to create integrated scope-cost-time model

	total tasks		software tools		repetitive tasks		concept tasks		potential tool		if tool avail.	
tasks	32	100%	13	41%	29	91%	16	50%	9	28%	22	69%
planning and setup	3	9%	0	0%	2	7%	3	19%	1	11%	1	5%
product model takeoff	**5**	**16%**	**1**	**8%**	**5**	**17%**	**2**	**13%**	**4**	**44%**	**5**	**23%**
process model	7	22%	3	23%	6	21%	2	13%	2	22%	5	23%
4D model	**1**	**3%**	**1**	**8%**	**1**	**3%**	**0**	**0%**	**0**	**0%**	**1**	**5%**
cost model	3	9%	1	8%	3	10%	1	6%	1	11%	2	9%
optimize for efficiency	13	41%	7	54%	12	41%	8	50%	1	11%	8	36%

Scope-cost-time planning tasks are tedious and prone to short cuts, the goal of optimizing project planning becomes lost, and soon the engineer cannot see the forest for the trees. A survey of Auburn University undergraduate building science students and industry professionals highlights the poor perception that students have about estimating tasks[xxxiii]. If this same attitude permeates the estimating departments where many new engineers start their careers, the results can be poor bid and project performance due to engineering shortcuts. In the same way, engineers can become focused on less important but time-consuming tasks[6], these then can outweigh core

6 calculating durations, completing the forward pass and back pass, calculating free float and determining the critical path & total float

tasks[7] of maximize productivity, minimize risk, and ensure feasibility. The result is like an error-plagued estimate, poor results.

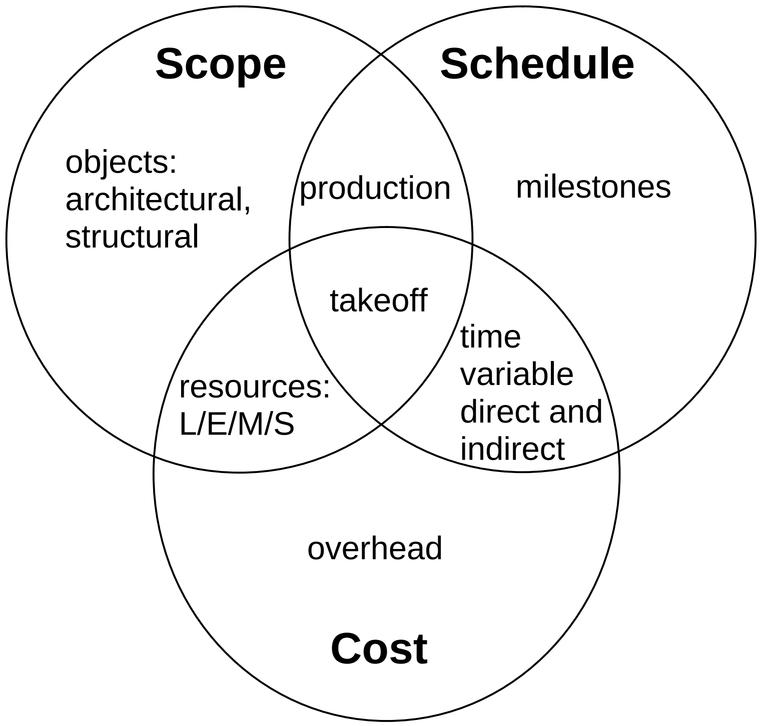

Figure 2 Venn diagram of scope-cost-time. The takeoff is central in all three areas and provides the foundation of all further modeling and analysis.

4. Scope-Cost-Time Defined

Project planning, scheduling and execution depend on valuating and trading of project control parameters so as to gain the optimum efficiency in resource utilization. As shown by figure 1, there are three project management process and control parameters, these are Scope-Cost-Time, a fourth Quality8 is implied to exist within the other three. A more difficult to conceptualize but still relevant factor is efficiency, which can never be 100%. Efficiency is the waste that does not result during implementation of the project plan. The decision to construct a project depends on the balance between scope and cost. Scope, as given by the plans and specifications, is the work required, both implicit (i.e., temporary structures) and explicit, to complete a project9. Scope indicates the project benefit and cost represents resources consumed, therefore

7 such as: adjust production rates for climate & conditions, level resources, optimize process model logic, adjust location sequence, check laydown & workspace detection, and calculate cost effect from changes

8 This material is offered to individual readers who may use it freely in connection with their project work. It may not be used by commercial or non-commercial organizations without permission.

9 "Scope (project management)." Wikipedia, The Free Encyclopedia. 13 May 2008, 14:44 UTC. Wikimedia Foundation, Inc. 6 Jun 2008 <http://en.wikipedia.org/w/index.php?title=Scope_%28project_management%29&oldid=212117853>.

defining project viability. To obtain scope, a takeoff is completed. If completed manually this is an error prone, time-consuming process[xxxiv]. Cost reflects the scarcity of resources at any given time and places a value on this scarcity. Cost is more difficult than scope to capture fully, due to the many affecting variables such as production, resource demand and time value of money. Cost includes: definition, associated externalities, design, fabrication, construction, operation and demolition, as shown in figure 5; this series of costs is known as the life cycle cost. Quality and time are the last two parameters. Time and quality affects cost in that absent any innovation, a reduced duration or increase in quality results in increased cost. This holds true as long as the project is operating at perfect efficiency, which is not possible, so in practice, duration can be reduced and quality can be increased through an increase in efficiency with no affect on cost. Time is the duration to move, arrange and assemble these resources. The quality factor reflects how these resources are used and what specific grades of resources are needed. The ultimate goal of the project planning and control process is to know what the resource demands to construct a project are and how these resource demands change during the construction process in response to existing conditions.

