Process-Based Cost Modeling to Support Target Value Design

by

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Abstract

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In the current practice of collecting construction cost data, the cost of an installed component is compiled by adding up the cost of materials plus the cost of all resources used to install that component. This total includes inefficiencies and wastes which are inherent in construction processes, especially in projects that do not rigorously use methods to eliminate process waste or that do not use continuous improvement. Traditional cost models such as Parametric, Assembly and System, and Unit Price and Schedule models rely on historical data to model the cost of new designs. These cost estimates are inflated by the wastes embedded in the historical databases, and result in increased estimated task durations and excessive estimated resource needs.

In Target Value Design (TVD), product- and process design are integrated and the design team needs rapid cost feedback to trade off design alternatives. However, traditional cost models do not reflect cost changes due to changes in process design. Therefore, a cost model that takes into account the cost implications of logistics and construction processes can better support TVD in integrating product- and process design. This raises a need for an alternative cost modeling method, which must be able to specify: (1) cost changes due to changes in product design (i.e., changes in materials, shapes, or dimensions), and (2) cost changes due to changes in process design (i.e., changes in sequencing, logistics plans, or construction processes). This dissertation provides a framework for a Process-Based Cost Modeling (PBCM) method including three phases: (1) collecting process- and cost data, (2) mapping process- and cost data to objects of a Building Information Model (BIM), and (3) providing cost feedback to inform TVD.

This dissertation develops a theoretical understanding of cost modeling in TVD and argues for the use of a PBCM to support TVD during the Design Development phase. It presents processes and tools that could aid in its implementation. It also examines the role of BIM in implementing the PBCM framework and explains the role of process modeling in a virtual construction environment in supporting PBCM.

This dissertation delivers a proof of concept of a PBCM framework and validates it through case studies and professionals' evaluations. The first case study analyzes conventional practices of designing, procuring, estimating, and installing a window system in a residential project in

San Francisco, CA. The second case study investigates the application of the model-based process simulation, the PBCM, and the Choosing By Advantages (CBA) Decisionmaking System to evaluate alternatives of Viscous Damping Wall (VDW) installation in the Cathedral Hill Hospital (CHH) project in San Francisco, CA. The third case study examines the application of a software tool to integrate product- and process cost of the VDW system with a BIM model.

Research findings illustrate the effectiveness of PBCM in providing rapid cost feedback to designers that facilitates the process of design to targets. In addition, PBCM helps to make both process-related cost and product cost explicit to designers when they are analyzing design alternatives. Further research can refine steps of PBCM applied in Design Development and explore the application of PBCM in design phases other than Design Development such as Conceptual Design or Construction Document phases. Further research is also needed to advance tools to facilitate the implementation of PBCM in the Lean Project Delivery System™.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ACRONYMS

ABC	Activity-Based Costing
AEC	Architecture, Engineering, and Construction
ANN	Artificial Neural Network
BIM	Building Information Model(ing)
BOQ	Bill of Quantities
CBA	Choosing By Advantages
CHH	Cathedral Hill Hospital
DB	Design-Build
DBB	Design-Bid-Build
DES	Discrete Event Simulation
GC	General Contractor
IFOA	Integrated Form of Agreement
IGLC	International Group for Lean Construction
IPD	Integrated Project Delivery
LPDS™	Lean Project Delivery System™
MEP	Mechanical-Electrical-Plumbing
NBIMS	National Building Information Model Standard
NIBS	National Institute of Building Sciences
OCCS	OmniClass Construction Classification System
OSHPD	Office Statewide Health Planning and Development
P^2SL	Project Production Systems Laboratory
PBCM	Process-Based Cost Model(ing)
PDCA	Plan-Do-Check-Act
PSD	Production System Design
QTO	Quantity Take-Off
RFI	Request For Information
TVD	Target Value Design
VSM	Value Stream Map
VDW	Viscous Damping Wall
WBS	Work Breakdown Structure

CHAPTER 1. INTRODUCTION

This chapter introduces the background of this research, defines key terminology and concepts related to this study, and presents the need for research. The chapter states research objectives, and then presents research questions. This chapter closes with a summary description of the dissertation structure.

1.1 INTRODUCTION

This dissertation reviews limitations of traditional cost modeling methods and explores how a process-based cost modeling method may be established and applied to facilitate Target Value Design (TVD) (explained in section 3.2.2) in a Lean Project Delivery System™ (LPDS™) (explained in section 1.2).

Researchers have been criticizing traditional cost models for their focus on resources rather than on processes. 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 estimates of building or component cost without explicit qualification of their inherent variability in product design and installation processes. Bowen et al. (1987) argued that traditional cost models such as regression models, bills of quantities, and elemental estimating methods do not explain the systems they represent. Such cost models are usually structured to represent building components or a finished building and are thus concerned more with ends than with means.

In TVD, product design goes along with process design and rapid cost feedback is required to facilitate trade off analysis between multiple design alternatives. Traditional cost models are inadequate in reflecting cost changes due to process changes (explained in section 1.3.1). Therefore, this research will examine if a cost model that takes into account the cost implications of logistics and construction processes can better support TVD in integrating product- and process design than traditional cost models do.

In the construction industry, process-based cost estimating has been mostly practiced by contractors to generate unit costs of significant activities (e.g., activities that consume large amounts of resources) for bidding and construction planning purposes (Ferry et al. 1999). The methods of calculating process-based costs vary. Data are mainly collected for a contractor's internal usage. In a TVD setting, early involvement of contractors, specialty contractors, and suppliers in design makes process information such as fabrication, standardization, transportation, inventory, and site logistics available to architects and engineers. With their experience of various work methods and up-to-date process cost data, a TVD team could estimate costs for different product- and process design alternatives. Therefore, there is a research opportunity to investigate how process-based cost modeling methods may be established and applied in the design phase of a project.

1.2 CONCEPTS AND TERMINOLOGY

This section defines key concepts and terminology related to this study, and presents them in alphabetical order.

Cost Model: a set of mathematical relationships to formulate a cost calculation in which outputs, namely cost estimates, are derived from inputs, such as quantities of resources and price. Cost models are used to calculate the cost effect of a design change or to estimate the cost of an element of design or the whole design. Thus all estimating methods can be described as cost models (Beeston 1987).

Cost Modeling: the process of formulating a cost model to estimate cost at some level of abstraction of a component or a system under design.

Discrete Event Simulation (DES): a computational technique for modeling, simulating, and analyzing systems and processes. Law and Kelton (2000) describe a discrete system as "one for which the state variables change instantaneously at separated points in time." In DES, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system (Robinson 2004). DES is well-suited to model construction processes (Odeh et al. 1992; Tommelein et al. 1994).

Just-in-Time: a "system for producing and delivering the right items at the right time in the right amounts" (Womack and Jones 2003).

Lean Project Delivery System™ (Figure 1.1): 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).

Lean Design: In the Lean Design phase, the Concept Design from Project Definition will be developed into a product design and a process design. To integrate the product- and process designs, specialty contractors will be involved in the design process, assisting with selection of equipment and components and with process design (Ballard 2000).

Model: "a representation of a real-world situation and usually provides a framework with which a given situation can be investigated and analyzed" (Halpin and Riggs 1992).

Process Mapping: a management tool for understanding how value is delivered; it captures knowledge about processes and then represents that knowledge using generally accepted signs such as boxes and arrows (Adams 2000). Process mapping helps visualize the flow of material and information as well as the links between and beyond the single process level (Rother and Shook 2003).

Process: a collection of activities connected by a flow of material and information that transforms various inputs into more valuable outputs (Gray and Leonard 1995).

Product: a physical component, assembly, or system of a construction facility.

Set-Based Design (SBD): a design methodology whereby "designers explicitly communicate and think about sets of design alternatives at both conceptual and parametric levels. They gradually narrow these sets by eliminating inferior alternatives until they come to a final solution" (Ward et al. 1995).

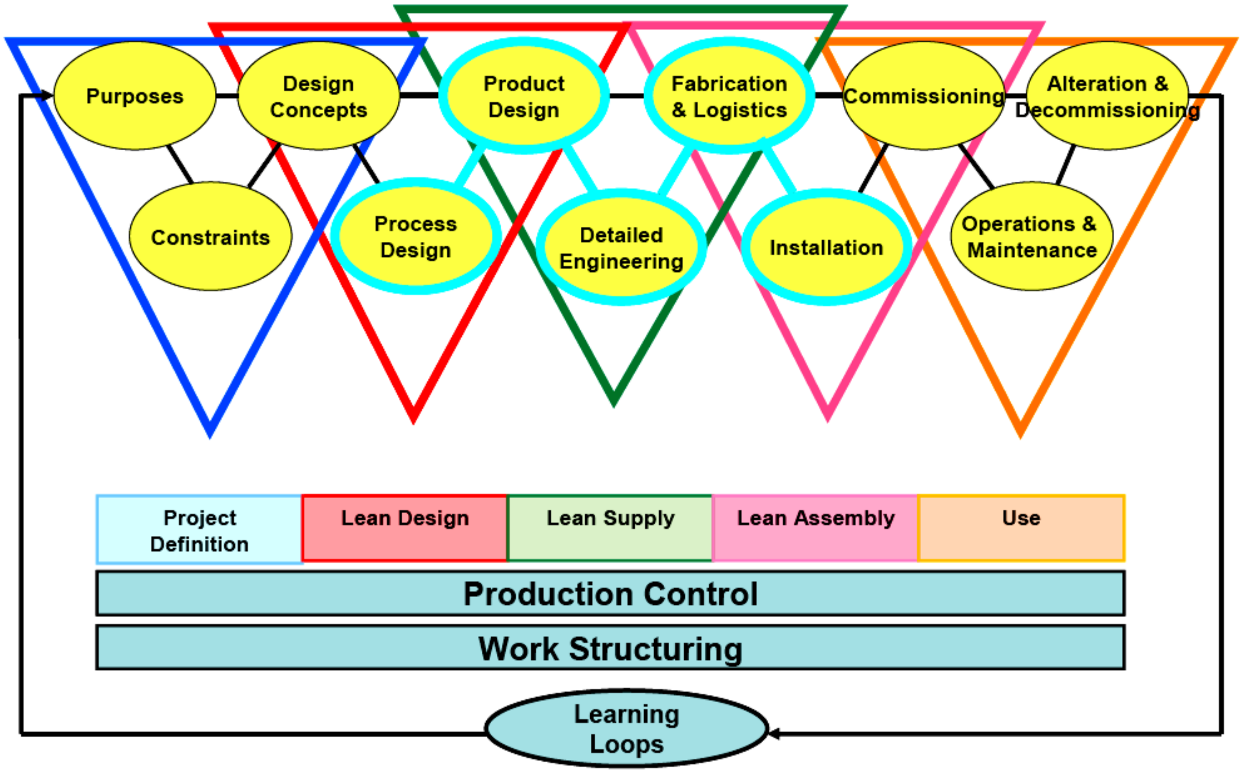


Figure 1.1 Lean Project Delivery System™ (Ballard 2006a)

Target Costing: a management practice that seeks to make cost a driver of design, thereby reducing waste and increasing value (Ballard 2006a). The process of designing to Target Cost requires the concurrency of Design Development and cost estimating (Ballard 2006c).

Target Value Design (TVD): broadens the concept of Target Costing, with the focus on "value." TVD covers additional design criteria beyond cost, including constructability, time, process design, design collaboration, etc. (Lichtig 2005). TVD spans from the Project Definition phase to the Lean Design phase and its principles help steer a design team to meet established design criteria. TVD encompasses five key principles: (1) Target Costing, (2) Work Structuring, (3) Set-Based Design, (4) Collaboration, and (5) Collocation (Macomber et al. 2007).

Traditional Cost Models: In this study, cost models using regression techniques, bills of quantities, or elemental analysis (cost-per-square-foot) are referred to as traditional cost models (refer to section 3.3).

Work Structuring: "the development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts with the goal of making work-flow more reliable and quick while delivering value to the customer" (Ballard 2000). Ballard et al. (2001) broadened the scope of work structuring by equating it with Production System Design (Explained in section 3.2.4).

1.3 NEED FOR RESEARCH

This section is intended to answer the question "Why is this research worth pursuing?" by identifying the problems of current practices in cost modeling and the needs for researching an alternative method of cost modeling.

1.3.1 LIMITATIONS OF TRADITIONAL COST MODELS

Figure 1.2 summarizes traditional cost models, their related estimating methods, their applications in different states of design, and the types of cost data they are associated with.

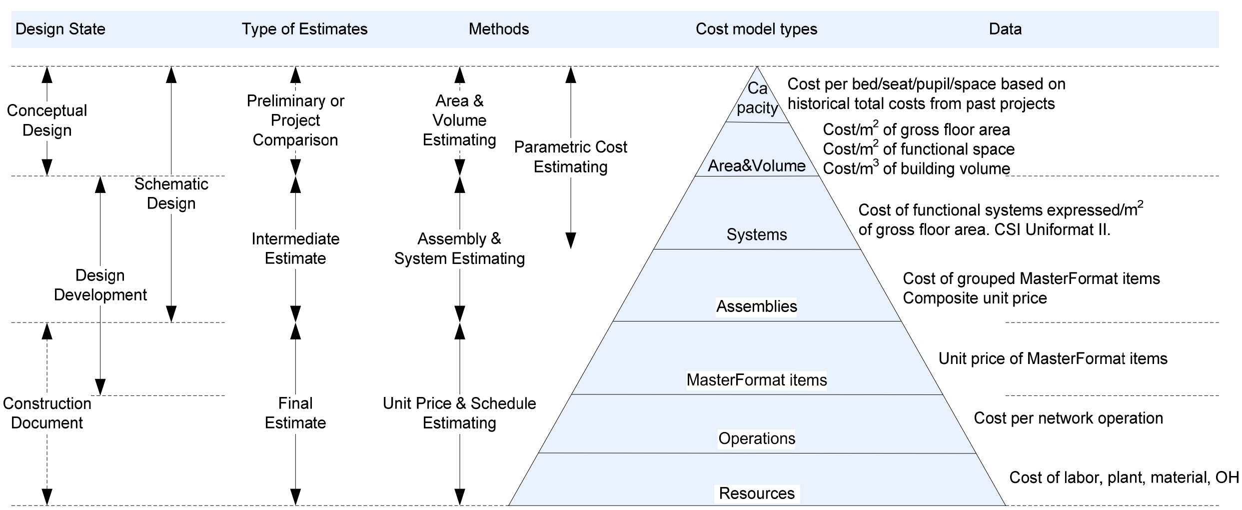


Figure 1.2 Types of cost models (adopted from Ferry 1999, Bledsoe 1992)

Beeston (1973) pointed out that, in analyzing design alternatives, a change that has little effect on product quantity could cause a significant change in a contractor's operation. "A change in product design affects the choice of plant, assignment of workers, durations of tasks and consequently affect bidding price. In contrast, some changes in product design to reduce the measured work content that are considered more economical by designers may not be fully achieved in the construction phase since the contractor may not be able to allocate fewer resources to a design change as anticipated by designers for reasons of plant capacity or continuity of operation" (Beeston 1973). He also criticized cost models using bills of quantities and historical cost data for the reason that cost items fail to represent the true work contents of the item as the contractor diverts costs in various directions and in particular towards costs related to mobilization. Therefore, these cost models are not capable of quantifying effects of design changes.

Wilson (1982) also 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. Tommelein (2003) augmented this notion by mentioning “a world in which no variation or uncertainty is recognized gets modeled deterministically thus are too optimistic.” Bertelsen (2003) proposed that construction must be perceived as a complex system, operating on the edge of chaos. According to Williams (1999), this complexity comes from the structural complexity, which is related to the number of interdependences between 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 databases 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 fuzzy models, probabilistic models, and risk models. However, recent research by Fortune and Cox (2005) on cost modeling practices of 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’ continued to be in overwhelming use.

Traditional cost models such as Parametric (refer to section 3.3.2.2), Assembly and System (refer to section 3.3.2.4), and Unit Price and Schedule models (refer to section 3.3.2.5) adjust historical cost data from similar works that are distributed to construction component to calculate cost of design alternatives; these data contain very limited process information to support trade off analysis in TVD. Bowen et al. (1987) suggested that models will be more realistic if they simulate the construction process and take into account the cost implications of the way in which buildings are physically constructed, on the grounds that different construction methods will significantly affect cost.

Historical cost databases provide average productivity and average cost measured based on completed projects. The problem is that those projects may or may not have used methods to eliminate process waste or improve productivity. Consequently, because historical databases may include waste, using these productivity- and cost data will tend to increase estimated durations, drive up estimated resource needs and thus inflate estimated cost.

Using traditional cost models, with inputs from historical cost data and elemental quantities from product design, it is possible to point out which design alternative appears to produce more savings than the others. However, with the consideration of cost implications of process changes in different design alternatives, these savings may be less than anticipated or even negative. Following cost advice as output of traditional cost models, designers may decide to choose an alternative that in effect is more costly to build. Therefore, traditional cost models are incapable of supporting decision making on TVD process.

1.3.2 Need for a Cost Model that Supports TVD in the LPDS™

During early design phases such as Schematic Design or Design Development, design decisions have the largest influence on the final construction cost (AIA 2007). 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 will be within an established budget while delivering target values.

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 databases. This practice doesn't make explicit the following aspects: (1) Logistics processes such as packaging, transportation, or storage; (2) The level of coordination between trades; and (3) Variations of construction/installation process implementation (Nguyen et al. 2008). To account for those factors, cost estimators need to imagine the process, make assumptions, and use judgment to estimate durations and costs. However, the outcomes of their imagined practices are not reliable since estimators may not have insight into every construction processes. In addition, their imagined processes are not verifiable because those processes are often not documented.

To align the physical design of a capital facility with the customer's values, TVD uses fundamental lean tools and principles such as SBD, PSD, Target Costing, IPD team (collaboration), and collocation (Figure 1.3). Following an IPD approach allows early participation of contractors and suppliers in the design phase. Collocation facilitates communication and team decision making. SBD helps to generate multiple design alternatives. PSD helps to integrate product- and process design. Target Costing helps to close or at least diminish the expected-allowable cost gaps. The application of TVD often results in multiple design alternatives with different product costs, process costs, as well as product features. As pointed out in section 1.3.1, traditional cost modeling methods are insufficient to trade off multiple alternatives of product- and process design in order to support TVD. This raised a need to search for an alternative cost modeling method that is able to specify how process changes affect overall cost and value.

