PROCESS-BASED COST MODELING TO SUPPORT LEAN PROJECT DELIVERY

Hung V. Nguyen[1], Iris D. Tommelein[2] and Glenn Ballard[3]

ABSTRACT

Using traditional cost models, with inputs of historical cost data and elemental quantities from product design, it is possible to point out which design alternative appears to produce more saving than the others. However, with the consideration of the cost implications of logistics and construction processes in different design alternatives, this saving may be less than anticipated or even negative. Following cost advice as outputs of traditional cost models, designers may decide to choose an alternative that is more costly to build.

The application of set-based design, production system design, and target costing in Lean Project Delivery System (LPDS) raises a need for a cost model which facilitates trade-off analysis between multiple alternatives of product and process design. Meanwhile, traditional cost models are incapable of supporting product and process design integration in LPDS. This paper describes a research initiative at Project Production Systems Laboratory (P^2SL) on investigating how process-based cost models support product and process design integration in LPDS.

KEY WORDS

cost modeling, lean project delivery system, target costing, production system design

INTRODUCTION

'Traditional' cost models such as regression models, bills of quantities and elemental estimating methods do not explain the systems they represent (Bowen et al. 1987). Such cost models are usually structured to represent building components or finished building and are thus concerned more with ends than with means. In traditional cost estimating practices, resources are allocated to cost centers (i.e., items in a Work Breakdown Structure (WBS)) based on historical cost data. Wilson (1982) criticized the reliance of these models on the use of historical data to produce deterministic estimates of building or components cost without explicit qualification of their inherent variability and uncertainty. Traditional methods focus on resources rather than processes, which are central to value creation.

As the result of decomposition practices, characterized by the use of a WBS, traditional cost estimating

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focuses on individual cost elements. In contrast, the integration of product and process design in LPDS requires cost estimating to focus on both cost elements and the interdependences between elements (i.e., systems). To facilitate this integration, cost modeling must be able to specify how process changes affect overall cost and overall value. In addition, the cost modeling process must facilitate trade-off analysis between incremental value and incremental cost.

This research preliminarily investigates if process-based cost modeling could be used effectively in evaluating integrated product and process design alternatives in LPDS.

CURRENT PRACTICES IN COST MODELING

A cost model is used to calculate the cost effect of a design change or to estimate an element of design or the whole design thus all estimating methods can be described as cost models (Beeston 1987). However, modeling is done in a broad level independently from specific projects (Skitmore and Marston 1999) while cost estimating is the usage stage of cost modeling and it is performed on a specific project. Fortune and Lees (1996) classified the development of the available cost models as follows: (1) 'Traditional' models (cost per square foot, elemental analysis, significant items, approximate quantities, detailed quantities, judgment, functional unit); (2) Mathematical (parametric modeling, expert judgment or Delphi techniques); (3) Knowledge based systems (Life cycle costing techniques: net present value, payback method, discounted cash flow); (4) Resource/process based models; (5) Risk analysis (Monte Carlo simulation); and (6) Value rated models.

Wilson (1982) criticized the reliance of traditional models such as on the use of historical data to produce deterministic estimates of building or components cost without explicit qualification of their inherent variability and uncertainty. Bowen et al. (1987) argued that traditional cost models do not help in explaining the systems they represent. These cost models are usually structured to represent building components or finished building and are thus concerned more on ends than on means.

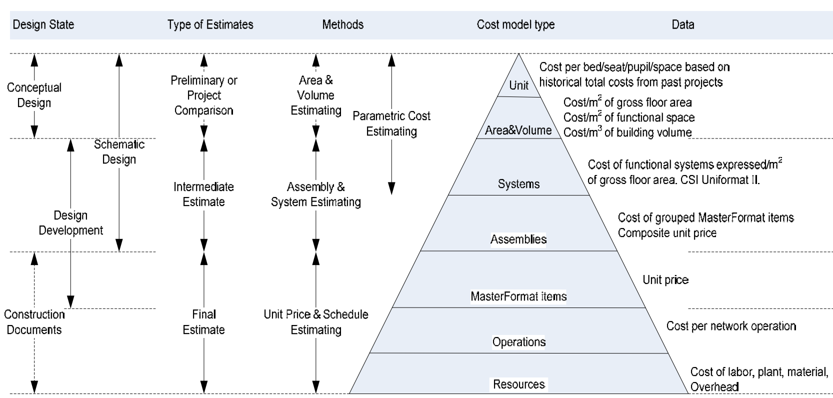

Figure 1. Types of cost models (adopted from Ferry 1999, Bledsoe 1992)