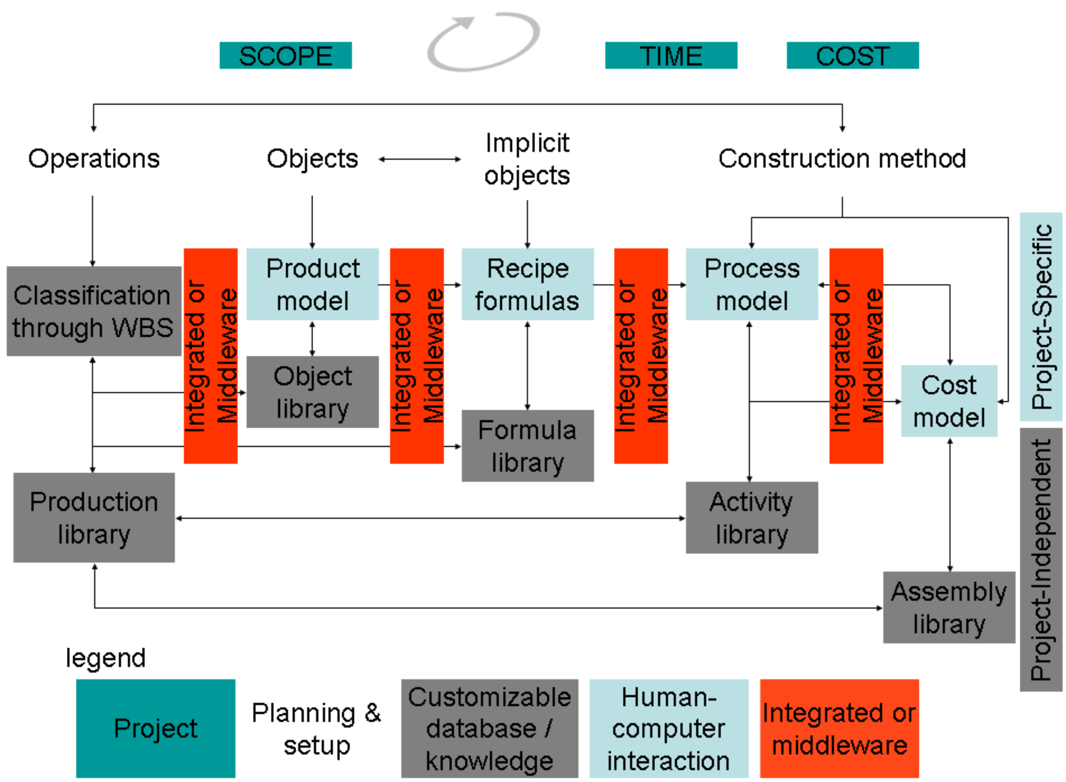

Figure 3 A general outline of interaction between scope-cost-time-quality software application tools within integrated scope-costing. Note the role of libraries to provide standardized information to models. Ideally, all models integrate with one another preventing the need to reenter data redundantly or manually transfer results to other applications.

5. Integrated Scope-Cost-Time

Before describing the three project management points embodied in software tools illustrated in figure 2, a short overview of each point and the types of models used is needed, refer to figure 3. Be aware, these systems are manifesting as two types, single vendor systems and integrated multi-vendor systems. The multi vendor system is illustrated in this case study. First, there is scope, represented by a product model; these can be a paper–based 2D drawing, represented as an electronic 2D or 3D drawing, as 3D Building Information Model (BIM) or as an animation incorporating time, i.e., 4D model. Second is cost, represented by a cost model known as a cost estimate. Cost models have a varying level of detail from typical project to parametric. The most detailed cost models are categorized into horizontal and vertical formats including[xxxv]: overhead, labor, temporary material, permanent material, equipment, subcontractor and haul[10]. The third and last is time, represented by a process model also know as a schedule. Process models have varying forms from spreadsheet three-week look-ahead, two month preliminary schedule, six month project planner and project billing schedule, each with an increasingly lower level of detail. These three models, scope-cost-time, ideally are integrated with quality models and efficiency analysis software to create a complete Project Planning and Control (PPC) system.

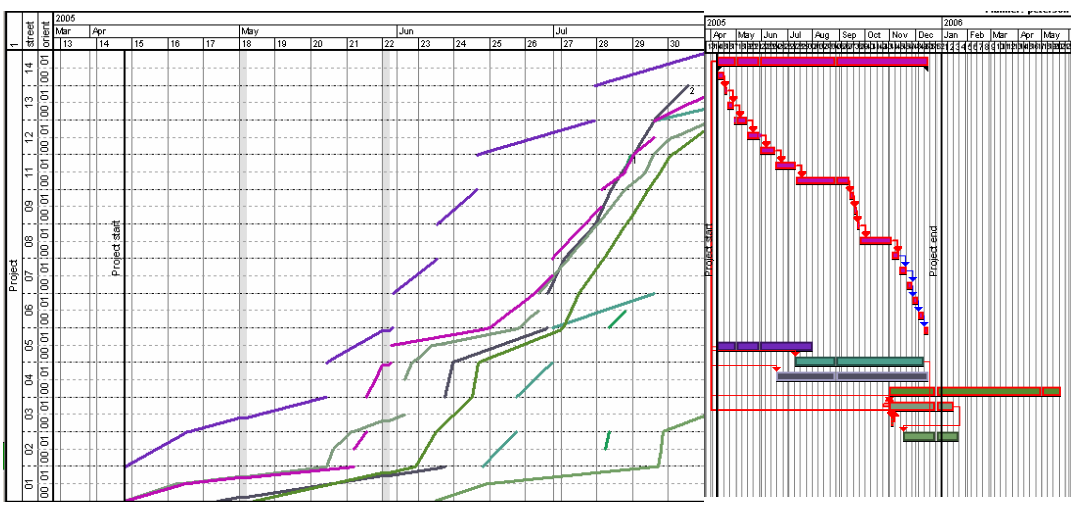

Figure 4 Side by side comparison of flowline (left) and Gantt (right) illustrates the affect of location phasing on production and which operation is the driving production rate. Four core concepts in Location-based Scheduling (LBS): 1) one task per task type is occurring in any given location, 2) workflow locations can be completed in any order, 3) maintain minimum 1-2 days buffer between tasks and 4) use the same location sequence for all the tasks.