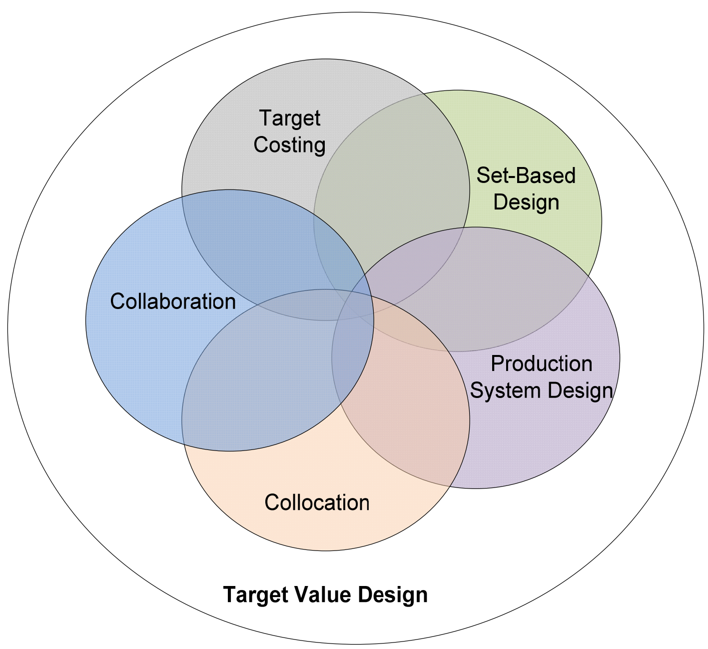


Figure 1.3 Fundamental components of TVD

To support TVD, a cost model should be able to specify: (1) cost changes due to changes in product design (i.e., changes in materials, shapes, or dimensions), and (2) cost changes due to changes in process design (i.e., changes in sequencing, logistics plan, or construction processes).

1.4 RESEARCH OBJECTIVES

(1) The first objective of the proposed research is to develop and validate a cost modeling method that supports TVD in LPDS™.

(2) The second objective of this research is to develop a method of collecting process- and cost data for the proposed cost modeling method.

(3) The third objective of this research is to establish a framework to integrate process cost data in BIM.

1.5 RESEARCH QUESTIONS

Based on the above objectives I developed the following research questions:

(1) How could PBCM support TVD in LPDS™?

(2) What could a process-based cost modeling method look like?

- When should PBCM be used in the TVD process?
- Who should be involved in the PBCM?
- How does the IPD team make decisions when considering factors other than cost?

(3) How should process cost data be collected to support PBCM?

(4) How should PBCM integrate process cost data to BIM?

1.6 RESEARCH SCOPE

I establish the scope of this research within the LPDS™ while focusing on projects in the building construction sector. This research focuses on developing a PBCM method to support the cost evaluation of multiple product- and process design alternatives. The study focuses on the application of the PBCM method in the Design Development phase (refer to Chapters 4 and 8 for the rationale of the choice). This study does not to evaluate the applicability of the PBCM method during the Conceptual Design phase or the Construction Document phase. The PBCM will be validated through case studies as described in Chapter 3.

1.7 DISSERTATION STRUCTURE

Chapter 2 presents the research methodology used in this dissertation. In this chapter, I describe the application of case-study research and action research to develop the PBCM framework.

Chapter 3 reviews the professional and research developments that have influenced this study and is divided into five sections. Section 1 introduces LPDS™, section 2 presents the literature on Target Costing and TVD as well as tools that support TVD, section 3 summarizes current practices of cost modeling, section 4 introduces BIM and model-based estimating and process simulation tools, and section 5 discusses related research. This chapter also highlights the need for a new cost modeling method to better support TVD during the Design Development phase.

Chapter 4 presents the current state of cost modeling during the Design Development phase in a TVD environment. This characterization of the current state is based on my direct observation of over a time period of sixteen months, document analysis, and answers to semi-structured interviews conducted with practitioners at CHH project in San Francisco. The findings lead to my proposal of an alternative cost modeling method and help structure case studies for a proof of concept. This chapter then illustrates the framework for PBCM that includes three phases: collecting process- and cost data, mapping process- and cost data to BIM objects, and providing cost feedback during design.

This research uses two case studies and a software application to examine how the proposed PBCM framework works in the context of actual projects. The implementation of these case studies gave me the opportunity to understand the challenges in the application of PBCM and to adjust the framework during its implementation.

Chapter 5 presents a window case study in a residential development project. This chapter describes the design, cost estimation, subcontractor selection, fabrication, transportation, material handling, and site installation of the window system. Further, this chapter demonstrates a method of collecting process data during the installation of the product. It also demonstrates the application of process mapping and discrete event simulation to measure process waste. This chapter highlights the use of 'lean' process data, which results from deducting waste from the originally collected process data, to benchmark the process cost of a future project.

Chapter 6 presents the application of PBCM in the CHH project. This chapter demonstrates a method of collecting process data for the Viscous Damping Wall (VDW) system, a product that is new to the integrated project team and thus the team needs to examine alternatives for material handling and installation processes. This chapter also documents the use of 4D simulations and the Choosing By Advantages (CBA) decisionmaking system applied to evaluate installation alternatives of a VDW system. This chapter highlights how CBA helps to make decisions considering both cost and target value.

Chapter 7 presents a demonstration of an Add-In program module that I developed jointly with Harmony® Soft Company (website: http://www.harmonysoft.com.vn/en/index.php) to use with Autodesk Revit Architecture 2010 (Autodesk 2010b) to connect process- and cost data to objects in a Building Information Model. It also demonstrates a method of providing rapid product- and process cost feedback to designers during design. This example synthesizes the learning from the literature review and the case studies and showcases the methodology for PBCM.

In closing, Chapter 8 presents conclusions drawn from the case studies and the software demonstration. This chapter discusses the contributions to knowledge and suggests possible future research in the area of cost modeling.

CHAPTER 2. RESEARCH APPROACH

2.1 RESEARCH METHODOLOGY

Research methods have been classified in different ways, one general approach distinguishes between (1) case studies, (2) experimentation, and (3) surveys. According to Eisenhardt (1989), case-study research can be defined as "a research strategy which focuses on understanding the dynamics present within single settings." The case-study method is to develop detailed, intensive knowledge about a single case or a number of related cases (Robson 2002). An experiment is to manipulate one or more variables and measure its/their effects on other variables (Yin 2003). In a survey, researchers use standardized forms to collect information from groups of people (Yin 2003).

One major distinction of research methods is between deductive reasoning and inductive reasoning. According to Fowler (1904), deductive reasoning applies general principles to reach specific conclusions, whereas inductive reasoning examines a number of particular cases to infer a general principle. In this research, an inductive approach was chosen because I have a limited number of case studies.

According to Yin (2003), a case-study strategy is preferred when "how" and "why" questions are being posed, when the focus is on a contemporary phenomenon within some real-life context. Due to the nature of this research; the form of the research questions (how and why), and contemporary events, I select case studies as my research strategy. The case-study design is described in section 2.1.3.

Action research occurs through case studies when new approaches or methodologies are being developed. In action research, the researcher is directly involved in the research project as a promoter of change (Susman and Evered 1978). In the context of this dissertation, the researcher promotes the change from a conventional elemental cost modeling method to a PBCM method. The researcher becomes part of the project team, works with team members to design and execute a case study, collects data, and helps to make adjustments during case-study implementation (P^2SL 2010). Since action research seeks to find solutions that are "localized" for specific situations, the results of action research are not necessarily generalizable for broad application (Stringer 2007).

I use case-study research and action research to develop the PBCM framework. 'Proof of concept' experimentation expands the theoretical understanding of the cost modeling and cost estimating practices in the construction industry.

The research process can be best explained by identifying different research phases and the research tasks associated with each phase. Figure 2.1 illustrates the overall research strategy of this study.

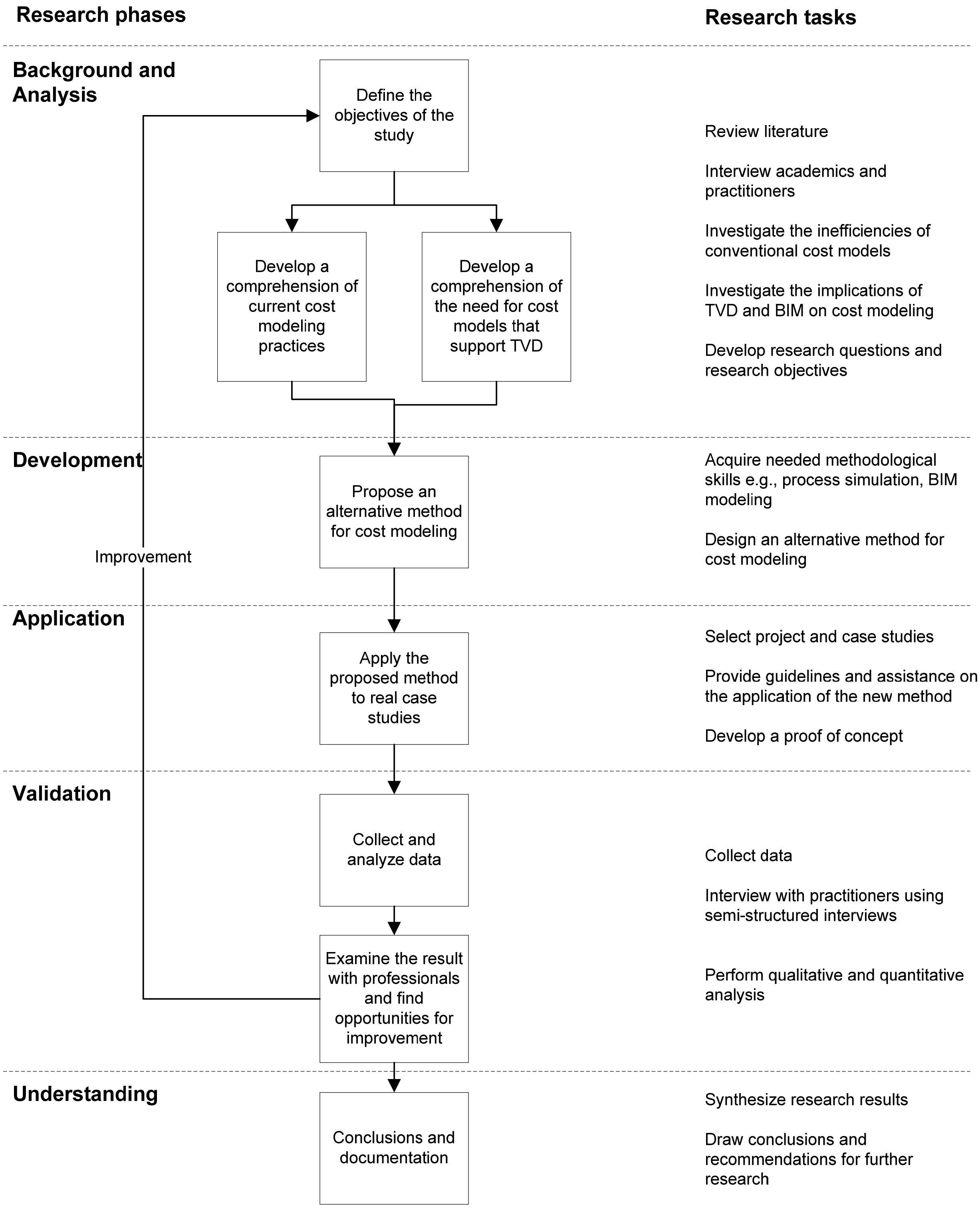


Figure 2.1 Research process

2.2 RESEARCH PROCESS

2.2.1 BACKGROUND AND ANALYSIS

To develop the knowledge background that supports the development of an alternative method for cost modeling, I reviewed literature and interviewed professionals on cost modeling practices. These two approaches helped identify the inefficiencies of current construction cost models and the cause of those inefficiencies. They also created a comprehension of the framework in which current practices of cost modeling are set. This understanding guided what, how, and where changes should be introduced to alter the current practices of cost modeling. To understand current practices of cost modeling and BIM in the construction industry, I interviewed practitioners from Davis Langdon, Rudolph and Sletten, Herrero Contractors, Boldt, DPR, Southland Industries, and Haahtela Group for cost modeling practices and BIM applications in their organizations.

To develop my understanding of the TVD process, I used direct observations and document analysis methods in addition to literature reviews and interviews. I observed weekly TVD meetings at CHH project for twelve months. In addition, I collected and analyzed documents and records including design drawings, Bill of Quantities (BOQ), cost estimates, BIM models, A3 reports, and process maps related to those TVD meetings.

2.2.2 DEVELOPMENT PHASE OF RESEARCH

The development phase involves two main tasks: (1) acquisition of knowledge, and (2) designing of an alternative method for cost modeling.

To accomplish the first task, I conducted literature reviews of alternative methods for cost modeling in both the construction and manufacturing industries. In addition, I interviewed professionals to study novel approaches on cost modeling of pioneering consultants in construction industry. I also acquired needed methodological tools, e.g., process mapping, process simulation, CBA decision making system, and BIM applications. Specifically, I learned how to use EZStrobe (Martinez 2001) and SIGMA (Schruben 1990; SIGMA 2009) simulation tools; Autodesk Revit Architecture 2010 (Autodesk 2010b) for modeling, Navisworks 2009, Navisworks 2010 (Autodesk 2010c) and Synchro Professional 2008 (Synchro 2008) for model-based scheduling and animation, and Innovaya Visual Estimating 9.3 (Innovaya 2009) and Timberline Estimating 9.4.0 (Timberline 2009) for model-based cost estimating.

To accomplish the second task, I synthesized the acquired knowledge to identify a method for cost modeling that supports the TVD process. Then I applied the proposed method on case studies to test its feasibility and to correct and improve it. Subsequently, I documented the process and information flow of the proposed cost modeling method. In addition, I prepared guidelines for the application of the proposed method before moving to the Application and Validation phases.

2.2.3 APPLICATION AND VALIDATION PHASES OF RESEARCH

The application and validation phases provided opportunity for implementing the proposed cost modeling method on real projects. I investigated multiple case studies to guarantee the robustness of the study. Each case was selected for a specific purpose. Figure 2.2 and Figure 2.3 illustrate the proposed case-study design for this research.

In case-study research, Yin (2003) recommended the use of data from multiple sources to guarantee the credibility of the research. In this study, the methods of collecting data included interviews, direct observations, and analysis of documents and records.

Interviews: I chose semi-structured interviews, in which, I prepared a set of questions for each interview but the use of these questions was flexible depending on interviewee's responses. For each case study, I interviewed architects, design engineers, cost estimators, cost consultants, trade partners, and General Contractor (GC) representatives.

Observations: I made direct observations at TVD meetings, design coordination meetings, and on construction sites in the role of 'participant-as-observer', where I was able to interact with people and ask questions (Robson 2002).

Analysis of documents and records: Documents and records analyzed included design drawings, BOQ, cost estimates, process maps, A3 reports, digital video files capturing construction processes, and BIM models.

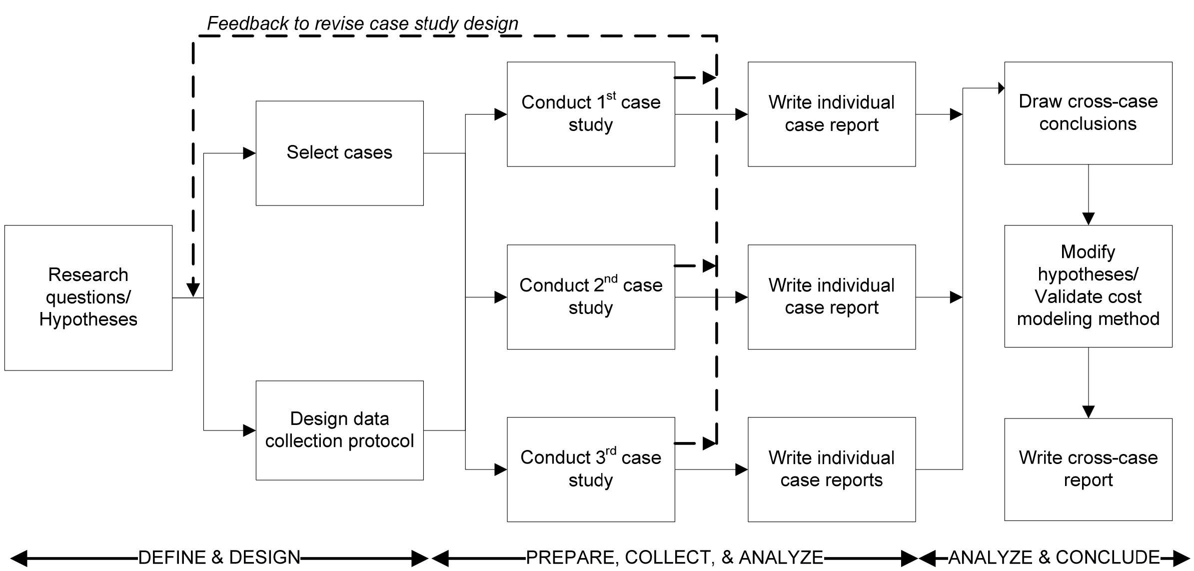


Figure 2.2 Case-study method (adopted from Yin 2003)

Acknowledging that "the selection of cases should be based on theoretical sampling, in which cases that differ as widely as possible from each other are chosen to fill theoretical niches"

(Stuart et al. 2002), I selected three case studies with different objectives to answer different research questions. Brief descriptions of the three case studies are as follows:

Case study 1. Window system

To verify the method for collecting process data, I selected the process of window installation at a multi-unit residential project located in San Francisco. The objectives of this case study were to (1) analyze conventional practices of designing, procurement, estimating, and installing a window system, to identify process inefficiencies and wastes, and to discuss how they may affect cost estimates of future projects; to (2) understand and quantify process waste; and (3) develop a method of collecting process data that separates true cost and cost of waste by using process mapping.

