

CASE STUDY OF USING AN INTEGRATED 5D SYSTEM IN A LARGE HOSPITAL CONSTRUCTION PROJECT

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ABSTRACT

3D models for constructability analysis, quantity takeoff, and model-based scheduling have been typically described as point applications. An integrated 5D system, where the 3D model drives quantity takeoff (along with model-based cost planning comprises the 5th D), which is automatically tied to a location-based schedule to generate resource and cost-loaded schedules (the 4th D), is a more novel concept. Integrated 5D approaches have been used in commercial applications since 2005 but there are only few case studies in technical literature to illustrate the benefits and challenges of implementation. The goal of this paper is to present the case study of Kaiser Oakland hospital project, the largest known implementation of integrated 5D systems combined with location-based planning. We analyzed specifically the preconstruction phase of foundations.

The benefits of the 5D system were studied with the following hypotheses based on the experiences gained in previous projects. First, model-based constructability based on a parallel construction model should identify more constructability issues than traditional model-based constructability processes. Second, model-based quantity takeoff should take less time than manual take-off. Third, integrated location-based scheduling should enable schedule optimization over CPM-based approaches, resulting in shorter overall duration with more continuous resource use.

Two out of three hypotheses were supported in the preconstruction of foundations. First, over 200 additional constructability issues were identified using the construction model. Second, Location-based scheduling enabled the planning of continuous work for subcontractors while compressing the duration of Foundation phase by six weeks. Contrary to the hypothesis there was no time saving benefits related to quantity take-off, although there were some qualitative benefits in terms of better communication.

KEY WORDS

Location-based management, constructability, 5D model, flowline schedule

INTRODUCTION

The use of 3D models for improving constructability has typically included model-based design and coordination by combining multiple models into one model and running clash detection (Staub-French & Khanzode 2007). This model-based coordination process allows resolution of most design problems before they happen

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on site, minimizing the RFI's (Requests For Information) and change orders (Khanzode et al. 2008).

In addition to constructability analysis, 3D models can be used for accurate quantity takeoff. Quantity takeoff is traditionally a very manual and time-consuming process. There is a lot of waste in construction process because quantity takeoff needs to be performed each time the design is updated, or when quantities need to be calculated on different level of detail. 3D models can produce quantities automatically based on a means and methods database. (Staub-French et al. 2003)

One of the most researched 3D model applications in construction is the combination of time and 3D geometry, a 4D model. Most of the applications described in literature have limited 4D to a link between a particular piece of scheduling software and 3D model, thereby giving a start and finish date to each element or group of elements in a 4D model. The resulting 4D model could be played as a simulation, or snapshots of individual dates could be explored. (Song & Chua 2006; Hartmann & Fischer 2007; Mahalingan et al. 2009) The reported benefits of 4D simulations have included clear communication to various stakeholders, improved reliability of schedules and a transparent understanding of scope and schedule which enables early discovery of conflicts (Hartmann et al. 2008).

Integrated 5D methods seek to combine the 3D constructability analysis, quantity takeoff and estimating, and schedule into one system. A constructible 3D model produces accurate geometry which can be used for quantity takeoff. By defining locations in the model, quantities can be taken off by location for each trade. By applying productivity rates and crew sizes to quantities in each location, a location-based schedule can be generated based on the model using a location-based planning system (Kenley & Seppänen 2010: 123-161). Because the locations, quantities and schedule are integrated, the schedule can be automatically cost loaded and derived from the model. Instead of attaching a separately generated schedule to a model, the model and schedule are integrated. If there is a design change, quantities will be updated in locations, which will result in an automated cost and time effect. Therefore any design updates should be less time-consuming to handle in an integrated system. Although there are many case study reports of using 3D models for simulation, cost, or time, integrated use of 5D applications combined to a location-based schedule has not been described in literature. Hartmann et al. (2008) found that most of the 26 case studies supported by Centre of Integrated Facility Engineering (Stanford University) only used 3D models for one or two applications.

The aim of Lean Construction is to reduce waste. The better integration of information should reduce errors, improve communication, and eliminate waste in design process and in production on site. Having a constructible design reduces the amount of RFIs (Contractor Requests for Information) and change orders related to field changes (Khanzode et al. 2008). Additionally, MEP (Mechanical, Electrical and Plumbing) contractors are able to use more prefabrication which improves productivity on site and improved safety. Location-based management systems enable the optimization of schedules and planning for a continuous flow. During production, location-based controlling tools give early warnings of problems and help to prevent cascading delays (Seppänen 2009: 153-175). By combining the design information to cost estimate, budget, and schedule, a lot of manual work can be eliminated and the information of the management system is always synchronized.