Bertelsen (2003) proposed that construction must be perceived as a complex system, operating on the edge of chaos. According to Williams (2002) this complexity comes from the structural complexity, which is related to the number of interdependence of elements, and from uncertainty in both methods and goals. In the views of uncertainty and structural complexity towards design and construction processes, the use of deterministic historical cost database to estimate cost of construction is not justifiable. For that reason, special cost models have been developed to deal with variability and uncertainty such as artificial neutral nets, fuzzy models, probabilistic models, and risk models. However, a recent research by Fortune and Cox (2005) on cost modeling practice on over 300 organizations in the UK revealed that these "new wave models" were not in widespread use while the "traditional single point deterministic types of models" were continued in overwhelming use. Figure 1 summarizes traditional cost models, their related estimating methods, their application in different states of design and their corresponding historical data.Related Work

Bowen et al. (1987) suggested that realistic cost models must simulate the construction process and take into account the cost implications of the process in which buildings are constructed, i.e., how different construction methods significantly affect cost. Recently, Li (2003) and Bargstädt (2004) attempted to simulate human resource activities on a high level of detail to determine process durations and associated process costs during simulation of production processes. By doing so the labor costs can be estimated while playing the production process on a site as a computer game by linking resources with processes. These approaches may achieve more accurate estimates, but they require detailed process data which may only be available in late construction documents phase. Moreover, it would be very time consuming and expensive to collect data and simulate construction processes on a high level of detail.

To facilitate estimators' judgment on cost implications of product customization, Staub-French and Fischer (2002) and Staub-French et al. (2003) proposed an activity-based cost model to help estimators customize a project's activities, resources, and resource productivity rates based on their preferences and the particular features in a given product model. Although this method may help estimators make more rational adjustment of project's activities and resource productivity rates it does not make explicit to estimators the cost implications of changes in process such as transportation and site logistics as the result of changes in product design.

PROCESS-BASED COST MODELING TO SUPPORT LEAN PROJECT DELIVERY

NEED FOR COST MODELS THAT SUPPORT LEAN PROJECT DELIVERY

During early design phases such as Schematic Design or Design Development, design decisions have the largest influence to final construction cost. Designers need comparative cost advice from cost consultants on different design alternatives to understand cost consequences of their design decisions. This early cost advice is to ensure that the estimated cost of the future facility is within an established budget.

According to Bargstädt and Blickling (2005), traditional cost models use deterministic time-based effort for the related working process, i.e., hours/m^3, taken as average values from historical cost database. This practice doesn't consider the following aspects: (1) Logistics processes such as packaging, transportation and storage; (2) The level of coordination between trades; and (3) Variations and uncertainties in the process. To account for those factors, cost estimators will need to imagine the process, make assumptions and use judgment to estimate duration and cost of a process. However, the outcomes of this imagination practice are not reliable since estimators may not have insight into all construction processes.

The Lean Project Delivery System (LPDS) is "a production management-based approach to designing and building capital facilities in which the project is structured and managed as a value generating process" (Ballard 2000). To align the physical design of a capital facility with customer's values, LPDS uses fundamental tools such as set-based design, production system design and target costing during Project Definition and Lean Design phases. Set-based design raises a need for evaluate and compare multiple design alternatives, production system design is used to integrate product design and process design, and target costing is characterized by using value engineering to resolve expected-allowable cost gap. The application of these tools raises a need for a cost model which facilitates trade-off analysis between multiple alternatives of product and process design.