This project is a new construction of a 5 storey residential building using a Design-Build (DB) project delivery approach. The purpose of this case study is to pinpoint deficiencies of conventional cost estimating practices in literature and in practice, and to test the method of collecting process data using a process mapping technique.

In this project, a window subcontractor was not identified until the Design Development phase was completed. As a conventional practice, the designer of the window system relied on historical cost data from completed projects and quotations provided by the window suppliers as the major sources of cost feedback to evaluate design options. In the final design, the designer specified over 300 variations of windows among the total of 468 windows used in this project. The variations mostly were in sizes, styles, hardware, and operations. The large number of variations created a challenge for the logistics, material handling, and site installation processes. I used process mapping to collect process data and identify waste in the process, then I used Discrete-Event Simulation (DES) to quantify process waste. From this case study, I proposed a method of creating a baseline process by removing waste from the original process map. This baseline process is to be used for future process cost benchmarking.

Case study 2. Viscous Damping Wall system at CHH project

To test the use of a new method for cost modeling, I selected the CHH project to conduct another case study. This project implements an IPD approach and extensively applies lean principles and BIM tools, thus offering an appropriate environment for performing experiments related to this research. In addition, the collaborative working environment of this project facilitates data collection and analysis for this research. This case study has two objectives. The first objective is to demonstrate the application of PBCM method including the application of 4D simulation in assisting cost estimating. The second objective is to demonstrate the application of CBA to make decisions when considering both costs and non-cost factors.

This case study presents the application of PBCM to evaluate the installation alternative of a VDW system in the IPD environment. With trade partners on board, the IPD team creates process maps that cover design, fabrication, packaging, transportation, site handling, and installation of important systems or components. With their field experience, trade partners provide estimates of process data as well as perform cost estimate for their work scope. In this case study, I also evaluate the application of 4D simulations in helping the IPD team focus discussion on constructability, logistics, make ready work, activity duration, crew composition, and types of equipment. I interview representatives on the structural steel team and the VDW trade partner to evaluate the effectiveness of the process-based cost modeling method in evaluating design alternatives.

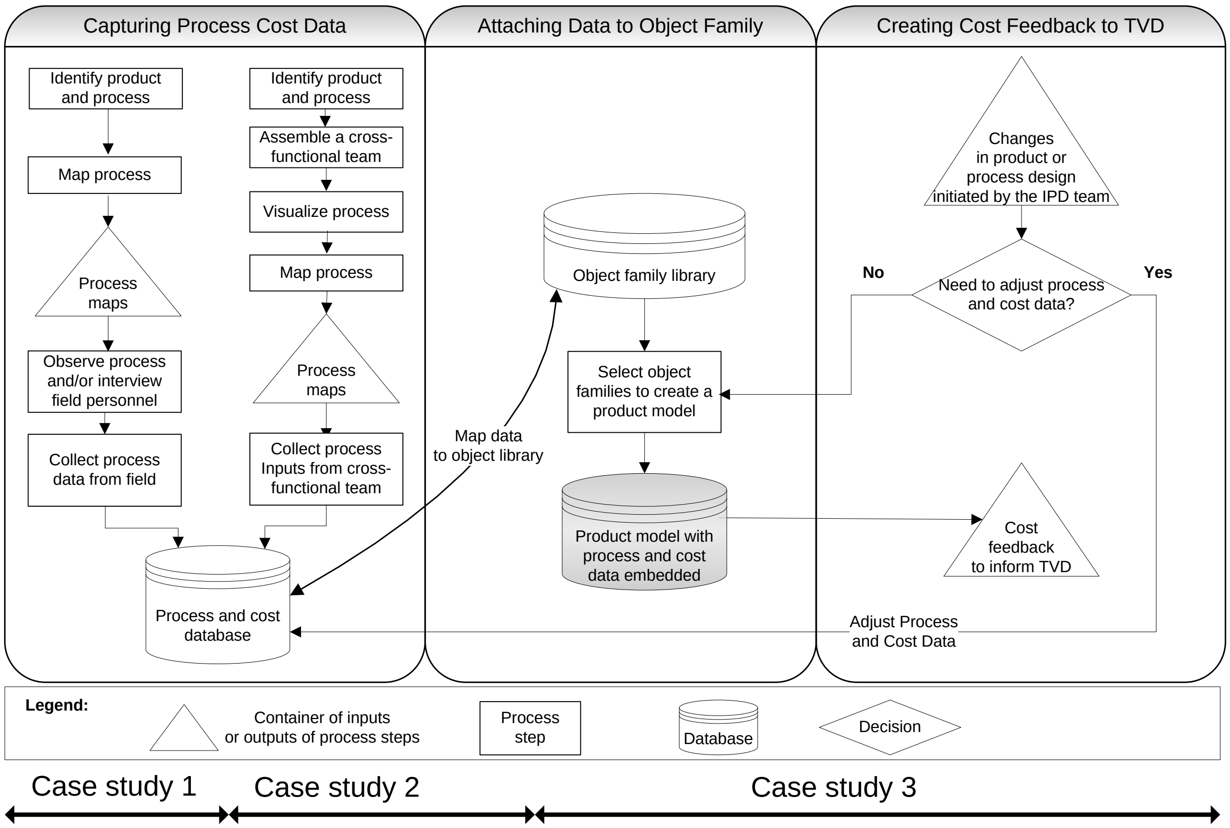


Figure 2.3 Use of case studies to deliver proof of concept for a PBCM framework

Case study 3. Using an Autodesk Revit Add-In to provide rapid cost feedback to designers

This case study demonstrates the application of an Autodesk Revit Add-In that integrates product cost and process cost of the VDW system to the BIM model at the CHH project to provide rapid cost feedback to designers. The objectives of this case study are to (1) demonstrate the technical feasibility of PBCM; (2) propose a method to map a BIM object family with process- and cost data; (3) provide an interface for adjusting process- and cost data through process maps; and (4) suggest a framework for establishing and utilizing a process database.

Success of the proposed cost modeling method is measured through subjective evaluations provided by the participants and through the use of objective metrics where available. During the course of pursuing case studies, I performed cross-case analysis and draw cross-case conclusions. These conclusions were validated by having key participants review the case-study reports.

2.2.4 UNDERSTANDING PHASE OF RESEARCH

In the understanding phase, I synthesized research results from the case studies, draw conclusions, and provided recommendations for further research. During the course of the study, research results were published in the International Group of Lean Construction (IGLC) conference proceedings and Lean Construction Journal to disseminate findings and trigger discussion. Feedback from those publications was analyzed to enhance this research and to shape future studies.

This chapter presented the research approach used in this dissertation. In this chapter, I described the application of case-study research and action research to develop the PBCM framework.

CHAPTER 3. LITERATURE REVIEW

This chapter reviews the relevant professional and research developments that have influenced this study and is divided into five sections. Section 1 introduces the LPDS™, section 2 presents the relevant literature on Target Costing and TVD as well as tools that support TVD, section 3 summarizes current practices of cost modeling, section 4 introduces BIM and model-based estimating and process simulation tools, and section 5 discusses related research.

3.1 LEAN PROJECT DELIVERY SYSTEM™

The 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). The LPDS™ model, as depicted in Figure 1.1 (Chapter 1), consists of modules organized into overlapping triads representing five different project phases (Ballard 2000). Each phase, as represented by a triangle, consists of essential steps that in combination lead to project completion.

Throughout all phases of a project, Production Control and Work Structuring are complementary and managed concurrently. Production Control comprises processes that "govern execution of plans and extend throughout a project where 'control' means causing a desired future rather than identifying variances between plan and actual" (Ballard 2000). Production Control uses master scheduling, phase scheduling, and look-ahead planning to manage work-flow control and it uses weekly work planning to manage production unit control (Ballard 2000).

Work Structuring in lean construction is defined as "the development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts with the goal of making work-flow more reliable and quick while delivering value to the customer" (Ballard 2000). Initially the term Work Structuring equated to process design (Ballard 1999). Ballard et al. (2001) broadened the scope of Work Structuring by equating it with Production System Design (PSD) (refer to section 3.2.4).

Project Definition is the first phase in lean project delivery. It is understood as "the phase in which business planning occurs and feasibility studies are performed." Deliverables are decisions whether to fund projects and decisions to set target scopes and costs for the funded projects (Ballard 2006a). In this phase, the design team establishes a Target Cost for the facility and produces design criteria for both product- and process design.

In the Lean Design phase, the conceptual design from Project Definition is developed into product- and process design. To integrate product- and process design, specialty contractors must be a part of the design process. These specialty contractors assist with the selection of components and equipment and with process design (Ballard 2000). In addition, to align the physical design of a capital facility with customer's values, the design team uses innovative approaches to set targets and design to targets, explore alternatives, and integrate product- and process design. Examples of such approach are TVD (refer to section 3.2.2), IPD (refer to section 3.2.3), PSD (refer to section 3.2.4), SBD (refer to section 3.2.5), and BIM (refer to section 3.4).

3.2 TARGET COSTING IN THE MANUFACTURING INDUSTRY AND TARGET VALUE DESIGN IN THE LPDS™

3.2.1 TARGET COSTING IN THE MANUFACTURING INDUSTRY

Target Costing has been in use in the Japanese automotive industry since the 1960s (Pennanen et al. 2005). Target Costing can be understood as a management tool for reducing the overall cost of a product over its life cycle with the help of all the firm's departments and the active contribution of the supply chain. The long-term, proactive principles of Target Cost management contradict the traditional after-the-fact treatment of conventional cost control (Kato 1993).

Surveys carried out by the Kobe University Management Accounting Research Group in 1992 (Kato and Yoshida 1998) revealed that a majority of Japan's largest manufacturers used Target Cost management and benefited from its continuing cost reduction power. These surveys also showed that concurrent engineering, cross-functional teams, inter-organizational cost management or supply chain cost management were key components to reinforce the power of Target Cost management.

The well-known formula of Target Cost computation is: Target Cost = Target Price - Target Profit (e.g., Ansari 1996, Cooper and Slagmulder 1997, Clifton et al. 2004). 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 in the product planning, research development, and prototyping. In the manufacturing industry, Target Costing is supported by four fundamental techniques: (1) market intelligence, (2) value engineering, (3) variety reduction programs, and (4) inter-organizational cost management systems (Kato 1993).

According to Kato and Yoshida (1998), the first article on Target Cost was published in 1977. Japanese researchers dominated in this research area until the early 1990s. After that, Western researchers, such as Ansari (1996), Cooper and Slagmulder (1997), Horngren et al. (1997), and Clifton et al. (2004), also studied approaches for cost reduction through Target Cost management.

According to Nicolini et al. (2000), although Target Costing proved highly successful in new product development for commodities in manufacturing, its application in capital-intensive sectors such as construction has been limited. Cost-plus approaches have prevailed in the construction industry. These start with cost estimation to which a profit margin gets added using the formula Price = Cost + Profit. Ballard and Reiser (2004) described that the traditional practice in construction was to produce design to an agreed level of detail, estimate its cost, then try to alter the design in order to bring the estimated cost within budget. This approach is wasteful since the iteration of design/estimate/re-design cycles cause rework and frustration. A cost cutting exercise during re-design may include reducing scope or lowering material quality that may result in less value for customers. Table 3.1 compares cost-plus and Target Costing approaches.

Table 3.1 Comparison of cost-plus and Target Costing (Nicolini et al. 2000)

Cost-plus	**Target Costing**
Costs determine price	Price determines costs
Performance, quality, and profit (and more rarely inefficiencies and wastes) are the focus of cost reduction	Design is key to cost reduction, with costs managed out before they are incurred
Cost reduction is not customer driven	Customer input identifies cost reduction areas
Cost accountants are responsible for cost reductions	Cross-functional teams manage costs
Suppliers involve late in design process	Early involvement of suppliers
No focus on life-cycle cost	Minimizes cost of ownership for client and producer
Supply chain only required to cut costs	Involves supply chain in cost planning

In early attempts to apply Target Costing in the construction industry, Ballard and Reiser (2004) suggested using cross-functional teams to anticipate the cost consequences of different possible designs or design decisions, and limiting eligibility of designs or decisions that fit within the Target Cost. They also recommended Value Engineering (VE) and the use of integrated product/cost modeling as needed support tools for designing to Target Cost. Pennanen et al. (2005) defined three steps for implementing Target Costing as follows: (1) define functional criteria, (2) determine Target Cost, and (3) design to the targets.

3.2.2 Target Value Design

TVD is an adaptation of Target Costing to project production systems. TVD covers value targets beyond cost, including constructability, time, safety, work structuring, etc. (Lichtig 2005).

TVD is “a management practice that drives design to deliver customer value within project constraints… it rests on a production management foundation and treats cost as an outcome of PSD, operation and improvement” (Ballard 2009). TVD spans from the Project Definition phase and continues through the entire project and its principles help to steer the design team to meet established design criteria.

According to Macomber et al. (2007), TVD turns current design practice upside-down: (1) Setting the Target Cost for design: “Rather than estimate based on a detailed design, design based on a detailed estimate”, (2) Work Structuring: “Rather than evaluate the constructability of a design, design for what is constructable”, (3) Collaboration: “Rather than design alone and then come together for group reviews and decisions, work together to define the issues and produce decisions then design to those decisions”, (4) Set-Based Design: “Rather than narrow choices to proceed with design, carry solution sets far into the design process”, and (5) Collocation: “Rather than work alone in separate rooms, work in pairs or larger groups, face to face.” Figure 1.3 (Chapter 1) depicts these five fundamental components of TVD.

Figure 3.1 shows that TVD starts from the Project Definition phase and continues through the entire project, moving from setting targets, to designing to targets, and finally building to targets.

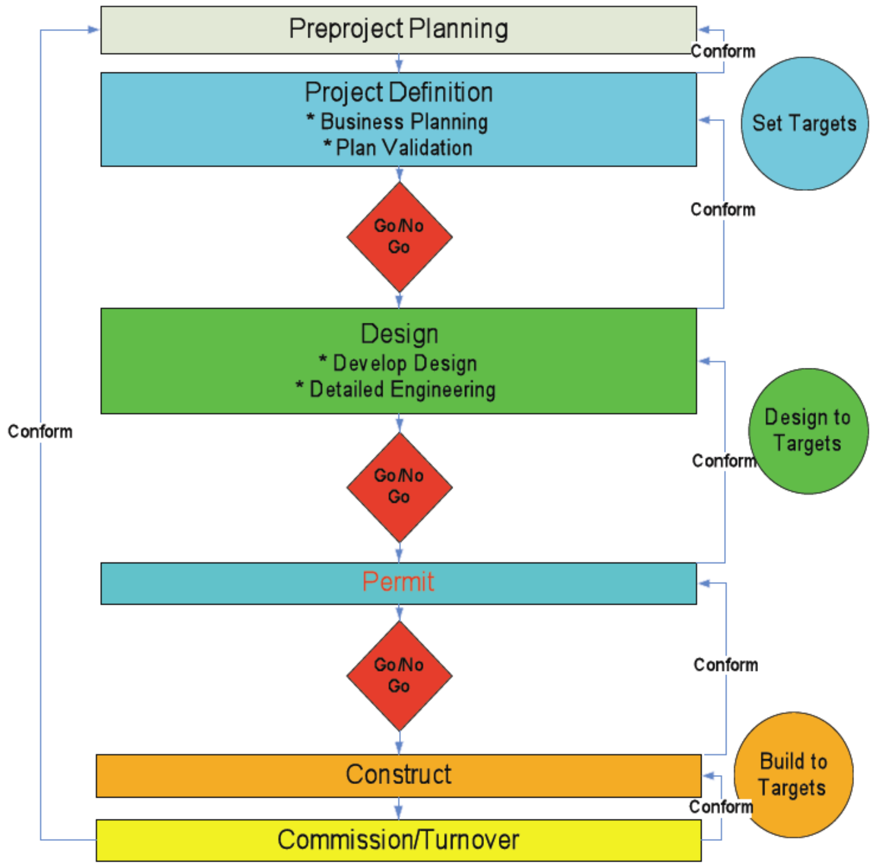


Figure 3.1 Project phases and Target Value Design (Ballard 2009)

Ballard (2009) specified the following steps to implement TVD in the Project Definition and Lean Design phases:

- Set the Target Cost that is typically lower than the budget that assumed current best practice,
- Form TVD teams by system and allocate the Target Cost to each team,
- Hold a kick-off workshop,
- Start a meeting schedule,
- Use a SBD approach and evaluate sets against target values,
- Provide cost and constructability guidelines for design, e.g., product/process standardization,
- Promote collaboration and have designers get cost input before developing design options,

- Do rapid estimating and hold frequent budget alignment sessions,
- Use value engineering proactively, and
- Hold design reviews with permitting agencies.

Specifically on the process of design to targets, Ballard (2006c) proposed a seven-step process that emphasized concurrency in Design Development and cost modeling, as well as the advantage of automated costing: (1) Allocate the Target Cost to systems, subsystems, and components; (2) Establish a personal relationship between designers and cost modelers in each system team; (3) Have cost modelers provide cost guidelines to designers up front, before design begins; (4) Encourage designers to consult with cost modelers on the cost implications of design alternatives before they are developed; (5) Incorporate value engineering/value management tools and techniques into the design process; (6) Schedule cost reviews and client signoffs, but develop design and cost concurrently; and (7) Use computer models to automate costing.

TVD aims at achieving the best possible design for the available budget. Cost is a constraint on design beside value targets spelled out by the customer. Design decisions usually comprise trade-off analysis of time, form, function, product cost, logistics cost, installation cost, and life-cycle cost. TVD also requires behavioral changes in comparison to the traditional design process. Owner representatives must learn to act as an integrated part of the team to specify customer value in order to direct design efforts. Architects, engineers, and design consultants must learn to tolerate contractors' assessment on the constructability and cost of their designs.

3.2.3 Integrated Project Delivery (IPD)

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 2007).