INTEGRATED 5D SYSTEM

The Vico Virtual Construction Suite of software was utilized in the case study. It is an integrated 5D system which connects 3D models to a database for quantity takeoff, and enables the planning of locations to support location-based planning and scheduling. The system is integrated by using model-based quantities and locations to link design, cost, and schedule.

Quantities are handled on three levels. Recipes are attached to model geometry, and integrated with the 3D model via a means and methods database. As illustrated in figure 1 below each recipe can contain multiple methods, which define the steps required to complete construction of the model element. For example, a concrete column could be linked to a recipe which gives quantities for formwork (using the surface area of the column), rebar (using volume with a multiplier), concreting (using volume) and surface finish. Each of the methods is linked to resources which are needed to complete that step. For example, formwork method may include formwork labor and materials as resources.

Schedule and 5D Model

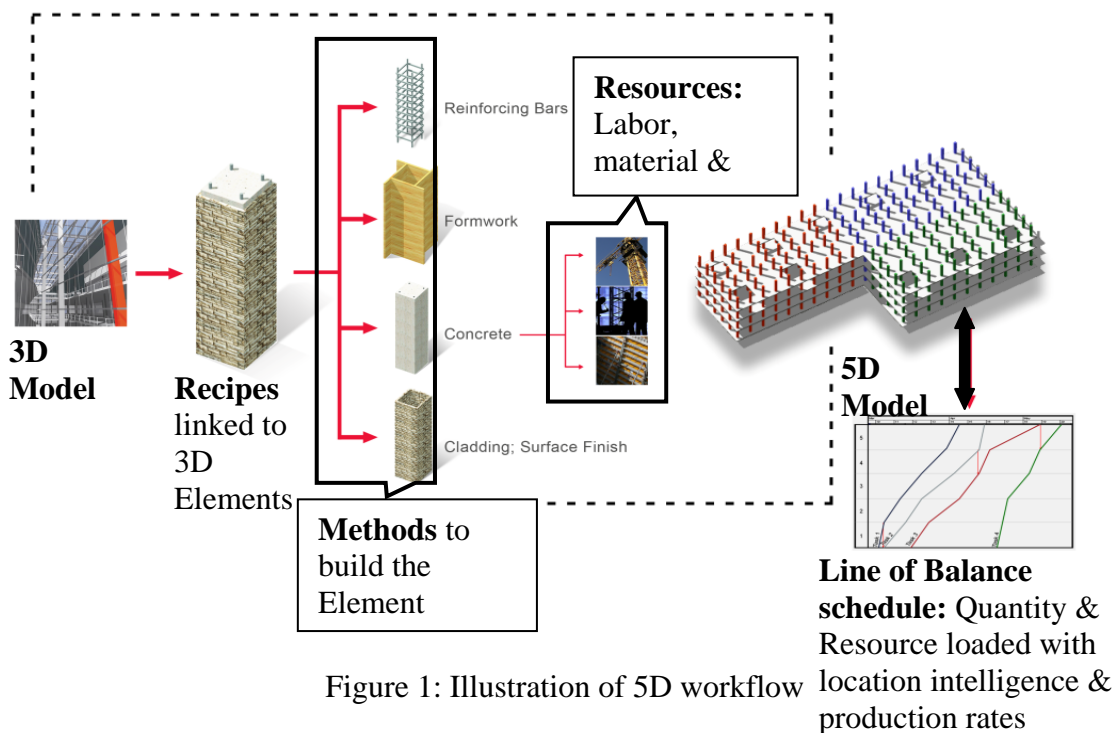


Figure 1: Illustration of 5D workflow

The model, quantities, and schedule are linked by defining a Location Breakdown Structure (LBS) in the model. Because model elements are physically located in locations, quantities can be calculated for each location. If a model element spans multiple locations, the quantities can be split or the element can be considered part of the location with larger quantities. Because the LBS is defined dynamically in the model, quantity takeoff can be automatically regenerated if there is a change to the LBS without need of manual takeoffs.