10 Haul, the cost for hauling material, is calculated and entered in its own column in cost models. Haul is also given its own subcode in cost accounting to better track this cost separate from other activity cost. Distance hauled is an implied component of cost since haul cost is a per hour rate. The equation for haul cost is (quantity/capacity)(2x haul distance)(rate of transportation)(cost per hour). This equation ignores load/unload time and assumes zero queue time at load/unload, these require additional calculations dependent on equipment and site layout. Cycle time calculations incorporate the number of haul trucks and load/unload time.

Within the described scope-cost-time models, there is a distinction between *project specific* and *project independent data* to categorize the source of information, see figure 3. Project independent data is that universal to any project, an example is material density. Project specific data is that which is peculiar to a project and may not be true for any other project. An example is the sequencing of project phasing on a hospital project which may be determined by the helicopter flight path. Though this phasing is the most efficient for that project with its constraints, it is not necessarily the most efficient solution for any other project. With accurate and precise quantities, forecasting becomes more accurate and precise[xxxvi].

6. Integrated Software Tools

The process model or schedule can manifest in several forms, the most common are as a Gantt chart or a line of balance chart, see figure 4. The line of balance chart is commonly associated with Location-based Scheduling (LBS). A key benefit of LBS 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 1/10th 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. The value of this reduction in links is most observable in updates to the work process sequence to reduce project duration or stay on schedule, a common change due to changes in conditions and constraints. As a scheduler the more frustrating tasks is to be told to change the work sequence due to some change, then be told to change the sequence back the next week when the expected change did not materialize or the re-sequence fails to bring the expected benefits. For a single scheduler, on a large civil project, a re-sequencing of only a small portion of a project phase can take eight hours or more. Removing links and creating new links can take several hours, often completed at night after the scheduling meeting so to provide an updated schedule for approval the next morning. At some point the construction manger became hesitant to re-sequence the schedule since the labor required and uncertainty of benefits outweighed the labor required to model different options. The sequence of individual activities is not what is changed but often it is the location sequence that is changed. Changes in sequencing should not require relinking of activities but simply rearranging the location sequence, leaving the underlying work logic the same. Resource leveling is a fundamental component of duration calculations. Through adjustments to the number of crews productivity is adjusted to attain the needed durations. In addition factors such as: crew size, labor resources, production rates and quantities must be defined in location-based schedules.

The following five software tools are used in this case study: (1) Tocoman Group Ltd., a Finnish company, provided a takeoff and quantity calculating middleware software suite consisting of: iLink, Quantity Manager (QM), Construction Model Server (CMS) and Express. This software suite enables takeoff of quantities directly from multiple types of product models and integration with many different vendors' software tools. This is desirable since the user can select the software applications best suited to the task, they are most comfortable with or fits best with their legacy system. (2) Another Finnish company, Vico Software Ltd., provided Control, a Location-based Scheduling (LBS) software tool containing labor and material resource leveling and risk analysis features. The Vico company has positioned themselves for construction industry specific project planning and control applications[11]. (3) Sage-Timberline in addition to their estimating extended tool provided their estimating Commercial Knowledgebase[xxxvii] which has operations grouped as assembles with the necessary recipe formulas predefined. Recipe formulas are equations to convert from measured units to reported units and to infer quantities based on associated measurements. In this way, the user only needs to enter a quantity for one item and a group of associated items, or an assembly, is given an assumed takeoff value. (4) RSMeans production and cost libraries are used to provide the operation descriptions, classification codes, work breakdown structure (WBS), production rates, unit costs and the crews' compositions. (5) As the information model AutoCAD Civil 2007 was used with custom properties defined for location, sub-location, soil properties and compaction zones.

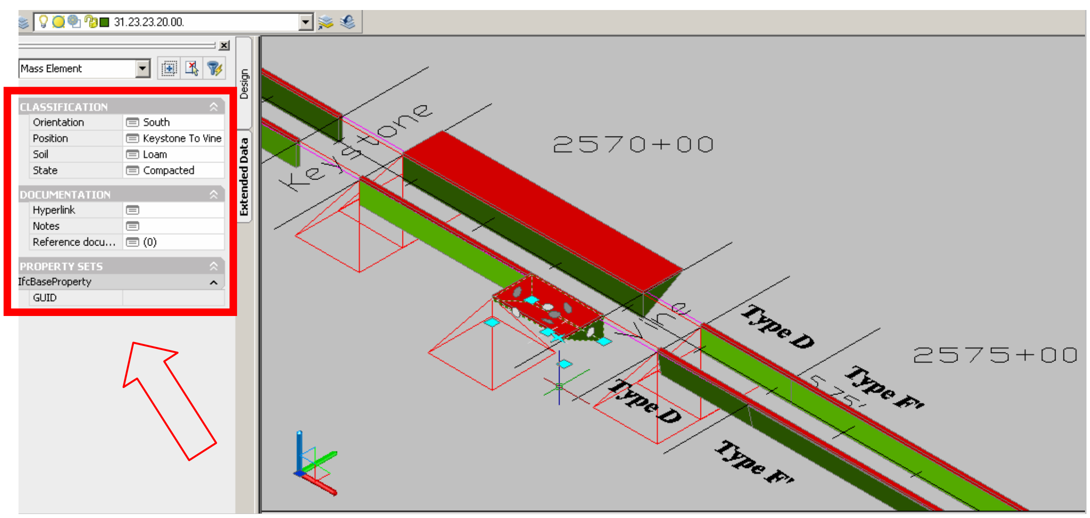

Figure 4 Product Model - the information model properties expanded to include: Level 1 – project, Level 2 - location (position) , Level 3 - sub-location (orientation), Level 4 – discipline, Level 5 – Master schedule activity, Level 6 - resource, soil type and soil state, i.e., compacted, and Level 7 – object, backfill mass elements and grade slabs. The object classification codes are Construction Specification Institute (CSI) Work Breakdown Structure (WBS). Notice the layer naming embodies level 4 through level 7 while custom properties embody level 1 through 3 and expand on the level 6 resource properties.