IPD has an advantage of encouraging team involvement in the early phases of design over traditional project delivery system such as Design-Bid-Build (DBB) or Design-Build (DB) (Matthews and Howell 2005). It allows downstream players (e.g., the GC, specialty contractors, suppliers), who have the most process-related knowledge and experience (such as experience in fabrication, logistics, work method selection, and trade coordination) to provide input to design phases. The IFOA, developed by Lichtig (2006), promotes collaboration in an IPD team and offers a method of risk sharing. Due to the collaborative nature of TVD, the IPD approach is an enabler for the implementation of TVD.

3.2.4 Production System Design (PSD)

Initially, Work Structuring in LPDS™ was mentioned as process design (Ballard 1999). Ballard et al. (2001) expanded the scope of Work Structuring by equating it with PSD. In conventional practice, "project planning has focused primarily on organizational structuring and creation of work breakdown structures (WBSs) that divide the work to be done." In contrast, PSD "extends from global organization to the design of operations; e.g., from decisions regarding who is to be involved in what roles to decisions regarding how the physical work will be accomplished" (Ballard et al. 2001).

In conventional project management as characterized by decomposition (i.e., using WBSs), designers often leave the resolution of interface and issues of scope gap and scope overlap, to the builders (Tsao et al. 2004). While the design of each part in a WBS 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- and process design for the whole project.

As the result of decomposition practices, conventional cost modeling practices focus 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 interdependencies (e.g., physical and temporal) between elements. To support PSD, a cost model could be more realistic if it is able to specify how changes in product- and process design affect overall cost and the output of that cost model must support trade-off analysis between incremental value and incremental cost.

3.2.5 Set-Based Design

According to Ward et al. (1995), SBD is a process in which designers communicate and think about sets of design alternatives and they "gradually narrow these sets by eliminating inferior alternatives until they come to a final solution." SBD focuses on keeping sets of design options "as open as possible for as long as possible" (Parrish et al. 2007). Design alternatives are defined and communicated between all disciplines, and the choice of a single alternative is made at the last responsible moment. This occurs at each level of Design Development, from concept to detailed design (Parrish et al. 2008a; 2008b).

3.3 CURRENT PRACTICES OF COST MODELING

3.3.1 Estimating Formats and Work Breakdown Structures

Cost estimates are often organized according to certain formats, i.e., WBSs. Widely used WBS systems in the United States are Uniformat (1998) and MasterFormat (1995). Uniformat represents WBS costs according to a hierarchy of system elements. An estimate using Uniformat may be used in early design such as the Conceptual Design phase or the Design Development phase (Bledsoe 1992, Charette and Marshall 1999). In contrast, as MasterFormat aligns well with the way specialty contractors specify their work results, it is widely used to organize cost estimates late in the Design Development phase and in the Construction Document design phase (Bledsoe 1992). MasterFormat currently organizes the WBS into 16 divisional categories based on trades and materials. The Construction Specifications Institute (CSI) is in the process of expanding MasterFormat to 49 divisions.

In an initiative to address the construction industry's needs for organizing different forms of information generated throughout the life cycle of a project including: design, specification, cost estimate, construction, commissioning, and facility management. The OmniClass Construction Classification System (OCCS 2008) was jointly developed by the Construction Specifications Institute and the International Alliance for Interoperability. OmniClass incorporate other existing systems currently in use such as MasterFormat for classifying work results, UniFormat for classifying elements, and EPIC (Electronic Product Information Cooperation) for sharing information between construction product databases (OCCS 2008).

3.3.2 COST ESTIMATING METHODS AND HISTORICAL COST DATABASE

3.3.2.1 Cost Models

According to Halpin and Riggs (1992), a model is "a representation of a real-world situation and usually provides a framework with which a given situation can be investigated and analyzed." In this sense, a cost model in construction can be understood as a representation of the cost of a component, a system, or a facility under design. A cost model is used to (1) calculate the cost effect of a design change or to (2) estimate the cost of an element of a design or the whole design. Any cost estimating method that has one or both of the mentioned capabilities can be described as cost models (Beeston 1987). Fortune and Lees (1996) classified the development of the available cost models as follows:

- 'Traditional' models (cost per square foot, elemental analysis, significant items, approximate quantities, detailed quantities, judgment, functional unit)
- Mathematical (parametric modeling, expert judgment or delphi techniques)
- Knowledge based systems (life cycle costing techniques)
- Resource/process based models
- Risk analysis (Monte Carlo simulation)
- Value rated models

According to Wilson (1982), the purpose of cost models is to support at least one of the following tasks: (1) to compare a range of possible design alternatives at any stage in the design process, (2) to compare a range of actual design alternatives at any stage in the design evolution, and select the most preferred design according to predefined criteria of expected performance, (3) to predict the total price that the client will have to pay for the building, and (4) To predict the economic effects on society for changes in design codes and regulations. The first two tasks play an important role in cost control during the design stage of a project.

Figure 1.2 in chapter 1 summarizes traditional cost models, their related estimating methods, their applications in different states of design, and types of historical cost data needed for each cost model.

According to Bledsoe (1992) and the National Institute of Building Sciences (NIBS 2006), the construction industry uses four primary methods to estimate construction costs. Those methods are known as: (1) Parametric Cost Estimating (also known as Preliminary or Project Comparison Estimating), (2) Area and Volume Estimating (also known as Square Foot and Cubic Foot Estimating), (3) Assembly and System Estimating, and (4) Unit Price and Schedule Estimating. Each method of estimating offers a level of confidence that is in relative to the amount of time required to prepare the estimate (Figure 3.2).

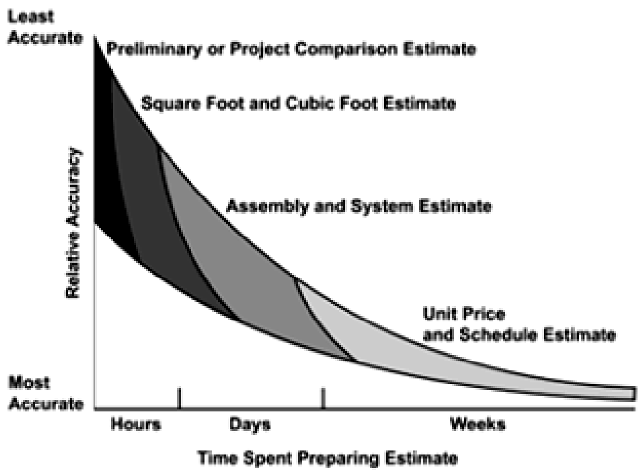


Figure 3.2 Relative accuracy of estimate types (Bledsoe 1992)

3.3.2.2 Parametric Cost Estimating

Parametric Cost Estimating models are used in the Conceptual Design phase when a project's scope information is limited. According to Hegazy and Ayed (1998), a Parametric Cost Estimating model consists of one or more functions, or cost estimating relationships between the cost as the dependent variable and the cost-governing factors as the independent variables. Traditionally, cost estimating relationships are developed by applying regression analysis to historical project information. The development of these models, however, is a difficult task due to the limitations of regression analysis: (1) regression analysis requires a defined mathematical form for the cost function that best fits the available historical data (Creese and Li 1995) and (2) regression analysis is unsuitable to account for the large number of variables present in a construction project and the numerous interactions among them. These limitations have contributed to the low accuracy of parametric models and their limited use in construction (Garza and Rouhana 1995).

The regression equation usually takes the linear form: $Y = A + B_1X_1 + B_2X_2 + \ldots + BnXn$. Where (1) Y is the dependent variable (cost), (2) A is the intercept, (3) B_1, B_2, …, Bn are the regression coefficients of the predicted variables, and (4) X_1, X_2, …, Xn are the independent variables or measures of some characteristics that affect Y (such as gross floor area, number of storeys, wall-to-floor ratio, etc.). Table 3.2 shows a more complete list of independent variables, called cost drivers, in building construction. This method is used in those situations where a correlation exists between the variables. Different types of regression models can be developed. They include a simple linear-, a multiple linear-, or a non-linear polynomial regression (FAA 2002).

Cost drivers are the controllable system design or planning characteristics, and have a predominant effect on system cost. The parametric method focuses on the cost drivers, not the miscellaneous details. This method uses only important parameters, i.e., parameters that are judged to have the most significant cost impact on the product being estimated. As presented in Table 3.2, Soutos (2005) identified some significant cost drivers used in the Conceptual Design phase.

Hegazy (1998) proposed the application of an Artificial Neural Network (ANN) modeling for Parametric Cost Estimating at the early stage of a project. According to Boussabaine (1996), ANN is an information processing technology that simulates the human brain and the nervous system. Resembling the human brain, ANN can be trained to learn from experience and abstract essential characteristics from inputs containing relevant data. However, due to its complexity in development and use, the ANN model has limited application in the construction industry (Fortune and Cox 2005).

Table 3.2 Cost drivers used for parametric estimating model (Soutos 2005)

Project Strategic:	Contract form, contract type, duration, procurement, purpose, tender strategy.
Site Related:	Site access, topography, location type, site nature.
Design Related and Building Definition:	Envelope, building function, gross internal floor area, height of building, number of levels above ground, number of levels below ground, quality, shape complexity, structural units, wall-to-floor ratio.
Structure:	Substructure, piling, frame, upper floors, roof construction, roof profile, roof finishes, stairs, external walls, windows, external doors, roller shutter doors, internal walls/partitions, internal doors.
Finishes:	Internal wall finishes, floor finishes, ceiling finishes.
Mechanical Installations:	Air conditioning, lifts, total mechanical installations.

3.3.2.3 Area and Volume Estimating

The Area and Volume Estimating method is often used in the Conceptual Design phase, when design detail allows measurement of floor areas and volumes of the proposed spaces. Estimators use historical databases that provide composite unit costs per an area unit (i.e., $/Square Foot) or per a volume unit (i.e., $/Cubic Foot). Estimators can use historical data maintained by their own firm or provided by commercial sources. Estimators adjust historical data according to time, location, local labor market rates, and scale and features of the planned facility. Then estimators multiply the adjusted unit cost by the total area or total volume to produce a cost estimate (Bledsoe 1992; NIBS 2008).

3.3.2.4 Assembly and System Estimate

Assemblies and systems are defined as major parts of the building that always perform the same function irrespectively of their location or specification. For example, beams transmit slab loads to columns and internal partitions always vertically divide two internal spaces. The cost of a functional element expressed per unit of the gross floor area is used in combination with a cost index to calculate element cost (Ferry 1999).

The Assembly and System Estimate is an intermediate-level estimate, it is performed when a project is in the Design Development phase, i.e., when design is in between 10% and 75% complete. Assemblies or systems group the work of several specialties or work items into a single unit for estimating purposes. For example, a concrete beam usually requires formwork, reinforcing steel, and concrete and these works may be performed by different specialty contractors. But Assembly and System Estimating prices all of these items together by applying values available in historical databases, either from internal or commercial sources. These cost data are expressed by cost of a functional system per unit of gross floor area, typically organized in a Uniformat system that represents the progress of building construction (Bledsoe 1992; NIBS 2008).

3.3.2.5 Unit Price and Schedule Estimate

This type of estimate is often used late in the Design Development phase and during the Construction Document phase, when detailed drawings and specifications are available. It offers the greatest accuracy of the four types of estimating, but is also the most time consuming. Line items reflect quantities according to a WBS that adopts the MasterFormat.

Estimators measure and calculate quantities of the components of a facility from design drawings. Estimators then list the calculated quantities in a BOQ and assign a unit price to each line item in the BOQ. The total estimated cost is a summation of the products of the quantities multiplied by their corresponding unit costs. Various levels of sophistication in terms of measurement detail and description exist with BOQs but the same principles apply.

To determine a unit price an estimator needs to (1) assume a work method, (2) estimate a productivity rate, (3) estimate labor cost, (4) estimate material cost, (5) estimate overhead and profit, and (6) add an allowance for assumed conditions. Each step requires judgment by the estimator and this judgment is based on historical data, the estimator's own past experience, previous experience of others, and gut feeling. The subjectivity of these judgments is the main reason for variations in estimating from one estimate to another and different estimators often come up with different cost estimates for the same set of drawings (Sinclair et al. 2002; Kanaya 2009).

3.3.2.6 Historical Cost Database

Historical cost data may come from internal or external sources. A company compiles its internal historical cost database from records of completed projects and price quotations from specialty contractors and suppliers. Estimators may collect these data from projects that they have been involved with and therefore are the most knowledgeable of. However, no two projects are the same. Projects vary in scope, shape, structure, material, underground conditions, site restrictions, and so forth. The estimator may face many challenges in using historical cost data, such as: (1) understand the source and timing of the historical data, (2) understand what the historical data contain, (3) understand specific conditions of the completed project that may impact historical data, (4) convert the historical data to reflect the timing and location of the new project, and (5) manipulate the data to represent specific conditions of the current project (Sinclair et al. 2002, NIBS 2008).

External sources of historical cost data are available in both printed and electronic versions, e.g., RSMeans Company (RSMeans 2010) and F.R. Walker Company (Walker 2010) annually publish cost information. But these data pose even greater challenges in comparison to those of internal data since estimators face the risk of manipulating data that they are not familiar with. Therefore, experienced estimators often use published sources as a reference only in order to cross-check their own numbers or to come up with a ball-park estimate for work for which they do not have internal data available (Kanaya 2009).

For an internal historical cost database to be useful and reasonably accurate, the actual cost of completed projects must be recorded and documented properly. The current practice of job cost accounting is to compile the cost of an installed component by adding up all costs of resources actually used to install that component. This total eventually includes inefficiencies and waste that prevail in construction processes, especially in projects that do not rigorously use methods to eliminate process waste or do not use continuous improvement. Thus historical cost data may contain inefficiencies and wastes previously experienced such as trade interference, location conflict, productivity loss, excessive logistics, and site handling costs. Field personnel such as superintendents and construction project managers may realize these process inefficiencies and wastes. However, the window case study (Chapter 5) and my interviews with estimators at Davis Langdon (a cost consulting company), Rudolph and Sletten, The Boldt Company, and Herrero Contractors, Inc. (General Contractors), and superintendents at CHH reveal that these data are rarely documented and thus hardly ever communicated to estimators.

In order to improve cost estimating practice, an estimator should compare his estimates against actual costs when the project is finished and as a learning exercise. Actual cost feedback helps the estimator verify the reliability of historical cost data used, review his data adjustment decisions, and adjust his cost model. However, according to Sinclair et al. (2002), the learning process is not carried out effectively within the industry, feedback of actual costs is not consistently used to review and adjust the cost data for estimating future projects. My interviews with estimators at CHH and cost consultants at Davis Langdon also confirmed the lack of consistent feedback loops in estimating.

3.3.3 ACTIVITY-BASED COSTING

Activity-Based Costing (ABC) is a method of allocating costs through activities to products and services according to the actual consumption by each (Cokins 1996; 2001). ABC was originally used in the manufacturing industry and it was experimented within the construction industry to analyze construction cost (Kim and Ballard 2001; Kim 2002) and construction supply chain cost (Kim and Jinwoo 2009).

Instead of using broad subjective percentages to allocate costs (especially overhead cost) as is done in traditional Resource-Based Costing methods, ABC seeks to identify cause and effect relationships to more objectively assign costs. Once costs of the activities have been identified, the cost of each activity is attributed to each product to the extent that the product uses the activity. In this way, ABC often identifies areas of high overhead costs per unit and so directs attention to finding ways to reduce the costs or to charge more for costly products (Cokins 1996). Since ABC focuses on process and it is used to trace resources to activities and assign activities to products and services (Back et al. 2000), ABC data collected from a completed project is useful for analyzing processes of future projects. Table 3.3 compares the Resource-Based Costing that is widely used in construction and the ABC approach.

Table 3.3 Resource-Based Costing vs. Activity-Based Costing

Resource-Based Costing	Activity-Based Costing
• Focuses on resources	• Focuses on processes
• Focuses on individual cost elements rather than the interdependencies between elements and their immediate internal suppliers and customers (Brimson and Antos 1999)	• Embeds a process view, focusing on the interdependencies between elements and their immediate internal suppliers and customers (Back et al. 2000)
• One-stage costing, resources are traced directly to products and services	• Two-stage costing, resources are traced to processes then processes are assigned to products and services.
• The focus on allocating resources to cost centers is to provide inputs to a process rather than outputs or customer requirements (Brimson and Antos 1999)	• ABC focuses on providing outputs or customer requirements (Brimson and Antos 1999)
• Overhead and indirect expenses are allocated on an subjective basis and result in cost centers often 'absorbing' costs that they do not directly cause (Brimson and Antos 1999)	• Overhead and indirect expenses are more specifically assigned to activities where they occurs (Brimson and Antos 1999)
• Does not explicitly connect labor performance to customer value	• Places responsibility and accountability on labor to manage their activities to achieve their performance targets
• Does not look at the cost and benefit tradeoffs of different service levels	• Allows the analysis of cost and benefit tradeoffs of different service levels
• Established budget is often the results of looking at past projects and projecting some linear relationship to the future (Brimson and Antos 1999), resources are allocated to work items (or push) based on historical data (Kim and Ballard 2001)	• Provides an ability to understand how products/services create demand (or pull) for specific activities that in turn drive the requirement of resources (Kim and Ballard 2001)
• Does not connect budgeting to economic value and strategy	• Connects budgeting to economic value and strategy
• Reflects a transformation view (Kim and Ballard 2001)	• Reflects a process view (Maxwell et al. 1998)

3.4 BUILDING INFORMATION MODELING

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).

In the conceptual phase of a project, the owner establishes design and construction criteria, functional requirements, functional adjacencies, and programmatic area allowances. These requirements are handed off to the designer to pull together into a cohesive plan including building code, site, cost, and engineering requirements. BIM can be applied to create an early design view to capture early planning data in a comprehensive and computable exchange format to pass to down-stream technologies, such as design modeling and engineering analysis. Once in a standard computable format, this early design information can be used to validate proposed design solutions against the owner's requirements (NIBS 2007).

3.4.1 Model-Based Quantity Take-Off and Cost Estimating

Common quantity take-off methods include manual input of the design data into spreadsheets, digitization of paper drawings using a digitizing tablet, and more advanced methods generate quantity take-off of individual elements directly from electronic files. BIM models contain dimensions and characteristics of design elements; therefore they have the potential for object quantities to be generated automatically.