Information is linked by allocating methods to tasks. Tasks can contain methods that can be done by the same crew, have the same external dependencies to other tasks, and can be completely finished in a location before moving to the next location. Durations are calculated by summing the total man-hours (labor resources) related to each method in the location, and by dividing by the number of workers and shift length. This enables the model to drive the schedule durations. The schedule is optimized by changing the number of crews so that work can be performed continuously with a synchronized production rate (Kenley & Seppänen 2010). The outcome of this planning process is a location-based schedule. Because each of the resources can have unit prices, the schedule is automatically cost loaded. This can be used to automatically generate a 5D model where each model element belongs to a location and has one or more tasks associated with it. All elements know the start and finish dates in their location and the associated costs, completing the 5D workflow.

Detailed description of location-based planning is outside of the scope of this paper. A more detailed description, including the history of LBMS development and comparison to CPM, can be found in (Kenley & Seppänen 2010).

KAISER OAKLAND PROJECT

The Kaiser Permanente Oakland Medical Center Replacement Project, Phase II, consists of approximately 1,000,000 ft² (93,000 m²) of medical spaces, made up of a California Office of Statewide Health Planning Department (OSHPD) 339 bed, 12-story and basement, 684,000 ft² (63,500 m²) replacement hospital, 225,000 ft² (21,000 m²) ancillary hospital support building (local agency, non-OSHPD permit), 140,000 ft² (13,000 m²) medical office building (local agency, non-OSHPD permit), a 1,216 car garage and a 40,000 ft² (3700 m²) central utility plant, set on roughly 6 acres in densely populated downtown Oakland.

The replacement hospital is in response to OSHPD requirements (State Bill 1953) for the seismic retrofit of all hospitals in the state of California by 2013. As a result, Kaiser Permanente requested an aggressive, integrated approach for delivering the project in record time and under budget during the initial planning phases of the project. At the time, hospital projects in the San Francisco Bay Area were highly inflated from global prices as well as local demand for skilled builders. The team adopted several strategies to meet the deadline efficiently: early construction coordination with key stakeholders (subcontractors as design assist role), and phased permit review and approval based on construction milestones.

Designed to withstand a Maximum Credible Earthquake (MCE) from the nearby Hayward fault, the hospital has a complex structural system for the foundations, which will be the primary material presented in this paper. To give an idea of scale, the total concrete for the foundations is approximately 20,000 yd³ (15,300 m³), and is comprised of (340) 120 ft (36.5 m) deep drilled piers, a grade beam and pier cap system, with (16) largest pier caps under the bed tower measuring 19 ft *w* by 19 ft *l* by 10.5 ft *d*, (5.8m *w* by 5.8m *l* by 3.2m *d*) 10" (254mm) sub-slab, 42" (1066.8mm) sand layer, and 6" (152.4mm) slab on grade. The large pier caps will have embedded steel columns, spliced at 4 ft above finished floor, weighing approx. 27,000 lbs (12,250 kg).

Early involvement of the General Contractor, McCarthy Building Companies, Inc., and key subcontractors has allowed the team to focus on the design-to-

construction transition, and has shortened the overall duration by at least a year. A detailed review of the construction schedule through value stream mapping/pull-scheduling helped the team to prioritize design increments in order to hand over permitted segments earlier- with timelines required by the construction milestones. This review and integrated approach will be discussed further as it applies to the model updates.

RESEARCH HYPOTHESES AND METHODS

Our hypothesis regarding constructability was that by implementing parallel modelling more constructability issues would be found than by the traditional 3D method of clash detection alone. Constructability issues that would be captured this way would include errors and omissions in the 2D drawings which are not found by clash detection. This hypothesis was tested by evaluating the number of constructability issues found by virtually building the model and those issues which were not found by traditional methods.

The hypothesis related to quantity takeoff was that after building the cost database, the additional effort related to quantity takeoff would be much lower than with traditional approaches. This was evaluated by comparing the amount of hours related to keeping the quantity takeoff up to date to the hours spent in updating the traditional quantity takeoff. The quality of information was evaluated by comparing the quantities between the two takeoffs.

Regarding scheduling, the hypothesis was that the model-based schedule would result in better continuity of work, less fluctuation of resource, and a better synchronized schedule with decreased total duration without corresponding increase in resources. This hypothesis was tested by using the same quantities, logic, and productivity assumptions for both the CPM schedule and the location-based schedule and evaluating the resource loading, work continuity and production graphs (units of production as function of time) for the main trades related to the sub-structure scope.