Three software tools common to civil work that were not included in this case study with Tocoman but should be in any future work on civil integrated systems. These are:

11 Vico Software Inc. http://www.vicosoftware.com/

HCSS, DynaRoad and Trimble Pay dirt[12]. Due to the preliminary nature in civil integrated systems a collection of tools providing existing integration solutions was selected. The integration of these tools is not currently thought possible but due to market share should be investigated. In the CIFE survey 6 of 56 (10%) civil contractors defined HCSS HeavyBid as their cost estimating tool, 2 of 56 (3%) defined Maxwell American Contractor, the remaining 87% are assumed to use excel or non-electronic methods, @ 95% CL, confidence interval is 13%. The 2008 biannual Construction Financial Management Association (CFMA) questionnaire survey[xxxviii] found that 36% of civil contractors use HeavyBid and none used Maxwell. They found 18% use Hard Dollar, 12% use Excel, 11% use BID2WIN, 5% use Sage-Timberline, 2% use MC2 and 4% use an assortment of other vendor tools. HeavyBid is contains an import function for takeoff quantities from Trimble Pay dirt. Paydirt is intended to takeoff earthwork quantities and not mass concrete. Another location-based scheduling software, with many of the advantages in reduced activity linking, duration calculations, and resource leveling of Control is available; developed specific for earthwork called Dynaroad[13]. DynaRoad is intended for balance cut and fill operations similar to the Trimble pay dirt tool.

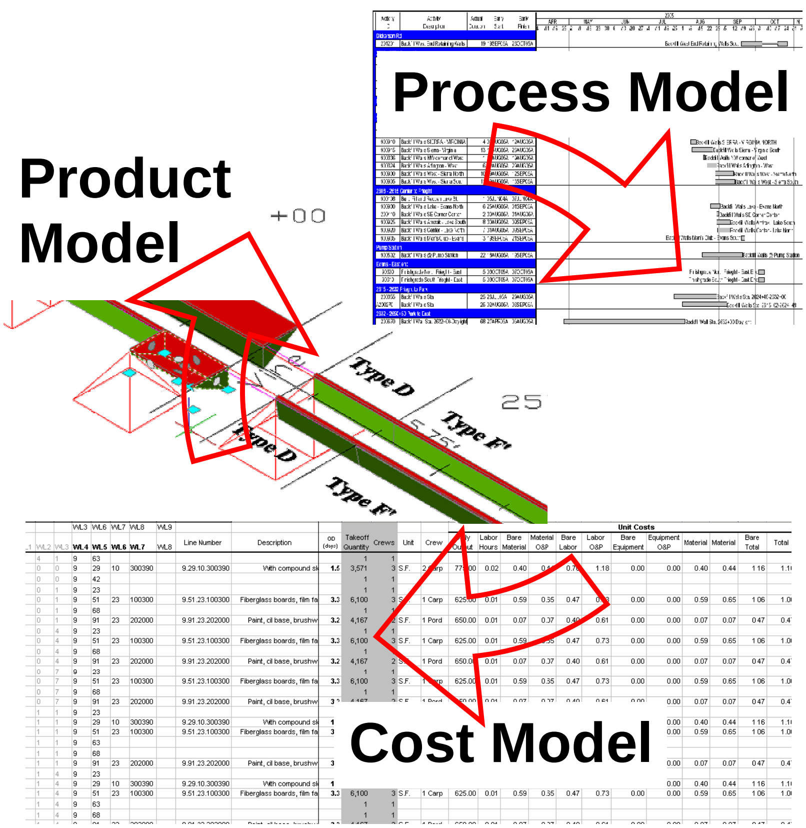

Figure 5 Iteration of changes in the method, scope or sequence requires a new pass, resulting in: 1) a new optimization of the schedule for project constraints, 2) a check of the 4D model for constructability and 3) a review of the cost estimate.

[12] http://www.trimble.com/paydirt.shtml
13 Dynaroad website accessed 1/25/2008 www.dynaroad.fi/

7. Results and Findings of Integrated System

The initial setup required for integrated system tools is less forgiving to skipping setup than with other software[xxxix]. Once the planning and setup, see table 2, are determined, they are difficult to adjust later in the design process or during the construction phase. Key to setup is a strategy for construction methods, planning of work locations based on this strategy, and the definition of a Work Breakdown Structure (WBS). The WBS provides a common classification across software providing an identification of the same operation or object across multiple software tools. Due to the correlation of location and WBS hierarchy, Location-based scheduling requires more attention to the WBS planning than the Critical Path Method (CPM)[xl]. In Primavera Project Manager (P6) and Microsoft Project it is possible to start with no defined level of detail or location hierarchies. If mid project, a WBS becomes necessary or the current version is inadequate, adding a WBS is not difficult. As a consequence the utilization of the WBS is traded off and so is also weaker.

The Tocoman, Vico, Sage-Timberline, RSMeans, AutoCAD and Navisworks software worked without any impossible problems. The operations CSI classification, description and unit of measure were imported from the Sage-Timberline estimate to the Construction Model Server through Tocoman Express. Later the quantities were returned to the estimate through the same method. The Commercial Knoledgebase assemblies allowed associated operations to be selected as a group, therefore saving time. The assemblies' technology could be leveraged more with the associated recipe-formulas reaining "live" mtherefore eliminating the need to redundantly assign recipe-frmulas in the CMS. Once the associations between operations and objects were mapped in Tocoman ilink, any changes to the existing objects resulted in a revised takeoff as hypothesized in earlier research on integrated[xli] systems. Through a wizard, Control imported quantities, operation descriptions, unit of measure and locations from the Construction Model Server (CMS). The jump from Control to Navisworks required the use of either Primavera or Microsoft Project as these are the only two supported by the 2009 version. The AutoCAD object geometry is interoperable with Navisworks. These integrations saved data entry labor and eliminated the risk of keystroke errors and transpositions. However, the production rates available in the RSMeans operation library could not be imported to the CMS, and so could not be imported to Control in one operation. An alternative to manual keying is the Sage-Timberline estimating software provides a print to comma delineated file. Used as a rudimentary integration function, once in spreadsheet form the production rates were matched to a Control spreadsheet export and then reimported. The key property allowing this was the CSI classification common to both data sets. It was not a smooth process, though if completed routinely the process may seem less out of place.