Early model-based cost estimating software such as Innovaya Visual Estimating (Innovaya 2009), Vico Estimator 2008 (Vico 2008), or U.S. Costs' Success Design Exchange (U.S. Costs 2008) took advantage of BIM models. During 2008, Innovaya Visual Estimating received more attention in the US than other model-based cost estimating software since it supports Autodesk Revit and Sage Timberline Estimating (Figure 3.3), two popular platforms used for 3D modeling and cost estimating.

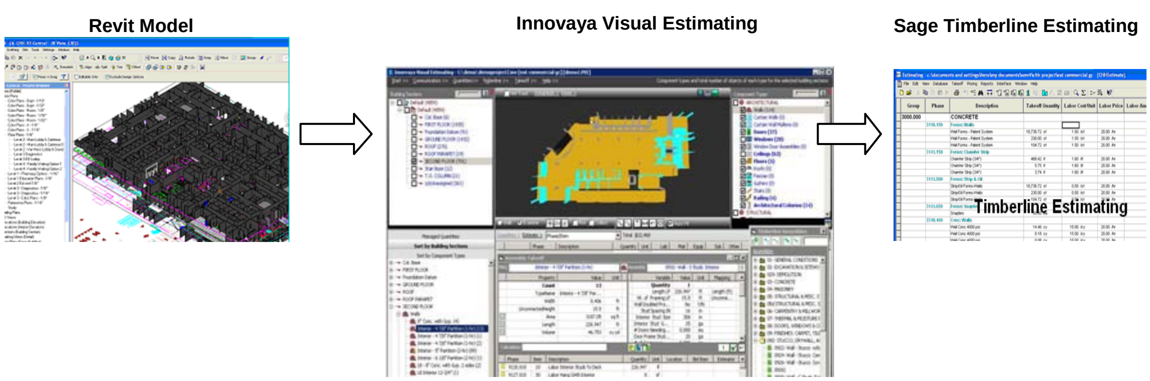


Figure 3.3 Model-based quantity take-off and cost estimating applications

Innovaya provides visual quantity take-off and visual estimating methods working in conjunction with Revit models. Cost estimating with Innovaya involves three steps: (1) visualizing and analyzing the design, (2) taking off quantities, and (3) estimating. The first step is exporting the Autodesk Revit model to a file format that can be opened in Innovaya. This interactive 3D user interface allows the estimator to understand and analyze the details of the design model. The second step is quantity take-off. Since the model contains dimensional information, it has the potential for object quantities to be generated automatically. However, default dimensional data from the BIM model may not always provide the needed values for the estimator to calculate detailed cost items, depending on how the cost assemblies are configured.

The final step in the process is costing. To perform this step, the estimator needs to link Innovaya to Timberline. The estimator can open up a Timberline database and drag and drop the object quantities generated in the previous step into Timberline assemblies or items (Khemlani 2006; Innovaya 2009).

Current model-based estimating solutions are more efficient and accurate than traditional estimating methods as they eliminate the need for manual measuring and quantity take-off: the dimensional information is already captured within the model. However, the improvement in the estimating process pertains to the quantity take-off and not to other parts of the process. Once quantities are established, the traditional cost estimating method using historical unit costs is applied to calculate costs of assemblies or of the whole facility. Modeling, quantity take-off, and cost estimating are often performed in different software platforms as shown in Figure 3.3. This approach does not take advantage of BIM that can combine various types of information in the model such as product, process, and cost information.

3.4.2 Model-Based Process Simulation

Model-based process simulation is also known as 4D modeling (product model in three dimensions (3D) plus the time dimension). The most common types of 4D models are the 4D sequencing models, 4D scheduling models, and 4D animation models:

- A 4D sequencing model illustrates the sequence of components showing up in a virtual environment according to their sequence indicated in a construction schedule. Durations of tasks are not part of this simulation. This study is useful for trade coordination during design phase, when task durations are not readily available, to identify interference and accessibility problems in order to improve the constructability of a design solution.
- A 4D scheduling model includes both task sequences and task durations. Components related to a task show up when the simulated time reaches the end time of a task. This permits the evaluation of issues pertaining to work area divisions and trade interferences. 4D scheduling is useful for visualizing phase schedules and look-ahead plans. Figure 3.4 depicts an example of 4D scheduling using Synchro Professional (Synchro 2008) in which objects in a 3D model are linked to activities in a Primavera P3 schedule (Primavera 2010).
- A 4D animation model helps to visualize the movement of equipment, labor, and components in a construction process. A 4D animation is useful in process design of challenging operations or in visualizing tasks in the weekly work plan to facilitate coordination of specialty contractors. When integrated with 4D sequencing or 4D scheduling, animation can bring more realistic visualization to these studies.

A model-based process simulation includes three steps: (1) acquire the 3D model and objects from designers and combine them into a single model for later process simulation, (2) obtain process information, such as schedule, resource, equipment, site logistics, and construction process from the construction team, and (3) integrate process data into the combined model to create a simulation of construction processes. Model-based process simulations enable the construction team to conduct ‘what-if’ analyses of different construction alternatives in a virtual environment, until a satisfactory method is obtained (Li et al. 2008).

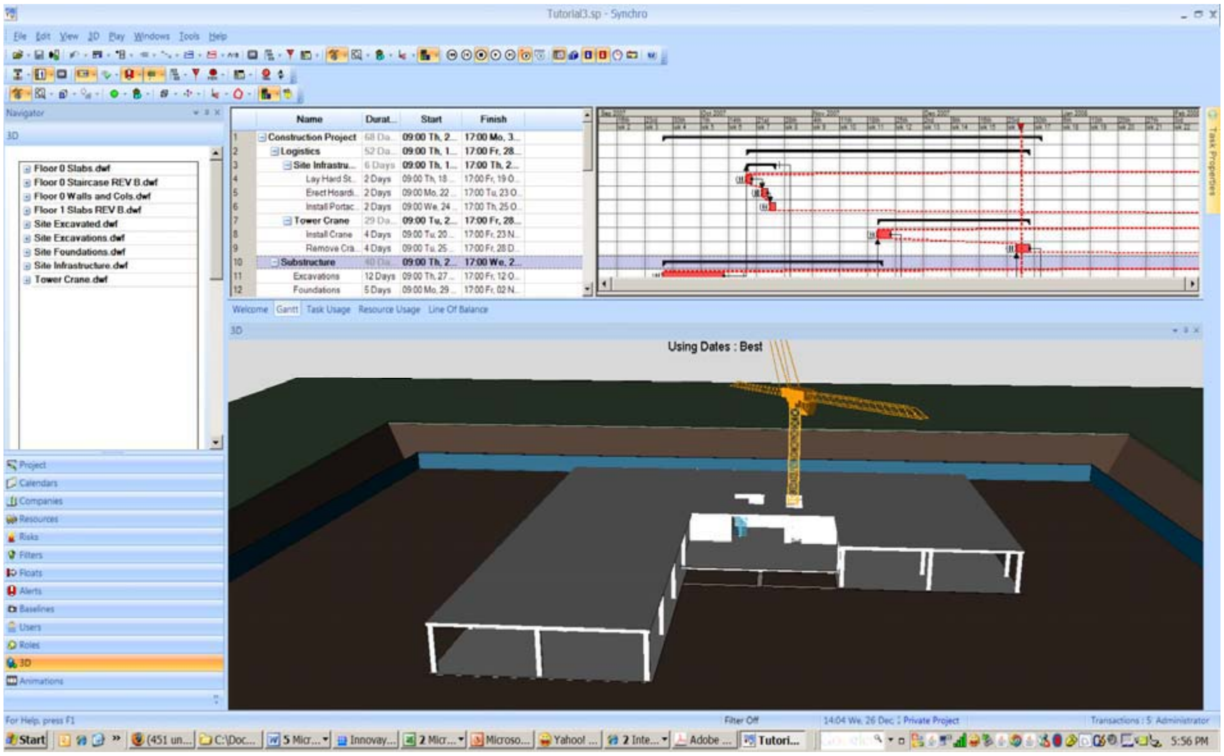


Figure 3.4 4D scheduling using Synchro

Many questions about the product and its construction process arise only at the moment someone tries to model them since accurate descriptions are required before modeling can take place. The process of creating a simulation is equivalent to the actual construction process, in that the simulation is a representation of the actual product and process, and the key reason to create a simulation is to find constraints that had not been anticipated. Processes that are difficult to simulate will likely also be difficult to construct (Kymmel 2008).

Researchers have analyzed the effectiveness of 4D modeling on different areas of design and construction. For example, Akinci et al. (2002) studied the use of 4D models for planning work space and site logistics. Hartmann and Fischer (2007) evaluated the use of 4D models for constructability review. Kamat and Martinez (2001) and Li et al. (2008) evaluated the application of 4D models for planning construction operations. With the IPD approach in a LPDS™, the cross-functional project team needs a framework for how to structure coordination meetings that take full advantage of process simulation. The challenge is to incorporate innovative ideas generated from the coordination meetings to both product- and process design in order to streamline fabrication, logistics, and installation processes.

Ballard and Howell (1997) recommended the adaptation and use of the Plan - Do - Check - Act (PDCA) cycle to study first runs of major operations during the construction phase. According to the Lean Construction Institute (LCI 2008), a first-run study is a “trial execution of a process in order to determine the best means, methods, sequencing, etc. to perform it.” Nguyen et al. (2009) introduced a virtual first-run study (VFRS) framework that helps to implement a first-run study in a virtual environment during a project’s design phase. A VFRS is defined as a

FRS carried out in a virtual environment, where objects of study are virtually created in three dimensions and those objects are linked to process information to simulate the course of construction. While FRSs help with process design during the construction phase, VFRSs are intended to help integrate product- and process design during the design phase. Figure 3.5 illustrates the VFRS work-flow.

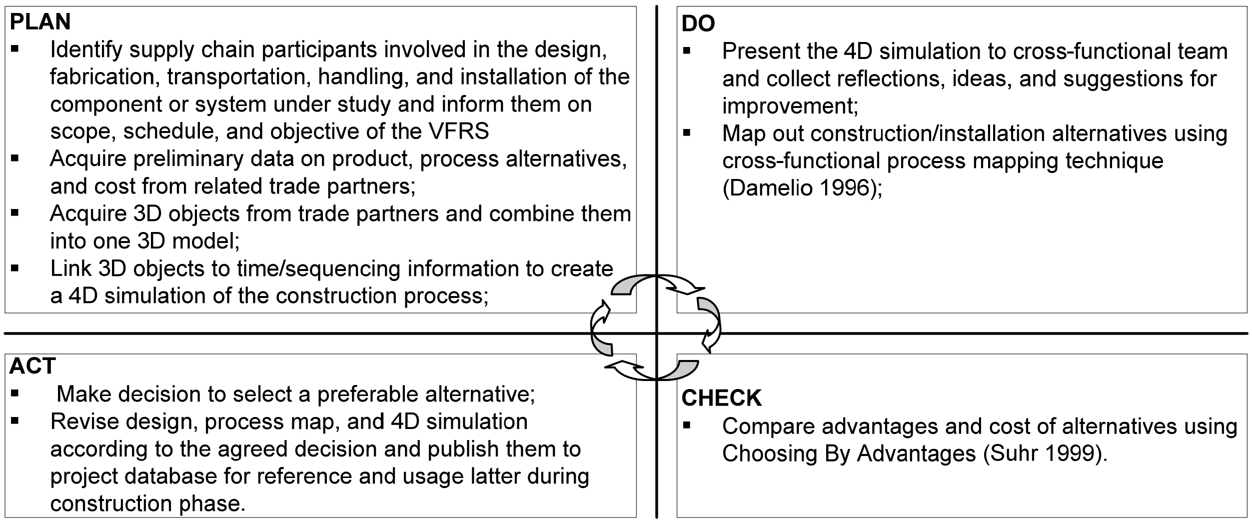


Figure 3.5 Virtual first-run study work-flow (Nguyen et al. 2009)

The main components of the VFRS framework include model-based process simulation, integrated team coordination meeting, process mapping, and CBA. Effectiveness of the VFRS framework is illustrated in the VDW case study at CHH (Chapter 6). By showing construction processes to a project team in a virtual environment, VFRS facilitates the coordination between specialists, assists with look-ahead planning, and yields reliable estimates of manpower and process-related cost as shown in the case study.

Popular 4D solutions include Innovaya Visual Simulation (Innovaya 2009), Synchro Professional (Synchro 2008), Navisworks Timeliner 2009, 2010 (Autodesk 2010c), Vico Control 2008 (Vico 2008), and Tekla CM (Tekla 2009). These applications are changing quickly and all their developers are trying to improve interoperability with other BIM applications as well as add more capabilities. However, each application has its own advantages in a certain area of its strategic focus. While Navisworks and Innovaya Visual Simulation aim at design visualization and coordination; Synchro, Vico Control, and Tekla CM focus on construction planning and control. Many architects, engineers and GCs in the United States use Navisworks for design coordination due to its advantage in interoperability with Autodesk modeling tools, such as Autodesk Revit and AutoCAD that are widely used by designers and specialty contractors. Appendix I provides more detail on these 4D applications.

3.5 RELATED RESEARCH

Staub-French and Fischer (2002) and Staub-French et al. (2003) proposed a method to capture estimators' rationale between product features and costs. A library of product features and cost relationships were proposed to help estimators make better judgments about cost implications of product customization to final cost. Although this library may help estimators make more rational adjustments of unit costs to account for product changes, the reliability of an estimate relies on estimators' past experience and the accuracy of historical cost data. In addition, this method was developed for traditional project delivery systems where design estimates were almost entirely done by cost estimators with limited involvement of specialty contractors during design. It did not take into account the significant changes in IPD systems where estimates often have direct inputs from specialty contractors. Therefore, it may tell how product customization affects the installation process, but it cannot make explicit to estimators or designers the cost implications of changes in processes, other than field installation, such as material delivery and site logistics as the result of changes in process design.

Bowen et al. (1987) suggested that cost models could be more realistic if they simulated the construction process and took into account the cost implications of the process in which buildings were constructed, i.e., how different construction methods affect cost. Recently, Odeh (1992), Li (2003), and Bargstädt (2004) attempted to simulate human resource activities with a high level of detail to determine process durations and associated process costs during simulation of production processes. By doing so, labor and equipment 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 time estimates, but they require detailed process data which may only be available in the late construction documents phase. Moreover, it would be very time consuming and expensive to collect data and simulate construction processes with a high level of detail.

Researchers and practitioners has been developing cost modeling methods to support TVD. The Boldt Construction Company developed a Project Baseline Index method (aka. the Quarterback Rating method). This is a parametric conceptual estimating method based on benchmarking cost data of completed projects. It takes into account broad project attributes such as the size of the building, the quality of building systems, and the nature of the construction site. This cost model can be used in Project Definition to estimate expected cost based on client requirements, prior to design (Morton and Ballard 2009).

Haahtela (2008), a project management firm in Helsinki, developed a building information cost model named Taku for the Finnish building sector. Taku models the facility cost during the Project Definition phase directly from client requirements. Taku uses the 'black box' modeling principles (Beer 1966) in which differences between the client's requirements are modeled by reference solutions, and the level of Target Cost is calibrated by continuously comparing the model's output to the actual bidding price. If these two results correlate, the difference is stored in the black box. Otherwise, the cost model needs to be improved (Pennanen et al. 2005; Pennanen and Ballard 2008). The two cost models proposed by The Boldt Company and Haahtela are mainly used during Project Definition to establish Target Costs at a system level.

This literature review provided a context for my research and contributions; it also highlighted the need for a new cost modeling method to better support TVD during the Design Development phase.

CHAPTER 4. PROPOSED FRAMEWORK FOR PROCESS-BASED COST MODELING

This chapter presents the current state of cost modeling during the Design Development phase in the TVD environment. This characterization of the current state is based on my direct observation over a time period of sixteen months, starting on May 2008, of the TVD process at the CHH project in San Francisco, as well as document analysis, and semi-structured interviews conducted with practitioners on that project. The findings led to a proposal of an alternative cost modeling method and help structure case studies and software development to deliver proof of concept. This chapter then illustrates the framework for a PBCM method, as follows: (1) collecting process- and cost data, (2) mapping process- and cost data to BIM objects, and (3) providing cost feedback during design.

4.1 PROJECT BACKGROUND

CHH is a new Acute Care and Women's and Children's hospital in San Francisco, California. It is a part of the California Pacific Medical Center (CPMC), an affiliate of Sutter Health. The project is budgeted at $1.7 billion. The hospital will have 555 patient beds and 912,000 building gross square feet (BGSF). Design of CHH began in 2007 and the project is expected to be completed by 2015. At the time of this publication, the project is in its preconstruction phase.

Sutter Health, one of northern California's largest health-care providers, has shown a commitment to lean practices as a new design and construction philosophy to execute its major capital projects. It translated lean ideas into an organizational philosophy based on "Five Big Ideas": (1) collaborate - really collaborate, (2) increase relatedness, (3) projects as a network of commitments, (4) tightly couple learning with action, and (5) optimize the whole (IFOA 2007).

The owner, the architect, and the GC formed an IPD team to facilitate design, construction, and commissioning of the Project. The IPD team included the owner, architect, consultants, GC, subcontractors, and suppliers. Table 4.1 lists the IPD team members who participated in the Design Development Phase.

The IPD team organized into cluster groups. Cluster groups are the organizational units for all phases of project delivery and members of clusters are physically co-located in a shared office (Validation Study Report 2007). Cluster groups are cross-functional teams of facility stakeholders, designers, construction managers, suppliers, and contractors. Cluster groups for this project included structural, MEP (mechanical, electrical, and plumbing), exterior skin, interiors, technology, virtual design and construction, equipment, vertical transportation, and production.

Figure 4.1 presents the structure of the IPD team. A core group including executive representatives from the owner (Sutter Health), owner's affiliate (CPMC), architect (Smith Group), and the GC (HerrerBoldt). The core group is responsible for reviewing and stimulating the progress of the project. The core group meets on a weekly basis and makes decisions by consensus.