RESULTS

CONSTRUCTABILITY

For a fully integrated model-based system, it is important to maintain the construction model at least at the same level of information as the design. For Kaiser Oakland, the modeling team has updated the model at design milestones, off of the OSHPD submittal, the re-submittal, and the final approval sets (2D drawings.) The hospital phased review split the building into three parts: sub and superstructure, exterior skin, and interior build-out. During the planning phase, these updates are required to obtain quantities from the model for continued schedule and cost planning.

Constructability reports were provided to the architect and engineers as a result of the update process. The modeling team maintains a system for identifying missing, incomplete, or conflicting information in the drawings which are identified during the process of converting design documents into construction model. The drawings themselves are the construction documents by contract; and much of the required notation for building is still on the 2D set, not the model. This is common practice in the industry and leads to a gap between plans and details. While the traditional reviews included experienced superintendent recommendations, and 3D clash

analysis, the added constructability reviews provided a comprehensive review of the cohesiveness of the document notation, dimensions, details, and references. For example, a discrepancy between a detail dimension and floor plan about the size and depth of a grade beam would lead to a field level question (RFI). On a project of this size, RFIs can exceed 6,000; the mitigation of these types of discrepancies ahead of field installation can substantially aid production flow.

Constructability reviews through modeling the design documents found more than 200 issues at each stage that were not found by the parallel traditional constructability process. Table 1 shows the number of additional issues found by construction phase and design stage. After a round of reviews, the comments were incorporated into the sets. A review at the next stage of the permit process brought out new issues from more drawing development and highlighted items that had not been resolved from previous reviews. The team has a running log with both open and closed comments.

Table 1: Open constructability issues by construction phase and design stage

	Design Phase/OSHPD Set		
	Submittal	Re-submittal	Approval
Hospital Substructure	74	85	77
Hospital Superstructure		204	188
Hospital Exterior Skin	50	45	44
Hospital Interiors/MEP	1178	future	future
Total	1302	334	309

MODEL-BASED QUANTITIES

The central piece of the integrated system is the model quantities. The team started the model creation and updates at Design Development phase, while elements were still shifting within the building. With the use of this platform, the team could analyze changes between one design iteration and the next. Since the model is integrated with schedule and cash flow, the model update can be an almost immediate prediction of new durations and cash flow.

Once the model was completed, the team used it to check quantities for the preparation of budgets at major design milestones. In the case of the concrete quantities, the team found that the quantities in the model were within a certain percentage of the estimator's quantities; in most cases, the difference could be explained by a small waste factor applied by the estimators. This increased the confidence for the team as they prepared updated budgets.

If quantity takeoff is considered in isolation, the results about time use were inconclusive. The time spent by estimators reviewing the drawings was offset by the time spent modeling the design. The true power of integration comes from the fact that the same modeling time also created the basis for integrated scheduling, cash flow, and constructability reviews. Additionally, visualization of the design in a 3D platform can reinforce an understanding of the building that is not particularly evident in 2D analysis. Over the course of the year, the estimating team generated 3 or 4 milestone estimates. For a project of this size, with a comprehensive review at the method level, the reviews take approximately a month. At the same time, the model

team updated the model to support quantity takeoff, scheduling quantities, cash flows and simulation files. The time spent for both processes is fairly comparable.

The quantities in the model were also used to evaluate subcontractor bids. With a visual reference in 3D, the team identified areas where bidders had deviated from the design in their assumptions. In the case of the concrete bids, the team generated a report of concrete by element and location, and used it to account for differences in bidders' responses. While evaluating the concrete bidders, the team was able to isolate specific areas where the bidder was not assuming correct quantities. This location-based analysis would have been difficult to achieve with manual quantity takeoff techniques.

SCHEDULE

The Location-Based Planning System was used to plan schedules in parallel to planning a CPM baseline schedule. The same Location Breakdown Structure was used in both schedules to make comparisons possible. Quantities were taken from the 3D model but the tasks and logic were taken from the P3 schedule (CPM) developed by McCarthy schedulers and superintendents. The same quantities and productivity rates were used in a Location-based CPM copy and an optimized Location-based schedule. The CPM schedule was replicated in location-based format by adjusting crew sizes to achieve durations close to CPM schedule. Exact same durations cannot be achieved because the duration in location-based schedule is a calculation based on quantities and crew sizes, however all activities had the start and finish date within two days of the CPM schedule.