Process-Based Cost Modeling and Production System Design (PSD)

Production System Design (PSD) "extends from global organization to the design of operations" (Ballard et al. 2001). Initially, work structuring in LPDS was mentioned as process design (Ballard 1999). Ballard et al. (2001) has expanded the scope of work structuring by equating it with production system design (PSD). In traditional project management, which is characterized by decomposition (i.e., using WBS), designers often leave interface resolution, such as dealing with issues of scope gap and scope overlap, to the builders (Tsao et al. 2004). While the design of each part may appear to be reasonable and logical upon inspection, the design of the overall assembly may actually be far from optimal. The uncertainties and errors created during design may prove to be detrimental to performance during installation (Tommelein et al. 1999). Therefore, the main principle of PSD is to integrate product design and process design for the whole project.

As the result of decomposition practice, conventional cost estimating focuses on individual cost elements. Meanwhile, the integration of product and process design in PSD requires cost estimating to focus on both cost elements and the interdependences between elements. To support PSD, a truly realistic cost model must be able to specify how changes in product design and process design affect overall cost and the output of that cost model must support trade-off analysis between incremental value and incremental cost. Process-based cost model, with advantages of embedding a process view, being able to identify the root causes and sources of variations (Back et al. 2000), can be used to provide cost implications of process changes in evaluating product and process design alternatives.

Process-Based Cost Modeling and Target Costing

Target costing has been in use in the Japanese automotive industry since the 1960s (Pennanen et al. 2005) and its principles has been employing as a new approach to project cost planning by the lean construction community. In manufacturing, target costing is used for the development of new products to reduce life cycle costs while ensuring quality, reliability, and customer requirements by examining all possible ideas for cost reduction at the product planning and prototyping phases (Kato, 1993).

In LPDS, target costing is defined as "a management practice that seeks to make cost a driver of design, thereby reducing waste and increasing value" (Ballard 2006a). To effectively implement target costing in construction projects, Pennanen et al. (2005) mentioned three steps: (1) define functional criteria; (2) determine target cost and (3) design to the targets. Ballard and Reiser (2004) suggested using cross functional teams to anticipate the cost consequences of different possible designs or design decisions, and limit eligibility to those that fit within the target cost. They also recommended value engineering (VE) and the use of integrated product/cost model as needed support tools for designing to target cost. Ballard (2006c) suggested a process of designing to target cost with emphases to the concurrency of design development and cost estimating, and the advantage of automated costing using computer models.

With the involvement of contractors in establishing target costs, information of constructability and implications of product/process changes on cost of different construction processes can be made explicit to designers and cost modelers. The early involvement of contractors would robustly support the development of process-based cost models. In turn, outputs of process-based cost models are useful in providing inputs for value engineering and selecting realistic target costs. Therefore, process-based cost models are potentially a good tool to support both target costing and design to target cost processes.

Process-Based Cost Modeling and Set-Based Design

Set-based design focuses on exploring many design options, the challenge is to analyze trade-offs of multiple design alternatives to come up with the optimum design solutions. A process-based cost model can help the estimator generate cost estimate of both the cost of the product and the cost of construction/installation processes related to the product. This information can be provided to designers and owners as cost advice in evaluating the tradeoff of multiple design alternatives.

MOTIVATING CASE STUDY

A windows installation process of a residential building with 100+ units in the Mission Bay district in San Francisco, California, was studied. In this project, an unusual number of 300 window variations specified by the architect. Many similar windows existed with minor variations in size or in the way they opened. In the opinion of the general contractor and the windows installation sub-contractor, these variations did not significantly contribute to either functionality or aesthetics of the project. Given the large number of variations, the windows were correctly labeled, but they were not bundled according to the floor where they were to be installed. As a result, windows in different floors were packed and delivered together. The reason was that the manufacturer optimized their productivity by grouping similar windows by similar types to fabricate in large batches. This local optimization delayed the installation process since workers did not have the windows they needed when they needed them.

13 truck loads were brought to the construction site, which totaled 465 windows. Since it was necessary to unload the windows off the truck and locate them to the room in which they would be installed, the windows installation sub-contractor had to implement extra steps to overcome the random packaging of the windows. Those steps were: (1) unload window packages to a temporary storage area on site, (2) unpack and sorted windows to group them according to designated floors, and (3) distribute windows to their corresponding rooms. The sub-contractor's record showed that these steps took 1,220 man hours to complete.