Table 4.1 IPD team members during Design Development

IPD Team Members	**Role/Specialty**
CPMC/Sutter Health	Owner
Smith Group	Architect/Engineer
HerreroBoldt	Construction Manager/GC
Degenkolb	Structural Engineer
Charles Pankow Builders	Concrete Structures Contractor
Olson Steel	Miscellaneous Steel Fabricator
Herrick Steel	Structural Steel Contractor
Pacific Erectors	Steel Erection Contractor
DIS	Viscous Wall Damper Fabricator
Ferma Corporation	Demolition Contractor
Ryan Engineering	Excavation Contractor
Ad-In Inc	Acoustical Contractor
ISEC	Doors/Frames/Hardware Contractor
KHS&S Contractors	Metal Frame and Drywall Contractor
Bagatelos Architectural Glass	Curtain Wall Contractor
D&J Tile & Exterior Stone	Exterior Stone Contractor
The Lawson Roofing	Roofing Contractor
Ted Jacob Engineering Group	Mechanical Engineer
Southland Industries	Mechanical Contractor
Capital Engineering	Mechanical Engineering Consultant
Rosendin Electric	Electrical Contractor
Silverman and Light	Electrical Engineer
Otis Elevator	Elevator Contractor
RLH Fire Protection	Fire Protection Contractor

To support lean thinking, the CPMC team developed its own relational contract called the Integrated Form of Agreement (IFOA). The IFOA created the contractual and financial framework to facilitate the effective collaboration of the owner, architects, engineers, specialty contractors, and supply chain members. According to this agreement, all costs such as labor, overhead, materials, and purchased equipment will be reimbursed at actual cost. Profit is a negotiated lump-sum and to be paid per schedule. The owner jointly with all other key members on the IPD team put a certain portion of their fee into a shared risk pool. The shared risk pool is paid to IPD team members if the project cost is less than or equal to the Estimated Maximum Price (EMP) (aka. allowable cost). If the project cost exceeds the EMP the at-risk pool will be used to repay the owner for the difference. IPD team members will not be liable to the owner for damages, claims, expenses and/or liabilities in excess of the total amount deposited in the IPD team at-risk pool account. With this arrangement, Sutter has removed all but a small quantified amount of risk from the project for IPD team members (IFOA 2007). This brings an incentive and the freedom for team members to collaborate and focus their effort in maximizing overall value of the project instead of trying to optimize their own operations. During the design phase, team collaboration efforts were orchestrated through the TVD process.

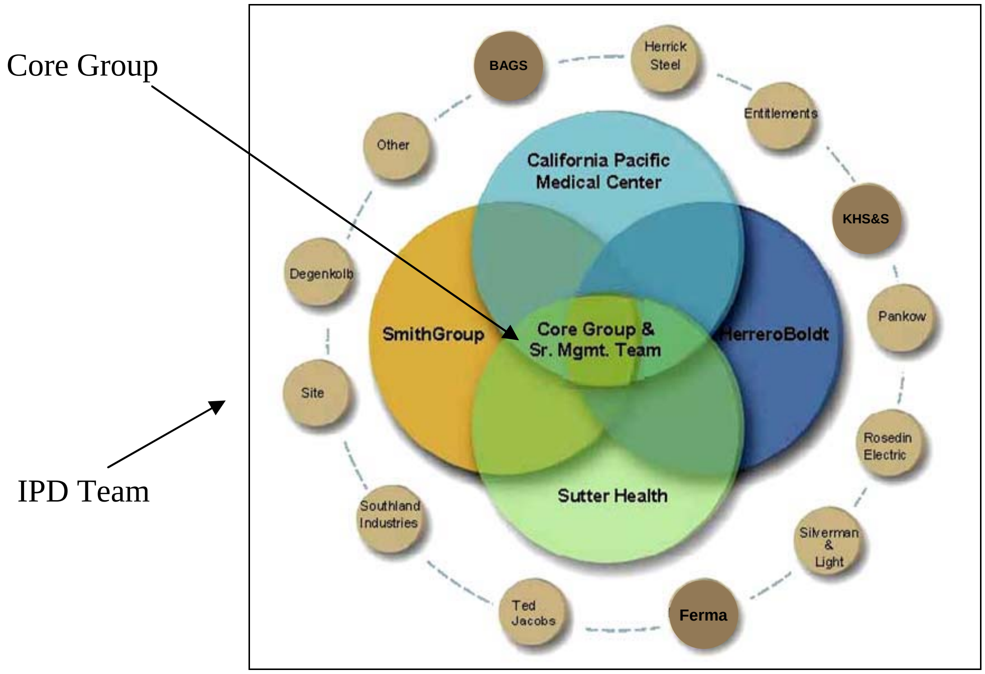


Figure 4.1 Organization structure of IPD team at CHH project (IFOA 2007)

An example of successful collaboration effort at CHH is an arrangement between the owner, the structural engineer, the GC, and the steel mills in addressing the volatility of the structural steel material. Volatility in the construction market is the predictability of the price and availability of a construction material (Cross 2004). Volatility has a great impact on the product design and the construction estimating practice. The potential availability of the product during construction may affect designers' decision on whether to select it or not, and the estimators need to reflect the impact of price changes and material availability in their cost estimates. Cross (2004) recommended that specialty contractors must be brought in early to the project and integrated into the design and construction team to lessen the risks of construction material volatility. Specialty contractors can offer expertise regarding material pricing, cost-saving techniques, process design, and working with material suppliers that owners, architects, engineers, and GCs do not possess. Cross' recommendations are proved to be valid in the case of CHH, the IPD team brought Herrick Steel into the early Design Development phase. Herrick worked with steel mills and collaborated with the IPD team and proposed a structural steel price protection plan. According to this plan, Herrick will act on behalf of the IPD team to negotiate material pricing with steel mills. Once agreed on the price, the IPD team will purchase a price protection guarantee for a total of 9,000 tons of wide flange structural steel at a cost of $270,000. This expense will be taken from a structural steel escalation budget of $1.4 million to handle future structural steel escalation. This plan not only protects the structural steel budget from escalation, it also ensures the availability of structural steel material during construction.

Considering these advantages, the IPD team decided to authorize Herrick to implement the price protection plan.

4.2 TARGET VALUE DESIGN AT CATHEDRAL HILL HOSPITAL PROJECT

TVD is a broadened concept of Target Costing (Ballard 2006). TVD encompasses key principles including: Target Costing, work structuring, set-based design, collaboration, and collocation (Macomber et al. 2007). The aim of TVD is to maximize value generation while remaining within the Target Cost (the cost that is set lower than the allowable cost in order to drive innovation beyond current practices). With the focus on value, TVD covers additional design criteria beyond cost, including constructability, time, process design, design collaboration, etc. (Lichtig 2005).

The IPD team at CHH specified target value from the project definition phase. The target value included both Target Cost and project goals that are to be achieved within the Target Cost. The Target Cost was established during an extensive business planning phase, followed by a four month business plan validation phase that included key members of the project design team, including architects, engineers, the GC, and critical trade partners (Ballard and Rybkowski 2009). The established Target Costs were assigned to each cluster group. TVD spans from the project definition phase to the design phase and it helps steer a design team to meet established design criteria. This effort may result in shifting costs from the construction phase to the design phase, or between Target Cost categories. In the case of CHH, fabrication drawing production and constructability coordination, which typically are accounted for as a construction cost, took place during design. In TVD, designers and engineers produce only those deliverables needed for permitting and needed by trade partners for detailing. Later on, trade partners and suppliers produce detailed design. This was made possible due to the owner's willingness to invest upfront and pay for the production of details well before the start of construction (Lostuvali et al. 2009).

To implement the TVD process, cluster groups structured meetings on a weekly basis to coordinate the design of major building components and systems. They attempted to simultaneously design the product (what is to be built) and the process (how it will be built). Table 4.2 introduces the weekly TVD cycle at CHH, where Tuesdays and Thursdays are designated as meeting days and formal cluster group workdays. Mondays, Wednesdays, and Fridays are designated as informal cluster group workdays and IPD team collaboration days.

In a TVD meeting, the TVD manager provides an overview of the project estimate including variances in cost relative to the previous week and to the Target Cost. Each cluster group leader reports on weekly progress. The report-out by cluster group leaders may include mention of the (1) status of current cost estimates belonging to their cluster, (2) review of current and outstanding issues, (3) report on value improvement ideas, and (4) path forward.

In cluster group working sessions, the focus is to: (1) innovate value into the design and budget, (2) understand the Target Cost budget and details behind what the budget includes, (3) identify constraints and areas of concern that impact design, cost, schedule and value, (4) thoroughly understand the issues and prioritize issues, (5) prepare A3 reports for outlining the situation and communicate alternatives and recommendations to the core group for approval to move forward, (6) use value analysis to analyze constraints and areas of concerns and to find and resolve value mismatches, and (7) inform, communicate, and collaborate with other cluster groups and IPD team regarding issues, constraints, and areas of concerns.

Table 4.2 Weekly TVD activities

Weekday	**Activities**
Tuesday	- Update cost at TVD meeting - Cluster group meetings: Designing and budgeting
Wednesday	- Ongoing TVD cluster group collaboration - Core Team meeting
Thursday	- IPD Last Planner™ meeting - Ongoing TVD cluster group collaboration - Design and information release to Buzzaw
Friday	- Design and ongoing collaboration
Monday	- Design and ongoing collaboration - Update estimate at the end of the day

A cluster group leader is responsible for: (1) initiating A3 reports, cost trends, schedule impacts, etc. as necessary to push progress towards project goals, (2) communicating information, findings, requests, constraints, and concerns to the IPD team, (3) identifying the need and the opportunities to negotiate budgets between cluster groups, and (4) reporting progress, issues, and recommendations in the weekly TVD meeting.

Designers and trade partners release their updated designs by posting them on Autodesk Buzzaw (Autodesk 2010a) every Thursday. Autodesk Buzzsaw is a secure, online collaboration project management service provided by Autodesk that allows team members to store, manage, and share BIM models and drawings from any internet connection. Each IPD team member has its own Autodesk Buzzsaw account.

Continuous value analysis and cost updating takes place within cluster groups in order to monitor estimated costs against Target Costs (Validation Study Report 2007). For components or systems that pose potential challenges to fabrication, logistics, or installation, the team needs to organize design and construction coordination meetings to address supply chain issues and identify the most preferred integration of product- and process design alternative that meet specified value targets.

Figure 4.2 shows the progress of the gap to Target Cost at CHH. At the start of the Design Development phase on September 2007, the Target Cost for CHH was set about 13% below market. During the two years and three months of design (from September 2007 to December 2009), the team reduced its estimate by $106 million. By December 2009, the construction estimate was about $13 million below Target Cost as shown in figure 4.2. Recently, in an attempt to find a budget for added value items, a new Target Cost was further established at $70 million below the original Target Cost with gain-sharing provisions.

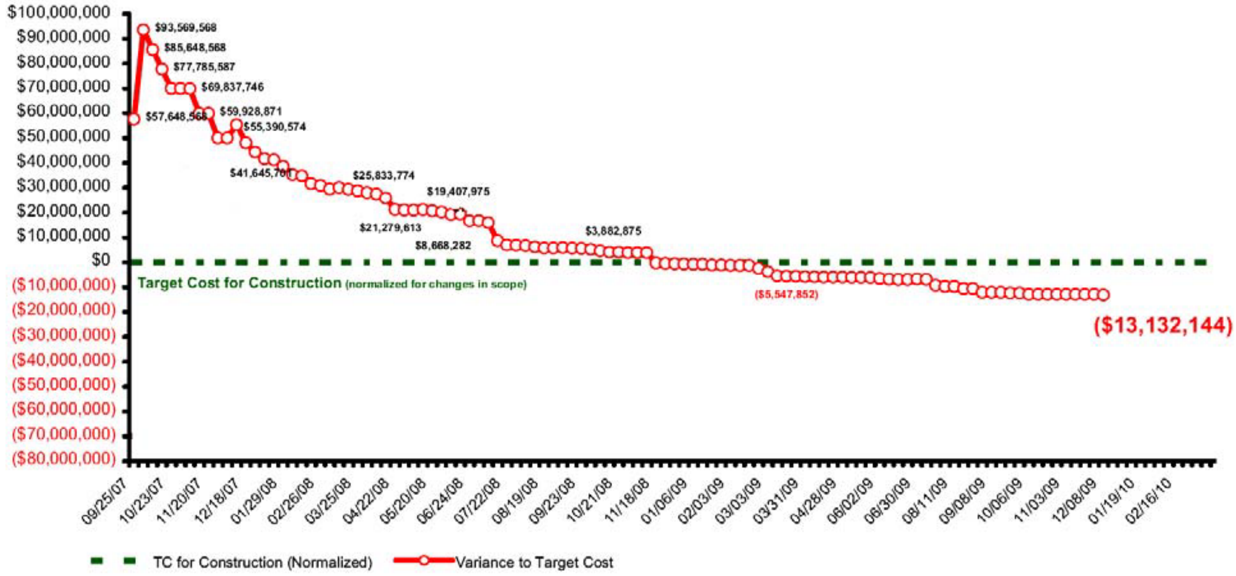


Figure 4.2 Progress of the gap to Target Cost at CHH

4.3 CURRENT PRACTICE OF COST MODELING TO INFORM TVD AT CHH

4.3.1 Cost Modeling to Inform TVD at CHH

Figure 4.3 presents the cost modeling process during the Design Development phase at CHH.

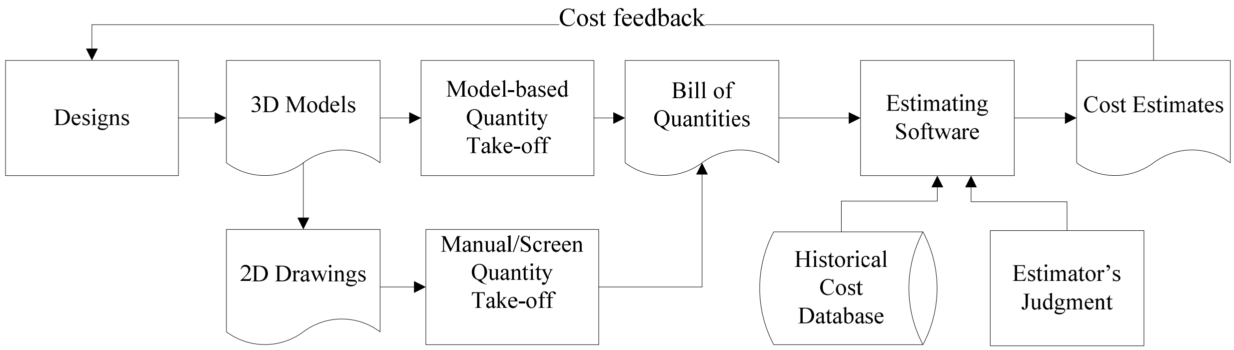


Figure 4.3 Cost modeling process during the Design Development phase at CHH

Cluster leaders were responsible for assembling cost updates for their clusters. For each update, cluster leaders requested cost estimates from trade partners and suppliers according to their most recent design. Cluster leaders then checked the scope of work, quantities, and unit costs submitted by trade partners and aggregated them to cluster cost updates to inform TVD. In general, cluster leaders trust trade partners with their estimates.

The IPD team desired frequent cost updates, such as on a weekly basis. Some clusters actually tried to oblige in the early Design Development phase, however, that took away a lot of time from trade partners and cluster leaders to track quantity changes and assemble cost updates. The IPD team then decided to request cost updates from clusters on a staggered basis: two or three clusters provide cost updates in one month and other two or three groups report out the month after. As a result, it often took from one to two months for one cluster group to report out their cost updates during the Design Development phase.

During Design Development, the IPD team performed most of the design work using 3D modeling applications such as Autodesk Revit and 3D CAD. However, only Herrick Steel established a model-based quantity take-off process to extract material quantities from their structural steel model. Other trade partners extracted 2D drawings from 3D models to perform manual or on-screen quantity take-off. A cost estimate of a component was calculated by multiplying its material quantity and its composite unit cost. Once having a bill of quantities, an estimate was calculated from the summation of the quantities multiplied by the corresponding unit costs as is done in 'traditional' detailed estimating. To adjust their baseline unit cost, they relied on their understanding of the project and their own experience to add to or subtract a certain percentage from a baseline. This way, estimators at CHH used a conventional method to estimate cost, using product quantities and historical cost data. Although these cost data contain specific trades' means and methods and thus are more accurate than commercial cost data such as RSMeans (RSMeans 2010) would be, it does contain inefficiencies and wastes from previous project such as trade interference, location conflict, productivity loss, excessive logistics and site handling cost as pointed out in section 3.3.2.6 in Chapter 3.

Besides, estimators may add a layer of contingency on top of the historical cost data. As mentioned by an estimator working at the CHH project "the number provided by trade partners may contain 'fat', people may put in a contingency for parking, waiting for the man lift and crane, and for other things they have to assume." However, as discussed in section 4.3.2, this "fat" may be minimized by taking advantage of the cross-functional collaboration opportunity offered by the IPD approach. Table 4.3 illustrates an example cost estimate using quantities and composite unit cost at CHH. The estimated unit costs often included all cost incurred from purchasing material to finishing installation. Costs related to storage, transportation, and site handling were not explicitly accounted for in the estimate. Cost estimators estimated unit costs using previous projects' cost data and quotes from subcontractors and suppliers as a baseline cost.

Table 4.3 Example cost estimate using quantities and unit costs at CHH

CODE	Description	Quantity	Unit	Unit Cost	Extension
09 30 00	Ceramic, Quarry & Stone Tile				
	Stone Tile Panel	1,982	sf	$58.00	$114,956
	Ceramic Tile Flooring	69,000	sf	$20.00	$1,380,000

Herrick Steel delivered the only example of the successful use of model-based quantity take-off to reduce its cost estimate lead time. Originally, it took Herrick Steel two and a half weeks with eighty man-hours to manually perform quantity take-off for the entire CHH structural steel system. After putting model-based quantity take-off system in place, it took only four man-hours to perform both the quantity take-off and the cost update. To achieve this, a Herrick Steel's cost estimator worked with a Degenkolb's Autodesk Revit modeler to create built-in material schedules in Autodesk Revit Structure 2009 so that when exporting these material schedules to Microsoft Excel, the format would match that of Herrick's cost estimating standard. As a result, when Degenkolb updated its design model weekly on Thursday afternoon, Herrick could extract updated quantities to its standard cost estimating spreadsheet, check, and then provide a cost update for the structural steel system to the TVD team.