Manually generating the estimate's list of operations from the *operation library* is necessary. The sample product model used a text-based description to differentiate objects. The RSMeans operation library uses a numeric coding system based on the

2004 50-divisions Construction Specifications Institute (CSI) Master Format work breakdown structure. Manually mapping from the text based description to MasterFormat codes is required to create a list of object to operation maps. This step is time consuming and non-standardized, what object is associated with what operation is not clear. If the naming convention used for the object[14] is equal with the coding system used for the operation library, then an automated process of both selecting operations and mapping objects to these operations is possible. Revit architecture 2009 includes a library of object MasterFormat and Uniformat[xlii] codes, though they have assigned the object classifier using a different numerical sequence than RSMeans, therefore preventing an exact match.

Integration of software was negated by version changes of the tools during the case study, requiring a new integration solution. Tocoman has been good at maintaining version compatibility between Architectural Desktop, Vico Control and the Tocoman Construction Model Server. An interesting secondary discovery is that software support located in an opposing time zone results in great turnaround. Tocoman would receive any support requests from the days work with the integrated system and usually have a solution the next morning my time.. The Tocoman software as configured for this application had a steep learning curve. An online server host[15] was used to simplify installation rather than a local install and this at first was a bit confusing. The concept of middleware seems simple in concept but in practice it takes time to acclimate to applying a half dozen software tools as one single tool. Once adjusted this is a more versatile system since any issues with a software is mitigated by swapping a comparable tool in its place.

The best concept demonstrated by Control is that increasing the production on an activity may have a negative effect on the overall project duration. In this way, resource increases applied haphazardly can be detrimental to project success. The software demonstrates clearly that slowing selected activities and changing work location sequence has a greater and more reliable affect on project duration. As one student stated, “I learned which activities were holding up the project and found out that by simply re-sequencing the location flow, I could drastically reduce the overall construction duration by releasing more critical areas to succeeding activities”. Insight of what activity is best to change or re-sequence is difficult to observe in Gantt CPM process modeling software such as Primavera or Microsoft Project Manager. Refer to figure 4 and notice the space between several of the activities. This is not a mistake but represents stockpiling of material. A common activity on the project was large stockpiles of material around the worksite then load out to smaller haul trucks. With a more detailed view of production as this chart provides, decisions may have been made differently.

14 layer-style or some other exportable parameter

15 Citrix is a company that provides server space for a fee, thereby removing the need to maintain servers.

Six Lessons Learned:

1. Organization
   - Contributes to reduced waste through enabling cross-functional communication
   - Changes culture, usually modelers work separately from the other key players, this method brings different working cultures together
   - The process modeler and constructor must be engaged in the product model creation process to identify what must be explicit i.e., included, to provide needed objects
   - The goal varies with the professional focus, such as: the takeoff, the cost estimate, the schedule, the constructability 4D check and the knowledge to efficiently build an object.
2. Scope-cost-schedule
   - Reduced rework and errors through automation
   - Recipe-formulas provide take-off for objects implied to exist in the product model. It is necessary to keep track of what objects are implicit, i.e., NOT modeled
   - Higher levels of detail (LOD), allowing greater accuracy per component line item
3. The "quantity" required for a crane, i.e., time variable cost, is measured in days, not in physical units
4. Slowing an activity can result in reduced project duration
5. Actual production measurements are collected more accurately, since the quantities are known more precisely, leading to a better basis to develop historic unit cost
6. Knowledge reinforcement and transfer
   - The post project write-up refines and solidifies concepts discovered through the process
   - The planning process replicates tribal knowledge existing in construction field crews

Pros and Cons of linking design information and construction information:

The same information basis for project planning, monitoring and control provides three main benefits. It allows: project team members to visualize the product, improved feedback quality, and facilitates two-way communication between the field and design office. The method could provide value by offering better handling of design options.

Three identified issues centered on software unfamiliarity and legacy systems. First, the softwares' security systems are cumbersome to navigate, compounded by the use of multiple vendors. Second, common software functionality like "copy", "paste", and "undo" are often missing. Third, not all software tools are integratable. Occasionally odd solutions must be found to move a specific property from one tool to the next or a secondary choice of software is used because it integrates with a legacy system component. These issues caused some level of frustration; the consensus is it would prove beneficial to hire someone who specializes in dealing with the software system and its peculiarities ahead of the critical path on projects. The vendors provided comprehensive software support and patches quickly, implying that custom solutions to specific field issues would be available. The upfront cost of implementing such a system could be a barrier to adoption, i.e., negative return on investment. Through the use of a combination of legacy software tools and few selected additions, while possibly not the optimum solution, the upfront costs of purchase and training are mitigated.

Figure 6 The compiled six lessons learned and pros and cons are provided by students from the autumn 2007 and autumn 2008 CEE241 courses. The need for greater interaction between disciplines and identification of what objects are implied in the model are core concepts highlighted here. Through the use of the software students felt the tools are effective but the learning curve is enough that a designated specialist for the system is needed on-site during implementation and an adjustment period.

a. Classification and Unit of Measure

As the production and cost library in the Sage-Timberline cost model we used the RSMeans historical library. The RSMeans library uses the Construction Specification Institute (CSI) 2004 MasterFormat[16][17], as a base template to classify operations. Standardized classifications provide knowledge of the specific activity by viewing the activity code. Given a product breakdown of *"Hauling excavated or borrow material, 20 C.Y. dump trailer, highway"* encoded as 30.18.02.01.31.23.23.18.12.55, any reader of this code, savvy to the classification breakdown, will understand what it is referring to. Even if it is not know what the prefix 30.18.02.01 is assigned to, it is know from the CSI MasterFormat that 31.23.23 is *Earthmoving backfill,* and that 30.18.02.01.likely refers to the company, project number, location two, north. So while it would be unknown what the operation method was, i.e., 20 CY highway haulers, we would know it was some type of backfill haul operation.