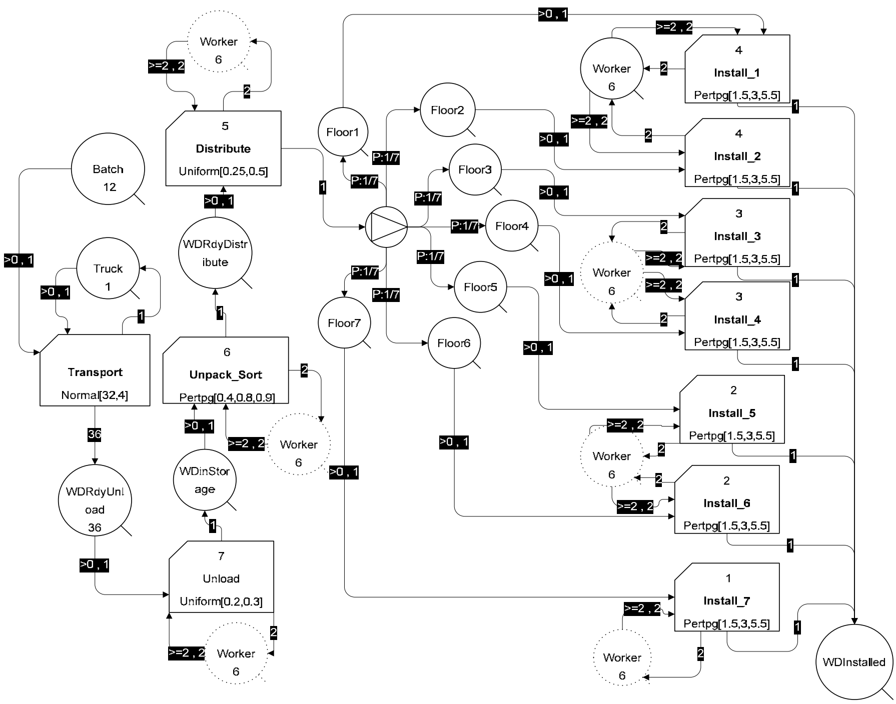

Figure 2. Current state model of window installation process

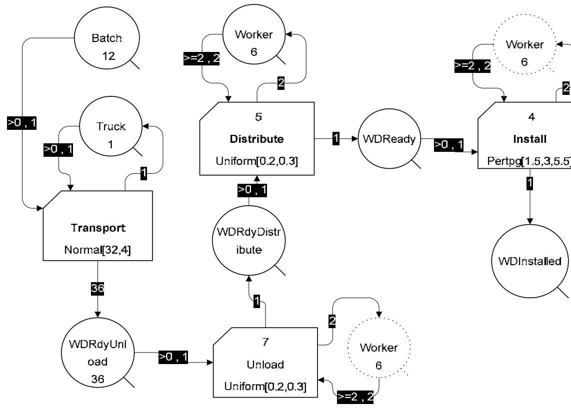

Figure 3. Future state model of window installation process

Process mapping technique was used to collect data of logistics and installation processes. Durations of activities were estimated through interviews and video taping. An EZStrobe© (Martinez 1996) simulation model was developed to simulate the current state of window installation process (Figure 2). The result of 1,000 replications indicates a total man-hour for unloading, unpacking, sorting and distributing processes has a mean of 1,231 man-hours with a standard deviation of 7.3 man-hours. Figure 3 demonstrates a simulation model of an improved window installation process with the assumption that windows are parked and delivered according to floors. In this manner, workers would only need to (1) unload window packages and (2) distribute window to their designated locations. In this revised process the unpacking and sorting activities were eliminated and there is no need of arranging windows in a temporary storage area.

The outcomes from 1,000 replications of the revised model revealed that a total man-hour for unloading and distributing processes has a mean of 465 man-hours with a standard deviation of 1.63 man-hours. Results from the two simulation models revealed a saving of 750 man-hours (or $30,000 with a $40/man-hour rate) can be achieved in site logistics of unloading and distributing windows. If the designer of the window system had been provided with this process information, he would have considered revising the product design solutions e.g., reducing the number of window variations. This change in product design would not only help reduce the cost of site logistics, but also streamline the fabrication process in the manufacturer side.