4.3.2 Findings about Cost Modeling at CHH and Directions for a Process-Based Cost Modeling Method

The TVD environment at CHH offered design phase opportunities including: (1) Collocation and collaboration of the IPD team, (2) Set-Based Design resulted in multiple design alternatives, (3) Frequent sharing of incomplete information, (4) Simultaneous design of product and process, (5) 3D Design/Modeling and digital prototyping, and (6) Specialty contractor and supplier participating in the design process.

The application of TVD often results in multiple design alternatives with not only different product cost and process cost but also different product features. As pointed out in Chapters 1 and 3, traditional cost modeling methods are insufficient to perform trade-off analysis between multiple alternatives of product- and process design especially as needed to support TVD. This raised a need for an alternative cost modeling method, which must be able to specify: (1) cost changes due to changes in product design (i.e., changes in materials, shapes, or dimensions), and (2) cost changes due to changes in process design (i.e., changes in sequencing, logistics, or construction processes).

CHH's current cost estimating practice applied during Design Development has not taken full advantage of the TVD environment. Most cost estimators from trade partners work remotely in their own company office and have little access to information from coordination meetings, logistics planning, and production planning. As a result, they may make assumptions on information already available and estimate cost based on those assumptions. These assumptions lead to 'contingency' built into the estimate to account for uncertainty. However, many of those contingencies could be eliminated if estimators were made aware of the ongoing logistics planning and production planning. Having cost estimators participate in key coordination meetings would make their estimate 'leaner' (meaning less contingency/fat). In addition, the coordination team could benefit from immediate cost advice in evaluating design alternatives from cost estimators who join the meeting. It should be noted that estimators are often busy with multiple projects at a time. Some estimators from trade partners at CHH indicated work pressure at their home office was a major reason preventing them from attending meetings at CHH. However, they also indicated that they spent about 30% to 70% of their time on taking off quantities or checking BOQs submitted by others. That time could be significantly reduced by taking advantage of BIM as will be mentioned later. In that case, estimators may have more time for more value adding activities such as helping project teams with value engineering or attending and providing cost advice at design coordination meetings.

CHH's current cost estimating practice during Design Development has not completely taken advantage of BIM. Except for the structural steel trade partner who managed to save two and a half weeks in providing each cost estimate update by using a model-based quantity take-off process as mentioned, other cost estimators perform quantity take-off using 2D drawings extracted out of 3D models. By converting 3D model to 2D drawings, the design was represented by multiple drawings such as plans and elevations, thereby increasing the likelihood of missing or double counting individual elements of the design. In addition, quantity take-off on 2D drawings was a time-consuming process, it took weeks for a cluster to complete updates on quantities. Upon completion of updated BOQs, designs had changed and that meant the BOQ and thus the cost estimate was out of date.

Key issues for not using model-based quantity take-off as identified from interviews with trade partners were (1) 3D models were not configured to provide quantities that match the estimator's cost breakdown structure, and (2) cost estimators did not have tools or training needed to perform model-based quantity take-off. However, these issues could be resolved by providing training to cost estimators and having modelers and cost estimators work together to ensure that quantity outputs from a 3D model are usable by cost estimators. This resolution proved to work successfully when Degenkolb's modeler collaborated with Herrick Steel's estimator, as described. Together with the VDC cluster group, I have been facilitating collaboration between modelers and cost estimators, as well as preparing standard processes to promote model-based quantity take-off at CHH. By the end of 2009, more trade partners had successfully adopted model-based quantity take-off, including the exterior stone panel, exterior metal panel, and door/frames/hardware trade partners.

By using historical cost data, cost estimators rely on data containing process inefficiencies and wastes. If these wastes can be eliminated during data collection process and inefficiencies are made explicit to estimators, cluster leaders, and the TVD team, the cost estimate may be further compressed.

4.4 OVERVIEW OF PBCM FRAMEWORK

The PBCM method proposed in this research is not intended to replace traditional cost models. While traditional models focus on the 'what' of cost, PBCM will focus on the 'how'. PBCM is intended to supplement traditional models by making process information explicit to designers and cost planners. By linking a product model to cost data, PBCM may provide rapid cost feedback to design and lessen the time required to assemble cost updates to inform TVD.

The purpose of PBCM is to support the selection of a design alternative during the Design Development phase, thus the model needs to give a relative cost and this can be useful even when it is approximate. To do this, as pointed out in Chapter 3, 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 analyzing design alternatives. Process-related cost may include cost of material handling and transportation, site logistics, and site installation depending on the scope of consideration.

The best project environment in which to apply this cost model is in projects that use an IPD approach, where key players from upstream to downstream of the project (such as owners, architects, engineers, the GC, specialty contractors, suppliers, and permitting agencies) are members of the design team. In addition, this cost model can be used in more traditional project delivery systems with integrated approaches such as DB, Construction Manager at Risk, and Multi-Prime with DB approach where their structures allow early involvement of constructors in the design process. A design-assist approach used in combination with these project delivery systems may further facilitate the participation of specialty contractors in design (Gil et al. 2000; Gil et al. 2001). Since such early involvement is limited when using DBB as the project delivery model, a PBCM has few opportunities for effective application in DBB. However, the owner in a DBB contract may allow early involvement of contractors during design, but in order to avoid the conflict of interest in bidding those contractors are often excluded from the owner's bidding list. Although those contractors may provide process- and cost advice to designers and they may help in estimating product and process cost, their cost estimates may not be reliable since the contractors who are actually selected to perform the work may use different means and methods for construction.

Figure 4.4 presents key process steps of PBCM including three phases: (1) Capturing process cost data; (2) Attaching cost data to an object family; and (3) Creating cost feedback to a design team.

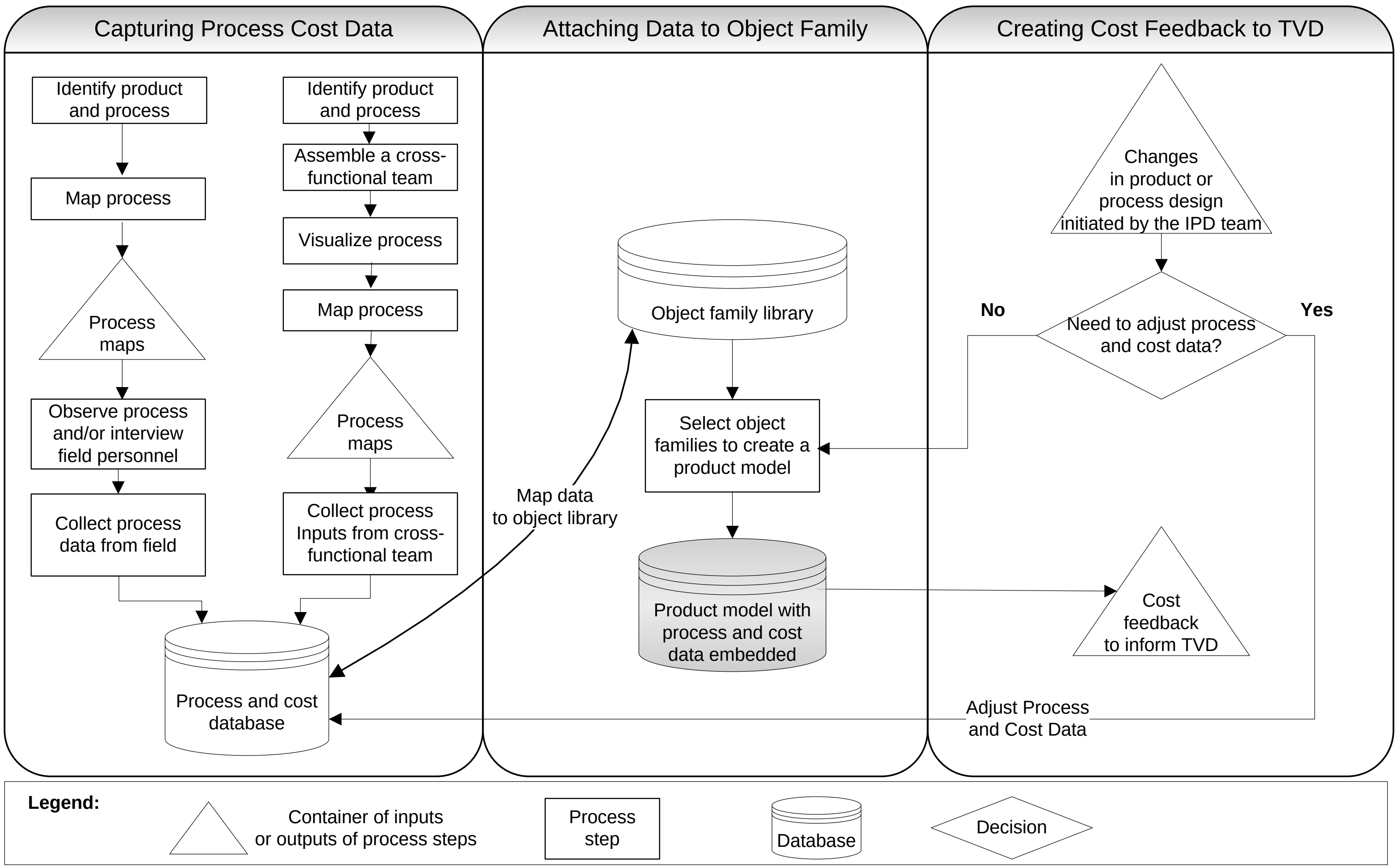


Figure 4.4 PBCM framework

4.4.1 CAPTURING PROCESS- AND COST DATA

This section presents two methods of collecting process- and cost data in two scenarios: (1) for products that have standard process designs and (2) for products that require new process designs.

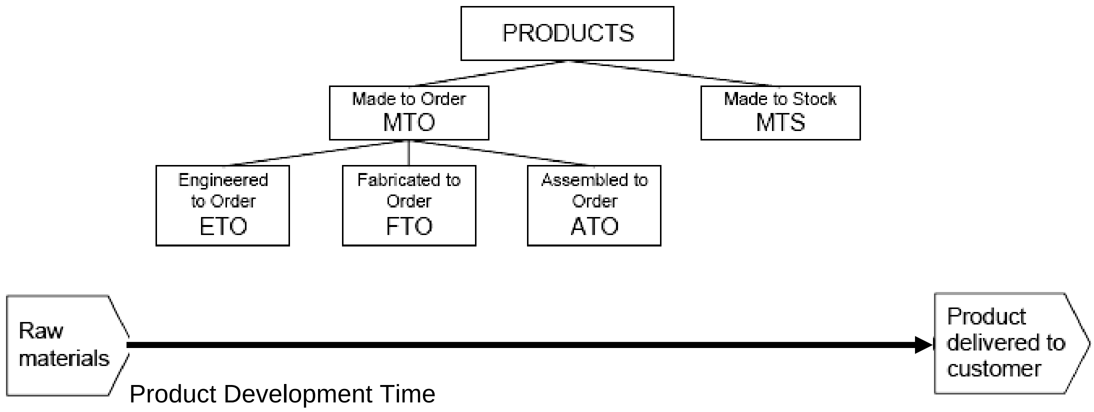


Figure 4.5 Types of products (Simplified from Tommelein et al. 2009)

With standard products or systems, it is possible for contractors to develop standard processes for installation over time and collect process data. Made-to-Stock (MTS) and Assembled to Order (ATO) products often fall in this category (Figure 4.5). Section 4.4.1.1 proposes a method to collect process data for standard products or systems.

In contrast, with products or systems with more unique designs, it may not be possible for contractors to develop standard processes for installation. The use of Engineered to Order (ETO) and Fabricated to Order (FTO) products often cause major changes of process design. As a result, installation activities and their durations are varied when the contractor installs ETO or FTO products that have different designs. Section 4.4.1.2 proposes a method to collect process data for products or systems that vary significantly in process design or require new process design.

Figure 4.6 illustrates steps for capturing process- and cost data in the two mentioned scenarios.

4.4.1.1 Products that Have Standard Process Design

Step 1: Specify a product under study and define the process boundary:

1.a. Specify a product under study.

1.b. Determine the scope of process data to be collected: process data may cover only one phase such as field installation or multiple phases such as pre-assembly, transportation, material handling on site, and field installation.

1.c. Identify responsible parties: parties who participate in design, fabrication, transportation, and installation of the product.

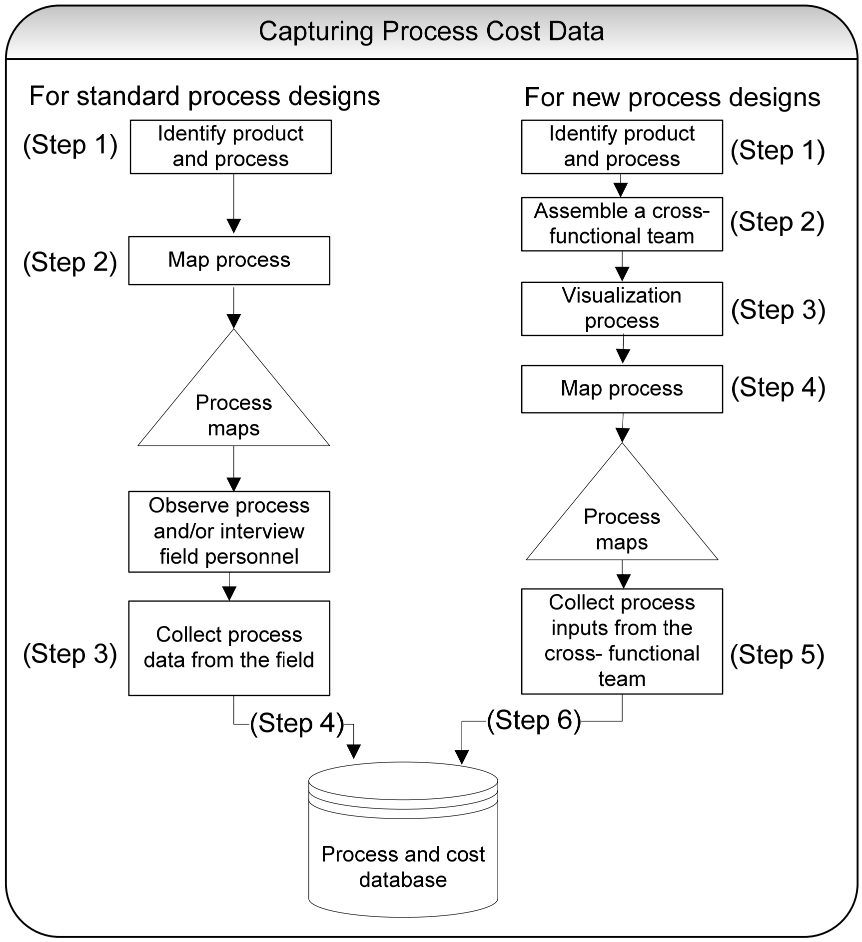


Figure 4.6 Steps for capturing process- and cost data

Step 2: Map the process and identify cost drivers for each activity:

2.a. Conduct interviews with field personnel such as superintendents, project engineers, and/or project managers to identify activities and their sequence.

2.b. Create a cross-functional process map, the level of detail in a process map is chosen to fit the needs of the decision maker who will evaluate design alternatives.

2.c. Identify a cost driver for each activity. A cost driver is parameter that has a predominant effect on the cost of activity, for example, the activity duration is often a cost driver for an installation activity.

Step 3: Capture process- and cost data.

3.a. Capture process- and cost data according to activities on the process map: Process data may include activities' names and descriptions, sequence, durations of activities, crew composition, the number of man-hours to complete each activity, equipment utilization, inventory space needs, and transportation distance. Process data can be collected by direct observation of actual processes or by interviewing field personnel or by combining both direct observation and interview methods. The technique for collecting data may include: videotaping, time tracking, and having inputs from crew, superintendent, project engineer, and project manager. Cost data may include material cost, crew cost, equipment cost, inventory cost, and transportation cost. These cost data can be obtained from the project's accounting system or from the project's records, such as purchasing receipts, time sheets, equipment rental contracts, etc.

3.b. Identify process waste and remove it from process- and cost data

Step 4: Feed process- and cost data into a database, calculate cost of each activity, and allocate activity cost to each product unit. Figure 4.7 depicts a sample in which different types of data from a process map are input to a database.

Chapter 5 presents a case study to demonstrate the method of collecting process- and cost data for standard products that have standard processes of installation.

4.4.1.2 Products that Require New Process Designs

Step 1: Identify product and process

Select products or systems that have a high installation cost, pose a challenge to site logistics, require tight coordination between specialists, or contain process uncertainty.