The Location-based schedule was optimized by planning continuous flow for any critical and high risk tasks and by having the same crew size in each location. Production rates were optimized by changing crew sizes to achieve synchronized workflow with less wasted downtime in locations and preventing crowding of crews in a particular area. For example rebar crew size was balanced to reduce overall duration, reduce mobilizations, create continuity of work and reduce mobilizations for following trades. All optimization decisions were validated by discussions with McCarthy superintendents who will manage the field operations.

The results were analyzed by comparing the number of mobilizations (calculated by the number of times a new resource needed to be mobilized) for each trade with over 4,000 man-hours in the foundations, the total duration of foundations, and a visual comparison of the resulting flowline diagrams to identify wasted downtime and location crowding. Table 2 below summarizes these results. The location-based schedule decreased the duration six weeks with a decrease in the number of mobilizations for formwork, concreting and waterproofing, and a modest increase in peak resource need for concreting and a decrease in resource need for waterproofing.

Table 2: Comparison between CPM and location-based schedules

Trade	Mobilizations		Peak resource need	
	CPM	Location-based	CPM	Location-based
Formwork	2615	2397	63	60
Rebar	168	210	27	27
Concreting	840	780	41	48
Waterproofing	144	67	26	10
Total duration	55 wks	49wks		

Figures 2 and 3 below show selected tasks from the comparison (the full substructure schedule includes 125 task types). Small numbers related to lines indicate crew size in that location or line segment. CPM copy (figure 2) tends to have varying crew sizes in locations. The optimized location-based schedule (figure 3) has uniform crew sizes and synchronized flow. By removing the empty spaces in the schedule and allowing durations to vary between locations depending on quantity of work, the location-based schedule achieves a shorter total duration, better flow and more consistent crew sizes. The CPM schedule shows a long period of inactivity before the reinforcement of pier caps. This empty area was removed in location-based schedule by increasing the crew size after discussions with the concrete superintendent.