The window supplier, the window installation subcontractor, and the general contractor were aware of these process inefficiencies but the architect and the developer were not. As suggested by conventional practice, the developer of this project may use the cost data of this window system to budget for a window system in a new development and the new budget would include process wastes and inefficiencies from the previous window system such as the labor cost for unpacking and for random redistribution. With the participant of subcontractors during design using process mapping to make process cost explicit, these waste and inefficiencies can be identified and eliminated. By incorporating the cost implications of logistics and construction processes into the cost model, the output from process-based cost models can play a realistic role as a decision aid tool for designer than the output of conventional cost modeling methods that built on 'standard' construction processes.

ENVISIONED PROCESS-BASED COST MODEL TO SUPPORT LPDS

New process-based cost model will be created to be used in the design development phase. Its main objective is to support target value design processes including target costing, set based design and production system design. To do this, the cost model should be capable of making both process related cost and product cost explicit to designers when they are in the process of developing any design alternative. Process related cost may include cost implications of fabrication process, site installation, supply chain logistics, site logistics, and project general conditions. The best project environment in which to apply this cost model is in projects with Integrated Project Delivery (IPD) approach where key players from upstream to downstream of the project, such as architects, engineers, general contractors, specialty contractors, suppliers, and permitting agencies are members of the design team. In addition, this cost model can be used in conventional project delivery systems with integrated approaches such as Design-Build (DB), Construction Manager at Risk and Multi-Prime with DB approach where their structures allow early involvement of constructor in the design process. Since this early involvement is not permitted in Design-Bid-Build (DBB) project delivery model, a process-based cost model has few opportunities for effective application in DBB. Key steps in developing a process-based cost model are envisioned as follows:

(1) Establish process cost database using process map and process simulation

With early involvement in design, downstream players provide data and knowledge to map out fabrication, logistics, and installation processes of design assemblies. Process maps play the role of a platform for the multidisciplinary team to provide input data such as process steps, time, cost, inventory, constraints and coordination requirements from each party. If there is sufficient data, process will be simulated using discrete event simulation, which is well-suited to model construction simulation as pointed out by Tommelein et al. (1994). A library of process maps and/or process simulation models can be established with inputs from contractors, subcontractors and suppliers to play the role of process cost database. This becomes worthwhile if the mapped or simulated processes are reused in future.

(2) Create process-based cost models

Once the team agrees on a process map, process cost implications will be calculated and recorded in a way that they would provide useful cost feedback to design. Process simulation helps formulate process cost changes due to changes in product design. When it comes to specific applications, cost estimators can adjust process maps and simulation models to reflect changes in work method and sequence to generate cost accordingly. The level of detail in simulation is chosen to fit the needs of the decision maker who will evaluate design alternatives. As a result, process cost can be calculated using outputs from simulation models which simulate the work process.

(3) Integrate process cost data to BIM

Process cost data will then be incorporated to Building Information Modeling (BIM) to create an integrated product/process/cost model. When designers consider a change in the characteristic of an assembly (e.g., form, type, material) they will be instantly provided with related changes in both product cost and process cost.

Qualitative benefits of process-based cost model may include:

- Cost output of process simulation models is probabilistic not deterministic, taking into account the inherent variability and uncertainty of construction processes.
- The cost model takes into account the cost implications of the process in which building components are fabricated, delivered and installed, revealing how product changes lead to process changes and result in cost changes. Provide chances for identifying inefficiencies in the process for improvement. As a result, the cost model concerns more with means than with ends.
- Using process mapping technique, process-based cost models help create a platform to utilize contractor's experience on work method and constructability analysis. The cost model can be adjusted according to changes in product and process design to generate corresponding costs.
- By integrating process cost data to BIM, an integrated product/process/cost model would help streamline design process and reduce rework in the Design/Estimate/Redesign iterative.

ENABLERS FOR APPLICATION OF PROCESS-BASED COST MODELING

INTEGRATED PROJECT DELIVERY

Integrated Project Delivery (IPD) is a collaborative project delivery approach that integrates people, systems, business structures and practices into a process that ties together the insights of all participants to "optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction" (AIA's California Council 2007).