The level of detail is also known by the degree of the work breakdown structure. Work levels one through three serve as the process model location breakdown structure. Work levels four through seven are intended to serve as the basis of process model activities descriptions and schedule work breakdown structure. Work levels four through nine are often used for classifying historical production rates.

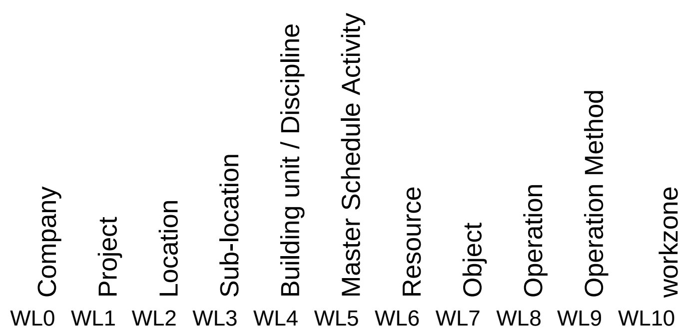

Figure 5 Eleven level Work Breakdown Structure. This WBS uses the CSI MasterFormat for work levels four through six. The RSMeans WBS is represented by levels six through nine. The Revit WBS is represented by levels six and seven. Work level ten conforms to the AROW format to provide a workzone. This classification format conforms to the AROW standard.

In addition to the importance of standardized classification is unit of measure. Units of Measurement are typical for various operations, such as concrete curb is measured in linear feet (LF), earthwork in Embank Cubic Yards (ECY), formwork in Square Yard

16 www.csinet.org

17 http://www.csinet.org/s_csi/sec.asp?TRACKID=&CID=1377&DID=11339

(SY) and asphalt in Tons[18]. Estimating and field collection methods may differ in unit of measure to ease collection. The basic units of measure are count, length, area, volume, time, magnitude, weight and relative. Of course, area and volume are derived from length. Determining what unit of measurement will be used for any object-component in the integrated takeoff has an impact on future use. Recipe formulas convert between units of measure but some forethought in takeoff unit of measure reduces the number of formulas needed.

With a universal coding system, for objects in the product model and the operation library there are many potential applications. One is a list of explicit objects contained in the product model could be automatically associated through predefined assemblies with operations in the operation library, eliminating the need to look these up. Another application is the conversion of the unit of measure to the unit of reported measure could be associated with predefined recipe formulas in a similar way.

The Rocky Flats decommissioning project, one of the most contaminated sites in the U. S. Department of Energy's nuclear weapons complex, 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"[xliii]. This provides an example of the industrial impact from standardizing the classification across project models, resulting in improved integration and a reduced learning curve.

b. Recipe formula and Implicit Objects

Of particular importance due to its relation to object-components represented implicitly and explicitly in the product model is the concept of a recipe formula. These are formulas derived to calculate multiple quantities from an explicit product model object input measurement, such as count, length, area and volume. Maximizing the use of formulas can reduce the resources required for constructing the model. The number of person-hours required to create a model is correlated to the scope and quality of objects represented within the product model[xliv]. Therefore the larger and more detailed the model is, the more person-hours required. To limit the resources needed, it should be determined what can be calculated implicitly from the fewest possible explicit variables. Additionally the most time consuming portion of the takeoff is mapping the operations to the objects to measure. Recipe formulas are much quicker to write and can be reused, therefore, minimizing the need to measure objects explicitly represented in the product model therefore reducing takeoff complexity.

These minimum explicit variables are what must be included in the product model, such as: mass concrete, structural steel members and MEP systems. For takeoff purposes,

18 volume times density

no item feasible to deduce from an object within the product model, need be included in the product model or if it is included for other purposes, linked directly to an operation.

Examples of implicit objects: reinforcing steel, electrical outlet covers, formwork and structural connections[xlv]. These implicit objects do not need to be symbolically modeled if these items can be inferred from other objects within the product model or are in the specifications. For example, pounds of reinforcing steel can be implicitly derived from a concrete object. A recipe formula converts from the concrete takeoff unit of measure of cubic feet to the reinforcing takeoff unit of measure of pounds as pounds per cubic foot of concrete. Though a more accurate and precise quantity takeoff, including splices, and the correct number of fabricated reinforcing components, is possible if sufficient details have been symbolically included in the product model.

Often Explicit Object	Associated Implicit
Cast-In-Place Concrete	Excavation
	Hand-trim
	Formwork
	Reinforcement
	Dry patching
	Caulk & Seal
	Backfill
Structural Steel	Fasteners & Welds
	Plates
	Painting
	Fire proofing
Demolition (as-built)	Stockpile & batching
Mass Excavation	Erosion Control
	Compaction zone
	Mobilizations
Paving	Base Course
	Saw Cutting
	Sub-grade
Utilities	Trenching
	Bedding
Temporary Structure	Temp fencing
	Climate consideration
	False-work
	Retaining Structures

Table 3 common implicit / explicit objects

The recipe formulas to calculate takeoff values from given explicit product model attributes are often created custom to project conditions. An analogy is if one was to derive a new structural connection formula from scratch each time a new connection occurred. A list of often-expected explicit variables and often-implicit variables could help with determining these recipe formulas. A predefined and customizable list to select from could reduce the risk of error and help with standardizing. The constructor and product modeler are assumed to successfully be able to determine the criteria for what to include explicitly in the product model and what to include implicitly. Once automated takeoff technology becomes more common, general rules of thumb and experience from past projects, will determine whether an object-component is implicit or explicit in the product model. Until then a basic set of guidelines or tagging of specific operations as explicit or implicit could prove to be valuable.