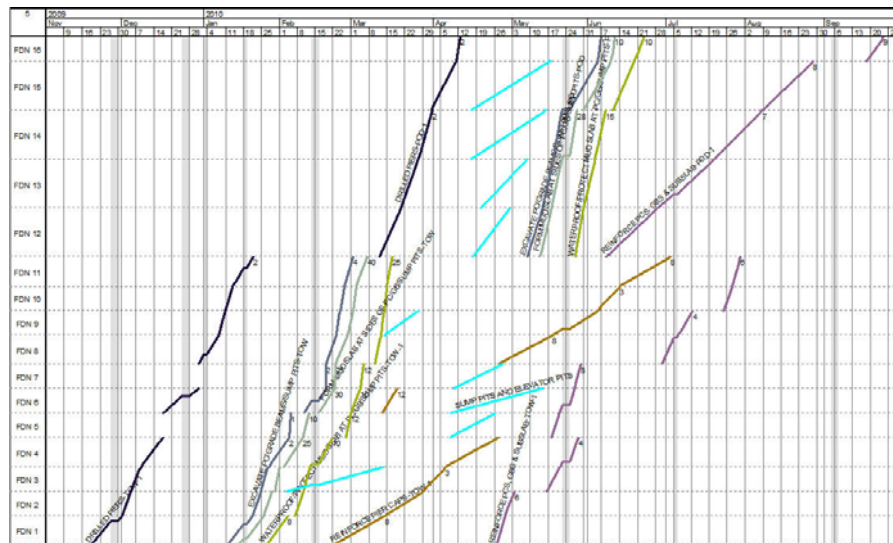


Figure 2: CPM copy of the schedule

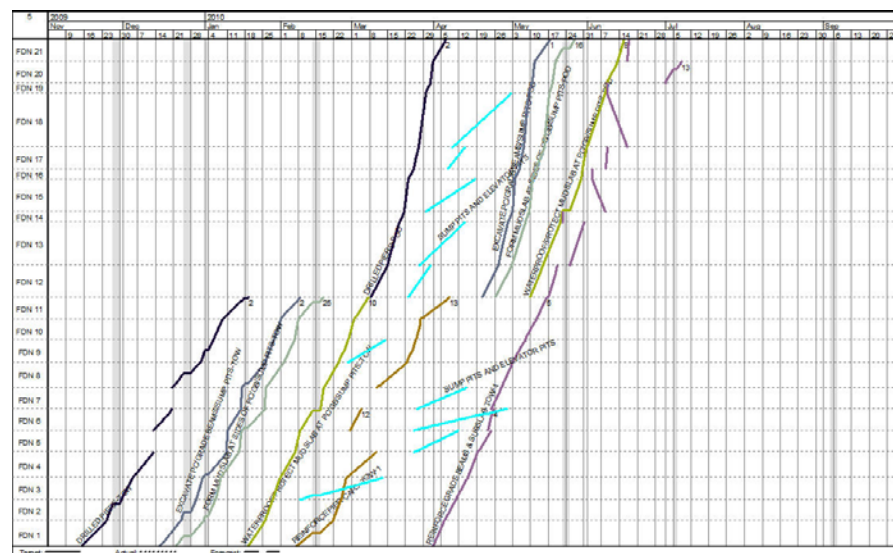


Figure 3: Optimized schedule

CHALLENGES

As with any major changes in a process or with a new tool, there is a certain amount of hesitancy from the team. This is a complicated, large-scale project, and the first major 5D implementation within McCarthy. Both McCarthy and Kaiser have established standard processes that have proven to be successful in the past. As a result, the implementation of 5D tools was done in parallel with the established mechanisms to provide validation to the 5D process against established processes. Additionally, the implemented 5D tools did not communicate with the established tools due to software limitations and conceptual differences.

The use of a separate construction 3D model, in lieu of the design team's 3D model, caused immediate questions within the team. In the pre-construction phase, the team used 3D models for coordination in lieu of coordination of 2D documents over a light table. Through early design-assist participation and using 3D models for coordination, the team has effectively reduced some of the traditional risk associated with 2D design. The question became a matter of whether or not 3D architectural model could be calibrated to provide quantities for model-based scheduling, productivity monitoring, automated takeoffs and cost tracking. This required greater level of detail than what could be expected from the architect's 3D model and from software's perspective it was not possible to calibrate architect's model. Hence, construction 3D model had to be built from scratch based on 2D drawings produced by the architect.

Similarly, there are conceptual differences between CPM and the location-based approach of creating and analyzing the schedule. Schedule development had to be done twice; once in CPM and then based on the same activities and logic the location-based schedule was developed manually. Also, any recommendations based on the location-based analysis had to be assimilated in CPM format manually. This was a challenge as it increased the margin for error.

In addition to that, the superintendents and the sub-contractors are looking at two different planning platforms and that has led to some confusion at times. Also this is the first implementation of a model-based, quantity-loaded, location-based schedule that any of the superintendents on the job have been involved in. Hence there was a learning curve for them to understand the flowlines, and how to interpret and optimize them and will continue to be a challenge as new superintendents are brought to manage the job as construction gets underway.

Estimating has also been a parallel effort. The case with estimating, though, is that the model quantities are a back-check to the McCarthy estimating group. As discussed previously, the model quantities were used to evaluate subcontractor bids. An improvement to this process would be further integration of the two systems.

CONCLUSIONS

Two out of three hypotheses received support in the case study. Regarding the first hypothesis, the creation of a construction model based on 2D drawings facilitated the finding of hundreds of constructability issues which were not found by using design models and 2D drawing analysis alone. The results related to the second hypothesis related to time savings in quantity take-off were inconclusive. The accuracy of information was comparable but the time spent creating the model was roughly equal to the 2D drawing analysis by the estimators. There are benefits of using the model

for quantities because it is easier to visualize quantities, and to integrate quantities to schedule and cash flow. By using the model-based quantities to optimize the schedule in a location-based planning, it was possible to decrease the duration of foundations and substructure by six weeks with a more continuous flow of resources. As a conclusion, the investment of creating a parallel construction model pays off for constructability and integrating quantities to schedule optimization. Creating a parallel construction model just for quantity take-off would result in minor, qualitative visualization and communication benefits.

FUTURE RESEARCH

The parallel processes of constructability, quantity take-off and scheduling will continue for other construction phases (superstructure, exterior, finishes and MEP). Foundations and substructure will start production in 2010. The integrated 5D system will be used in production control by updating progress information, generating schedule forecasts and updated cash flow based on actual progress. Progress will be quantified using the 3D model.

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