IPD has an advantage of encouraging team involvement in the early phases of design. It allows downstream players (e.g., general contractor, specialty contractors, suppliers), who have the most process related knowledge and experience such as fabrication, logistics, work method and trade coordination to provide inputs to design phases. Thus, the early involvement of constructors in design facilitates the data collection and team collaboration for the application of process-based cost modeling.

BUILDING INFORMATION MODELING (BIM)

According to the National Building Information Standard (NBIMS 2007) project committee, BIM is "a digital representation of physical and functional characteristics of a facility." BIM can be applied to create early design alternatives to capture early planning data of function, size, shape, quality and cost and it can be used to validate proposed design solutions against the owner's requirements (NIBS 2007).

BIM models contain dimensions and characteristics of design elements, therefore it has the potential for object quantities to be generated automatically. Early BIM-based cost modeling solutions such as Innovaya, U.S. Costs or Vico Estimator have taken this advantage. For example, Innovaya created a visual take-off and visual estimating methods working in conjunction with Revit models (Khemlani 2006). Current BIM-based estimating solutions are more efficient and accurate than conventional estimating methods as they eliminate the need for measuring and manual quantity take-off, since major dimensional information is already captured within the model. Process cost data which comes out of the process-based cost model can be entered to BIM as a property of an assembly or a system, designers will instantly have cost feedbacks on how process cost is affected by their changes in product design.

CONCLUSIONS

As the preliminary results of this study, process-based construction cost modeling may be used to assist designers, owners, and builders of facilities in resolving a variety of decisions, such as evaluating the cost of different design alternatives, establishing the cost impact of design changes and budgeting construction costs. In addition, process mapping and process simulation appears to be a practical tool to construct process-based cost model. Furthermore, the integration of a process-based cost data to BIM help cost estimators provide cost feedbacks in a timely manner to support project teams in implementing trade-off analysis and making decisions. However, further study and experiments are needed to assess the applicability and feasibility of those preliminary results. In the next steps of the study, process-based cost modeling method will be experimented in different projects to test its effectiveness on supporting product and process design integration in LPDS.

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REFERENCES

American Institute of Architects' California Council (2007) "Integrated project delivery: a guide". Version 1. Available online at http://www.aia.org/ SiteObjects/files/IPD_Guide_2007.pdf (assessed 04/17/2008)

Back, W. E., Maxwell, D. A., and Isidore, L. J. (2000). "Activity-Based Costing as a Tool for Process Improvement Evaluation", Journal of Management in Engineering, ASCE, March/April, 48-59.

Ballard, G. (1999). "Work structuring." *White Paper-5*, Lean Construction Institute, Ketchum, Id., (http://www.leanconstruction.org/pdf/WP5-WorkStructuring.pdf).

Ballard, G. (2000). "Lean Project Delivery System." *White Paper* 8, Lean Construction Institute.

Ballard, G., Koskela, L., Howell, G., and Zabelle, T. (2001). "Production System Design in Construction" *Proceedings of the 9th Annual Conference of the International Group for Lean Construction*, Singapore.

Ballard, G. (2006a). "Rethinking project definition in terms of Target costing" *14th Annual Conference of the International Group for Lean Construction*, Santiago, Chile, pp 77-89.

Ballard, G. (2006c). "Innovation in Lean Design" Power Point presentation. Available at http://www.leanconstruction.org/files/Mid_Feb_Updates/Introduction_to_Lean _Construction/T5-InnovationsinLeanDesign.pdf.

Ballard, G., and Reiser P., (2004). "The St. Olaf College Field house Project: A Case Study in Designing to Target Cost," *12th Annual Conference of the International Group for Lean Construction*, Elsinor, Denmark, pp. 234-249.

Bargstädt, H.J., and Blickling, A. (2004). "Effective cost estimate and construction processes with 3D interactive technologies: Towards a virtual world of construction sites". *Proceedings of the Xth International Conference on Computing in Civil and Building Engineering*. ICCCBE, Weimar, Bauhaus University.

Bargstädt, H.J., Blickling, A. (2005). "Determination of process durations on virtual construction sites". *Proceedings of the Winter Simulation Conference WSC*, December 4-7. Orlando, USA.

Bledsoe, J.D. (1992). Successful estimating methods… From Concept to Bid. Kingston, MA, R.S. Means.