Once this is completed, verifying that all the implicit objects in the product model have been referenced through the assemblies is necessary. These implicit objects could then be quantified through predefined recipe formulas using the explicit object list as inputs. Alternatively, if the cost model operations have *IFC*[19] classifiers as parameters then linking could be automated. IFC interoperability[20].

8. Conclusion

In this case study the following five points have been found: First the integrated scope-cost-schedule model system found that even the project 5-week lookahead schedule, considered to be the most accurate, contained coarse errors. Second, the manual take-off contained undiscovered double counts and omissions embedded in the project documents, these were easily found with an integrated system. Third, the recorded level-of-detail could be increased to provide production rates specific to project locations and not general to the project itself. Fourth, facilitated by the integrated system, the Location-based scheduling tool provided more accurate and precise dates and resource demand than available to the project team. And last, a uniform classification method across the system is important for project team members to correlate an item located in one aspect of the model with it’s representation in another.

If the first four results given above are high risk items for your market and the fifth result does not present an issue to implementation, then civil contractors should consider making a shift towards integrated model systems. An integrated model system helps project staff to focus on best practices in scheduling techniques and network analysis such as: defining where critical activities, activity float and total float reside, sequence of operations, access conditions, duration impacts, optimal crews, minimizing mobilizations, buffer, and feasibility. These result in a reduced emphasis on repetitive tasks such as: scope take-off, data entry and calculations for floats, start-finish dates, durations, total cost and delay.

Research to define guidelines for those project components usually (explicit) and usually-not (implicit) modeled is needed. From these guidelines it may be possible to define a library of recipe formulas to quantify unmodeled components from modeled components. These two items would reduce much of the redundant and error prone tasks involved in product model takeoff (17% repetitive tasks) and the project setup (7% repetitive tasks). If you are interested in a more detailed map of the system used for this case study, please contact the author and a more detailed documents will be provided.

References

19 Industry Foundation Classes (IFC), International Alliance for Interoperability (IAI), http://www.iai-international.org/

20 “interoperability is used to describe the capability of different programs to exchange data via a common set of exchange formats, to read and write the same file formats, and to use the same protocols.”

i Construction Financial Management Association (CFMA) 2008 Information technology Survey for the Construction Industry, 7th edition.

ii Sacks, R., Navon, R., Brodetskaia, I., and Shapira, A. (2005). “Feasibility of Automated Monitoring of Lifting Equipment in Support of Project Control.” J. Constr. Eng. Manage., ASCE, 131(5), 604-614.

iii Navon, R. “An Overview of Automated Project Performance Control Research at the Technion.” ISARC 2005, 22nd International Symposium on Automation and Robotics in Construction. September 11-14, 2005, Ferrara, Italy.

iv Akinci, B., Kiziltas, S., Ergen, E., Karaesmen, I. & Keceli, F. "Modeling and Analyzing The Impact of Technology On Data Capture and Transfer Processes at Construction Sites: A Case Study" Journal of Construction Engineering and Management ASCE / November 2006

v Saidi, K. (2002), Possible Applications of Handheld Computers to Quantity Surveying, PhD Dissertation, The University of Texas at Austin, Austin, TX

vi K. Futcher, User survey on a WAN portfolio MIS used for portfolio/project management in Hong Kong, Proceedings of IT in Construction in Africa, CIB W78 Workshop, South Africa, CSIR, Pretoria, 2001, pp. 44-1–44-14.

vii Davidson, I. N., and Skibniewski, M. J. “Simulation of automated data collection in buildings.” J. Comput. Civ. Eng., 9 1 , 9–20. 1995.

viii Saidi, K. S., Lytle, A. M., and Stone, W. C. “Report of the NIST Workshop on data exchange standards at the construction job site.” Proc., ISARC-20th Int. Symp. on Automation and Robotics in Construction, F. van Gassel, ed., Eindhoven, The Netherlands, 617–622. 2003

ix McCullouch, B. (1997). “Automating Field Data Collection on Construction Organizations,” Construction Congress V, 957-963, October 4-8, 1997.

x Cheok, G. S.; Stone, W. C.; Lipman, R. R.; Witzgall, C., "Ladars for Construction Assessment and Update." Automation in Construction, Vol. 9, No. 5, 463-477, 2000.

xi Reinhardt, J., Akinci, B., and Garrett Jr., J.H. "Navigational Models for Computer Supported Project Management Tasks on Construction Sites" Journal Of Computing In Civil Engineering ASCE / October 2004 pp 281 - 290

xii Liu, L.Y., Stumpf, A. L., Chin, S.Y., Ganeshan, R., Hicks, D. (1995). “Construction Daily Log Management System Using Multimedia Technology,” Computing in Civil Eng., 2nd Congress, vol. 2, 1084-1089, June 5-8, Atlanta, GA, ASCE.

xiii Rebolj, D., Turk, Ž., Sun, M., Huhnt, W. "European Master in Construction IT development project" First International Workshop on Construction information, 2002

xiv Märki, F., Fischer, M., Kunz, J. & Haymaker, J. "Decision Making for Process model Optimization" Stanford University, CIFE Technical Report #169, March 2007

xv Leu, S., Yang, C. and Huang, J. "Resource leveling in construction by genetic algorithm-based optimization and its decision support system application" Automation in Construction 10(2000)27–41

xvi Kiziltas S., Akinci B., “The need for prompt process model update by utilizing reality capture technologies: a case study”, Carnegie Mellon University, Pittsburgh, 2005

xvii A Guide to the Project Management Body of Knowledge (PMBOK Guide) 4th Edition, Project Management Institute, 2008, ISBN: 978-1-933890-51-7

xviii Fondahl, J. W. “A Non-Computer Approach to the Critical Path Method for the Construction Industry 2nd Edition” Department of Civil engineering, Stanford University, The Construction Institute, Technical Report Number 9, November 1961, revised 1962

xix "Critical path method." Wikipedia, The Free Encyclopedia. 31 Mar 2009, 01:06 UTC. 4 Apr 2009 <http://en.wikipedia.org/w/index.php?title=Critical_path_method&oldid=280767399>.