Beeston, D. T. (1987). A future for cost modelling. Building Cost Modelling and. Computers. P. S. Brandon, E & F N Spon: 15-24

Bertelsen, S. (2003). "Complexity – Construction in a new Perspective". Proceedings of the 11th Conference of the IGLC, Blacksburg.

Bowen P.A., Wolvaardt, J.S., and Taylor, R.G. (1987). "Cost modeling: a process-modeling approach". *Building cost modeling and computer*, 15-24, E&FN Spon, London.

Ferry D.J., and Brandon P.S. (1999). *Cost planning of buildings*. Oxford, Malden, MA, Blackwell Science.

Fortune, C., Lees, M. (1996). "The relative performance of new and traditional cost models in strategic advice to clients", The Royal Institution of Chartered Surveyors (RICS) Research Paper series, London

Fortune C., and Cox O. (2005). "Current practices in building project contract price forecasting in the UK", *Engineering Construction and Architectural Management Journal*, August, 12(5), pp. 446-457.

Kato, Y. (1993). Target Costing support system: lessons from leading Japanese companies. Management Accounting research, 4, pp.33-47.

Khemlani, L. (2006). Visual Estimating: Extending BIM to Construction. Available at: http://www.aecbytes.com, (assessed 03/01/2007).

Li, H., Ma, Z., Shen, Q., Kong, S. (2003). Virtual experiment of innovative construction operations. *Automation in Construction*, 12(5): 561-575.

Martinez, J.C. (1996). STROBOSCOPE - State and Resource Based Simulation of Construction Processes. Doctoral Dissertation. Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI.

National Institute of Building Sciences (NIBS) (2007). The National Building Information Modeling Standard™ (NBIMS) Version 1.0-Part 1: Overview, Principles, and Methodologies. Available on line at http://www.facilityinfor mationcouncil.org/bim/pdfs/NBIMSv1_ConsolidatedBody_11Mar07_4.pdf (assessed 04/15/2007)

National Building Information Standard (NBIMS) (2007). Facility Information Council. National Building Information Standard project. http://www.facilityinformationcouncil.org/bim (accessed 12/15/2007).

Nicolini D., Tomkins C., Holti R., Oldman A. and Smalley M. (2000). "Can Target Costing and Whole Life Costing be Applied in the Construction Industry?: Evidence from Two Case Studies". British Journal of Management, Vol. 11.

Pennanen, A., Haahtela, Y., and Vaananen, H. (2005). "Workplace planning and target costing techniques in project and facility management", CIB 2005 Conf., Helsinki.

Skitmore M., Marston V. (ed.) (1999). *Cost Modeling.* E FN Spon, London.

Staub-French, S., Fischer M. (2002). "Generating and Maintaining Activity-based Cost Estimates with Feature-Based Product Models." *19th International Symposium on Automation and Robotics in Construction,* Washington D.C., USA, Sep. 23-25

Staub-French, S., Fischer, M., Kunz, J. and Paulson, B. (2003). "A Generic Feature-Driven Activity-Based Cost Estimation Process." *Advanced Engineering Informatics*, 17(1), 23-39

Tommelein, I.D., Carr, R.I., and Odeh, A.M. (1994). "Assembly of Simulation Networks using Designs, Plans, and Methods." ASCE, *Journal of Construction Engineering and Management*, 120 (4) 796-815.

Tommelein, I.D. (1999). "Lean Construction Experiments using Discrete-event Simulation: Techniques and Tools for Process Re-engineering?" *International Journal of Computer-Integrated Design and Construction*, CIDAC, Special issue on Construction Process Re-engineering, 1 (2) 53-63, September.

Tsao, C.C.Y., Tommelein, I.D., Swanlund, E., and Howell, G.A. (2004). "Work Structuring to Achieve Integrated Product-Process Design." ASCE, *Journal of Construction Engineering and Management*, Nov/Dec, 130 (6) 780-789.

Williams, T. (1999). "The need for new paradigms for complex projects". International Journal of Project Management ,17(5), pp. 269-273.

Wilson A. J. (1982). "Experiments in Probabilistic Cost Modeling". Building Cost Techniques: New Direction, P. S. Brandon, ed., E&FN Spon, London.