xx Aalami, F. B., Fischer, M. A. and Kunz, J. C. "AEC 4D Production Model: Definition and Automated Generation" Stanford University CIFE Working Paper number 52, September 1998

xxi Leu, S., Yang, C. and Huang, J. "Resource leveling in construction by genetic algorithm-based optimization and its decision support system application" Automation in Construction 10(2000)27–41

xxii M. Fischer "Formalizing Construction Knowledge for Concurrent Performance-Based Design" Lecture Notes in Computer Science, I.F.C. Smith (Ed.): EG-ICE 2006, LNAI 4200, pp. 186 – 205, 2006.

xxiii Kevin Tantisevi, Burcu Akinci "Automated generation of workspace requirements of mobile crane operations to support conflict detection" Automation in Construction Volume 16, Issue 3, May 2007, Pages 262-276. (http://www.sciencedirect.com/science/article/B6V20-4KM46S7-1/2/4fd55b8235177da72d31e34156289504)

xxiv Akinci, B., Fischer, M., Levitt, R., Carlson, B. (2002) “Formalization and Automation of Time-Space Conflict Analysis.” Journal of Computing in Civil Engineering , Vol 6. No. 2, 124-135

xxv Akbas, R. and Fischer, M. "Construction Zone Generation Mechanisms and Applications" ISARC 2002: 19th International Symposium on Automation and Robotics in Construction, 2002, pp 293--298

xxvi Leu, S., Yang, C. and Huang, J. "Resource leveling in construction by genetic algorithm-based optimization and its decision support system application" Automation in Construction 10(2000)27–41

xxvii Fondahl, J. W. “A Non-Computer Approach to the Critical Path Method for the Construction Industry 2nd Edition” Department of Civil engineering, Stanford University, The Construction Institute, Technical Report Number 9, November 1961, revised 1962

xxviii M. Fischer "Formalizing Construction Knowledge for Concurrent Performance-Based Design" Lecture Notes in Computer Science, I.F.C. Smith (Ed.): EG-ICE 2006, LNAI 4200, pp. 186 – 205, 2006.

xxix Akinci, B., Fischer, M., Levitt, R., Carlson, B. “Formalization and Automation of Time-Space Conflict Analysis.” Journal of Computing in Civil Engineering , Vol 6. No. 2, 124-135, 2002

xxx Akinci, B., Kiziltas, S., Pradhan, A. (2006). “Capturing and Representing Construction Project Histories for Estimating and Defect Detection”, 13th Intelligent Computing in Engineering and Architecture (EG-ICE) Workshop, 25-30 June 2006, Ascona, Switzerland. Published in Lecture Notes in Artificial Intelligence, Springer.

xxxi Smith, D. and F., Offodile "Information Management of automatic data capture an overview of technical developments" Information Management and Computer Security 10/3, 2002, pp 109 - 118

xxxii Rainu Kaushal, MD, MPH; Kenneth N. Barker, PhD; David W. Bates, MD, MSc "How Can Information Technology Improve Patient Safety and Reduce Medication Errors in Children's Health Care?" ARCH PEDIATR ADOLESC MED/VOL 155, SEP 2001

xxxiii Fuller, S. and Kahn, D. E. "Construction Estimating: Student Perceptions vs. Industry Reality" Construction Education 2003 pp 146 - 156

xxxiv Alder, A., M. "Comparing Time and Accuracy of Building Information Modeling to On-Screen Takeoff For a Quantity Takeoff Of a Conceptual Estimate" Brigham Young University, School of Technology, Master Thesis, 2006

xxxv Bartholomew, s. "Estimating and Bidding for Heavy Construction" CSU Chico, Prentice Hall, Upper Saddle River, New Jersey, Columbus, Ohio. ISBM 0-13-598327-4, 2000

xxxvi Olli Seppänen and Russell Kenley "Performance Measurement Using Location-Based Status Data", Proceedings IGLC-13, July 2005, Sydney, Australia, http://www.cem.tkk.fi/fsr/Julkaisut/30_098_Seppanen_Kenley.pdf

xxxvii Commercial Knowledgebase Smart Assemblies, Sage-Timberline Office, 2006 http://www.sagetimberlineoffice.com/include/pdfs/CommercialKbase.pdf

xxxviii Construction Financial Management Association (CFMA) 2008 Information technology Survey for the Construction Industry, 7th edition.

xxxix Niclas Andersson and Knud Christensen in "Practical Implications of Location-Based Scheduling", Department of Civil Engineering, Technical University of Denmark, DK-2800, Kgs. Lyngby, Denmark 2007

xl Niclas Andersson and Knud Christensen "Practical Implications of Location-Based Scheduling", Department of Civil Engineering, Technical University of Denmark, DK-2800, Kgs. Lyngby, Denmark 2007

xli M. Fischer and J. Kunz "Circle Integration" Stanford University, CIFE working paper number 20, April 1993

xlii Charette, R. and Marshall, H. "UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis" NISTIR 6389, 1999

xliii Stevens, J.L., Titus, R. and Sanford, P.C. "Cost Estimating For Decommissioning Of A Plutonium Facility– Lessons Learned From The Rocky Flats Building 771 Project" WM'02 Conference, , Tucson, AZ, February 24-28, 2002

xliv Ju Gao & Martin Fischer "Framework & Case Studies Comparing Implementations & Impacts of 3D/4D Modeling Across Projects" Stanford University Civil and Environmental Engineering Dept CIFE Technical Report No. 172, 2008

xlv Martin Fischer and C.B. Tatum "Partially Automating the Design-Construction Interface: Constructability Design Rules for Reinforced Concrete Structures." Stanford University, CIFE Working Paper Number 004, May 1989.