Step 2: Assemble a cross-functional team

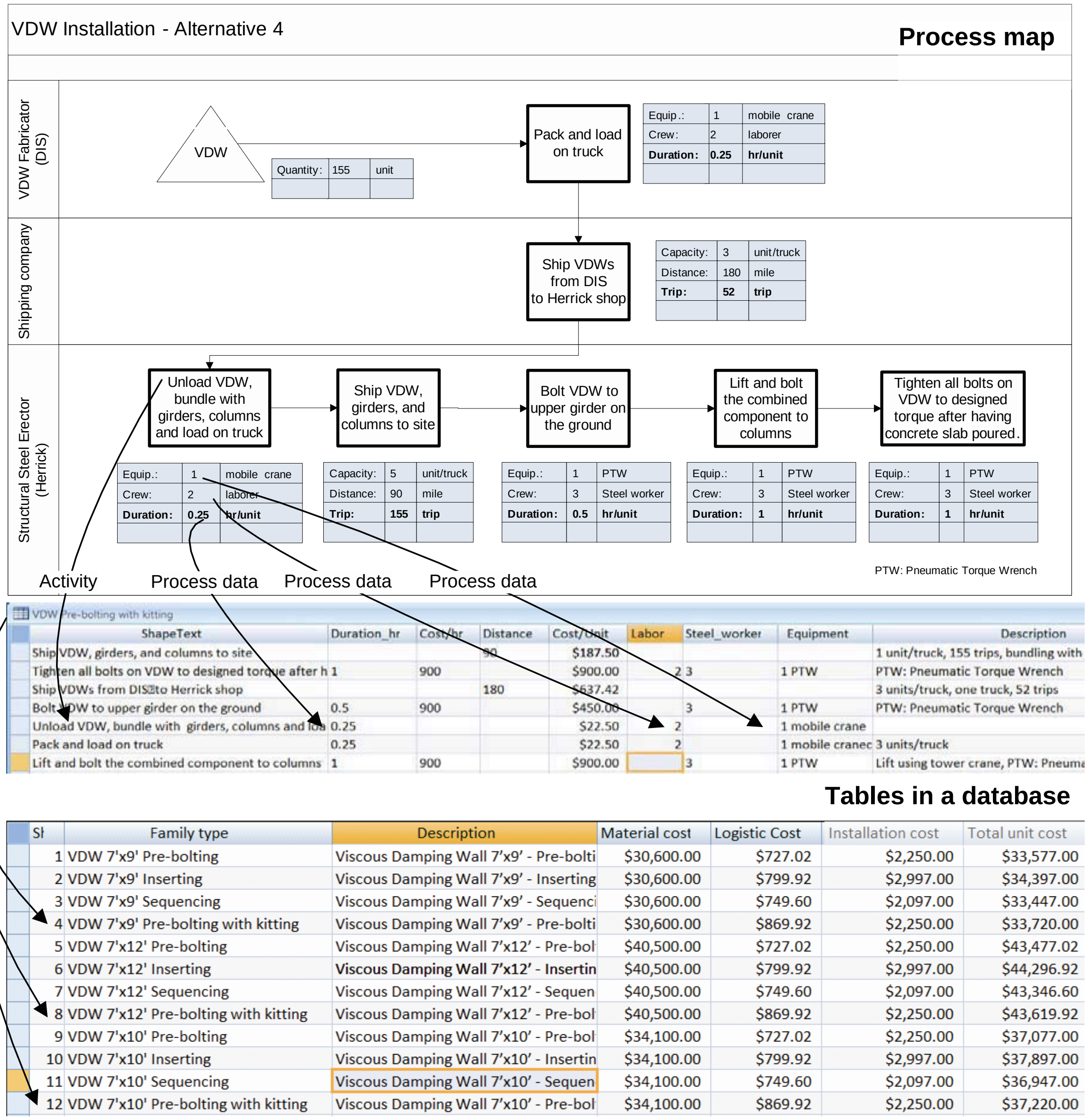
The cross-functional team should include the representatives of the designer or the engineer, the GC, the fabricator or the supplier of the product or system, and the specialty contractors who perform site installation work.

Step 3: Present 4D simulations of installation alternatives to the cross-functional team.

Objectives of process visualization are to: (1) graphically display construction processes to the team, (2) facilitate the coordination between designers, GC, suppliers, and specialty contractors to integrate product- and process design, and (3) help the team develop a common understanding of work conditions.

Step 4: Process Mapping

4.a. Define process boundary



VDW Pre-bolting with kitting

ShapeText	Duration_hr	Cost/hr	Distance	Cost/Unit	Labor	Steel_worker	Equipment	Description
Ship VDW, girders, and columns to site			90	$187.50				1 unit/truck, 155 trips, bundling with
Tighten all bolts on VDW to designed torque after h	1	900		$900.00	2	3	1 PTW	PTW: Pneumatic Torque Wrench
Ship VDWs from DIS to Herrick shop			180	$637.42				3 units/truck, one truck, 52 trips
Bolt VDW to upper girder on the ground	0.5	900		$450.00		3	1 PTW	PTW: Pneumatic Torque Wrench
Unload VDW, bundle with girders, columns and loa	0.25			$22.50	2		1 mobile crane	
Pack and load on truck	0.25			$22.50	2		1 mobile cranec	3 units/truck
Lift and bolt the combined component to columns	1	900		$900.00		3	1 PTW	Lift using tower crane, PTW: Pneuma

Sl	Family type	Description	Material cost	Logistic Cost	Installation cost	Total unit cost
1	VDW 7'x9' Pre-bolting	Viscous Damping Wall 7'x9' - Pre-bolti	$30,600.00	$727.02	$2,250.00	$33,577.00
2	VDW 7'x9' Inserting	Viscous Damping Wall 7'x9' - Inserting	$30,600.00	$799.92	$2,997.00	$34,397.00
3	VDW 7'x9' Sequencing	Viscous Damping Wall 7'x9' - Sequenci	$30,600.00	$749.60	$2,097.00	$33,447.00
4	VDW 7'x9' Pre-bolting with kitting	Viscous Damping Wall 7'x9' - Pre-bolti	$30,600.00	$869.92	$2,250.00	$33,720.00
5	VDW 7'x12' Pre-bolting	Viscous Damping Wall 7'x12' - Pre-bol	$40,500.00	$727.02	$2,250.00	$43,477.02
6	VDW 7'x12' Inserting	Viscous Damping Wall 7'x12' - Insertin	$40,500.00	$799.92	$2,997.00	$44,296.92
7	VDW 7'x12' Sequencing	Viscous Damping Wall 7'x12' - Sequen	$40,500.00	$749.60	$2,097.00	$43,346.60
8	VDW 7'x12' Pre-bolting with kitting	Viscous Damping Wall 7'x12' - Pre-bol	$40,500.00	$869.92	$2,250.00	$43,619.92
9	VDW 7'x10' Pre-bolting	Viscous Damping Wall 7'x10' - Pre-bol	$34,100.00	$727.02	$2,250.00	$37,077.00
10	VDW 7'x10' Inserting	Viscous Damping Wall 7'x10' - Insertin	$34,100.00	$799.92	$2,997.00	$37,897.00
11	VDW 7'x10' Sequencing	Viscous Damping Wall 7'x10' - Sequen	$34,100.00	$749.60	$2,097.00	$36,947.00
12	VDW 7'x10' Pre-bolting with kitting	Viscous Damping Wall 7'x10' - Pre-bol	$34,100.00	$869.92	$2,250.00	$37,220.00

Figure 4.7 Data inputted from a process map to a database

4.b. Identify process steps that belong to each specialty and specify hand-offs between specialties.

4.c. Map the process and it alternatives

For each design alternative, the cross-functional team provides data and knowledge to map out fabrication, logistics, and installation processes using process mapping. Process maps serve as a platform for the team to provide input data such as activities, sequencing alternatives, estimated duration of each step, estimated number of man-hours to complete each step, equipment, inventory space needs, constraints and coordination requirements from each party.

Step 5: Capture process data by getting input from the cross-functional team.

The GC, designers, trade partners, suppliers, and cost estimators provide data relating to each activity in the process map such as distance, truck capacity, design quantities, crew composition, activity duration, and estimated unit cost for each cost driver. Process cost is calculated using process data and established rates for labor, equipment and materials.

Step 6: Feed process- and cost data into a database, calculate cost of each activity, and allocate activity cost to each unit of product. Figure 4.7 depicts a sample in which different types of data, collected from the process mapping session, are input to a database.

Chapter 6 and Appendix C demonstrate the method of calculating activity cost and allocating activity cost to product unit in more detail. Chapter 7 demonstrates the mechanism to link process- and cost data in a product model. Chapter 7 also presents a method to automatically map data related to an activity (such as duration, crew composition, transportation distance, unit cost, etc.) in a database to the corresponding activity on the process map. This data connection creates an interface for users to access and edit the database.

4.4.2 ATTACHING PROCESS COST DATA TO OBJECT FAMILY

Figure 4.8 illustrates an example of linking three different family types of the VDW to process- and cost data pertaining to four alternatives of installation. The product model contains object families created by the architect, the engineer, or the specialty contractor. The process- and cost database contains product and cost data collected for the project as described in section 4.4.1. Each object family type, for example the VDW size 7’x9’, is linked to process- and cost data of its four installation alternatives including (1) pre-bolting, (2) inserting, (3) sequencing, and (4) pre-bolting with kitting. Chapter 7 demonstrates the mechanism of linking a product model to a process cost database in more detail.

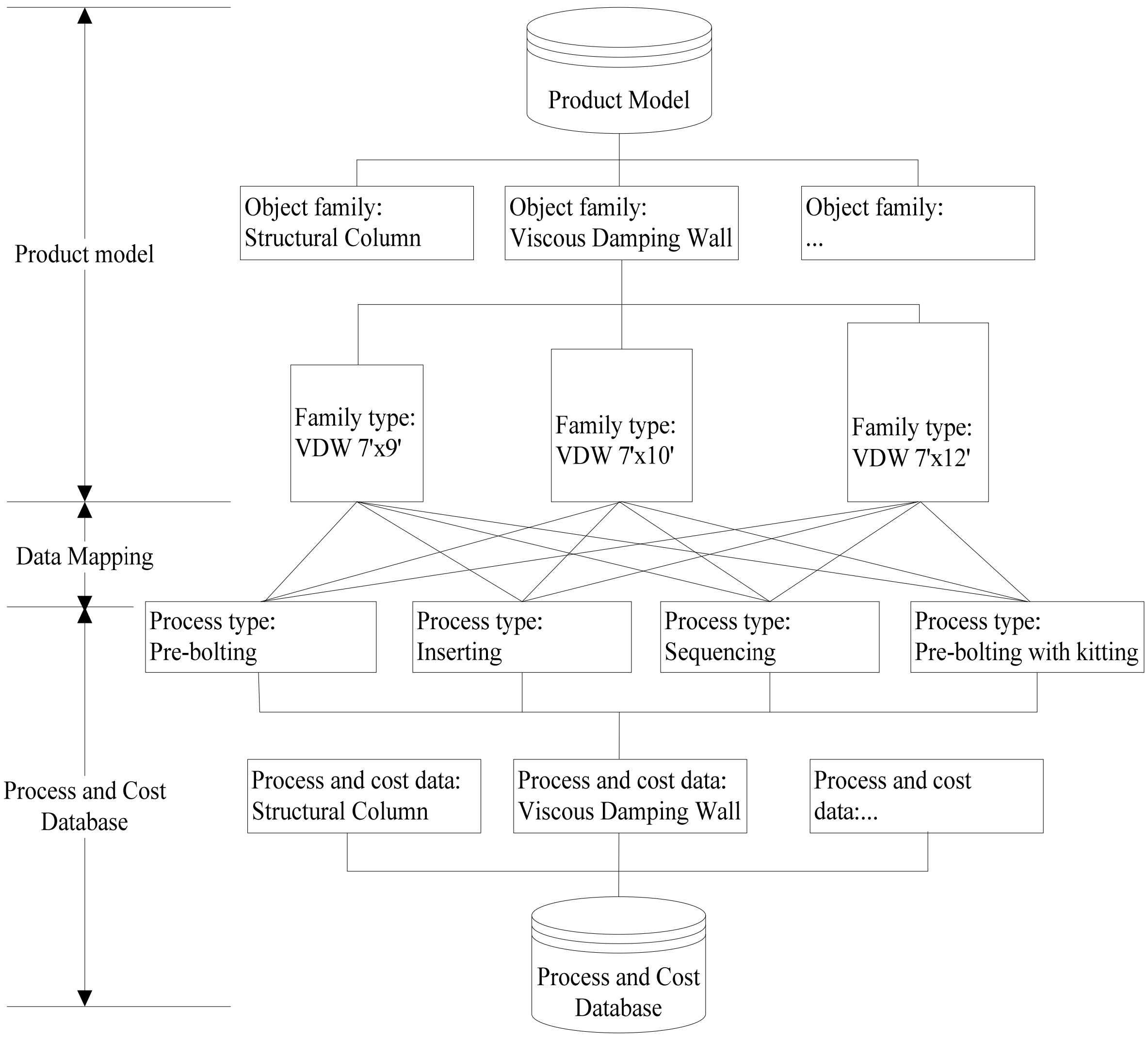


Figure 4.8 Linking object family types of a product model to process cost data

4.4.3 Providing Cost Feedback to TVD

When the IPD team members consider a change in product (i.e., change object family types) or change in process (i.e., change method of installation), they may swap a current object family in the product model with another one in the model's product library and select an alternative of installation to see changes in final cost. If the team sees the need for modifying process- and cost data, they could access the database to make adjustments. For example, team members may adjust crew composition, activity durations, transportation distance, etc. according to conditions of the current project. Since process- and cost data are linked to the object family, the team will be instantly provided with related changes in both product cost and process cost. The linking of data between product model and process cost model acts as an integrated product/process/cost model that can provide quick cost feedback to designers. Chapter 7 demonstrates the mechanism of providing cost feedback to design in more detail.

CHAPTER 5. WINDOW CASE STUDY

5.1 INTRODUCTION AND CASE-STUDY OBJECTIVES

This chapter describes the processes of design, bidding, packaging, transportation, site handling, and installation of the window system for a newly constructed residential complex located in San Francisco, California. The objectives of this case study are to (1) analyze conventional practices of designing, estimating, and installing a window system in order to identify process inefficiencies and wastes, and to discuss how they may affect cost estimates of future projects; (2) understand and quantify process waste; and (3) develop a method of collecting process data that separates true cost and cost of waste. This case study is based on collaborative efforts between Mr. Ahmad K. Sharif and I in the course of the class CE290N Lean Construction and Supply Chain Management during the Spring 2007 semester. Professor Iris D. Tommelein was the instructor of this course. At the time of conducting this case study, Sharif was a graduate student at UC Berkeley in the Civil and Environmental Engineering department.

5.2 DATA COLLECTION

Sharif and I visited the construction site, videotaped the window installation process, and took pictures of material handling locations. Then we conducted interviews with the window installation workers, superintendents, and project manager to understand supply and installation processes of the window system. We also conducted telephone interviews and exchanged emails with the architect's representative to learn about the design process, with the window fabricator's representative to learn about the fabrication process, and with the owner's project manager to understand material handling and site logistic issues. Towards the end of the study, we shared process analysis and findings with the owner's project managers and with the window subcontractor to obtain their feedback.

5.3 PROJECT AND WINDOW SYSTEM

5.3.1 PROJECT BACKGROUND

Since the Developer of this project requested to remain anonymous, this residential project will be referred as Project X. This project is a new construction of a 110-unit, seven-story residential building in San Francisco using a Design - Build (D/B) project delivery approach. The building structure was constructed of cast-in-place concrete with a Glass Fiber Reinforced Concrete (GFRC) exterior skin. The estimated date of completion was set for December 2006. However, due to project delays, the actual completion date was August 2007. Figure 5.1 presents a picture taken from the southeast corner of the completed building and Figure 5.2 presents the plan view of the fourth floor of the building.

Figure 5.1 Picture of the residential complex (courtesy of the A/E)

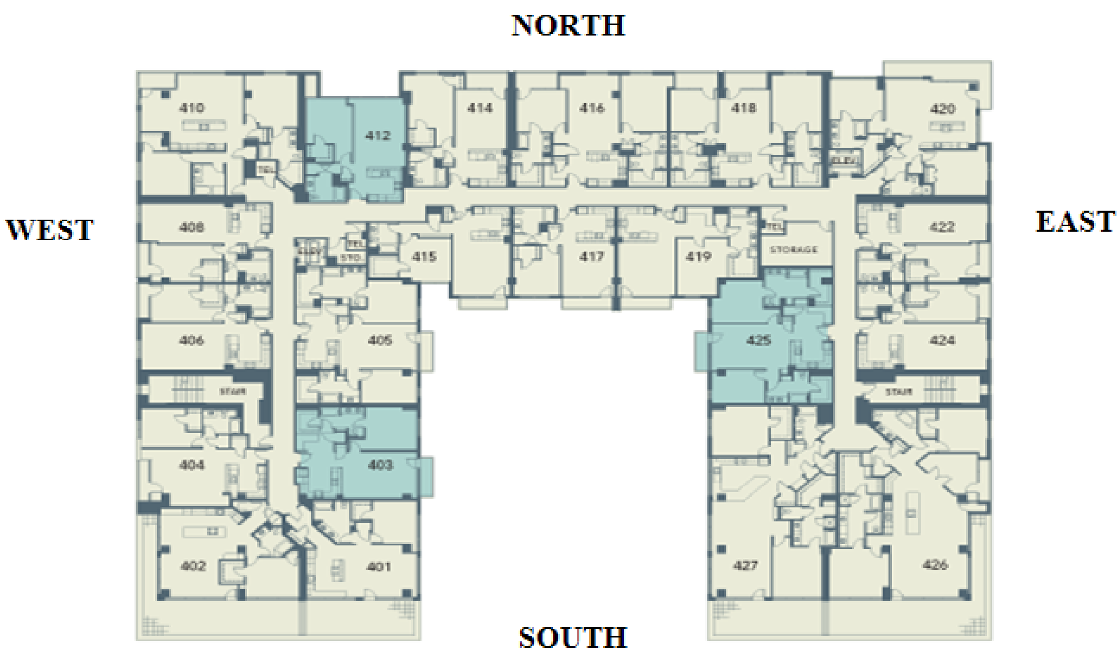


Figure 5.2 Floor plan of building (courtesy of the A/E)

For reasons of confidentiality, “Company A” and “Company B” are used to replace the real names of the window fabricator and the window subcontractor, respectively.

Company A is a fabricator of architectural aluminum windows, curtain walls, and storefront and entrance systems for commercial use. Currently, it is headquartered in a Midwestern state. It has offices in other states and employs over 2,000 people. In this project, Company A trained and certified a number of employees of Company B, the window installation contractor, in order to properly assemble and install windows.

Company B was responsible for installing the window system together with other architectural glazing works for this project. Its headquarter and fabrication facility are in California. Its contracts range from multi-million dollar commercial building construction to several hundred-thousand dollar contracts involving tenant improvements. Company B had a long time relationship with Company A. Company B felt confident with the quality of Company A's products since historically they passed the entire field mock-up test and the rate of damage while transporting and handling had been very low. In addition to that, Company B could order Company A to deliver windows directly from their fabrication shop to the construction site, thus saved costs and planning efforts for window handling and storage. Company A also prepared all necessary submittals and shop drawings to facilitate Company B in the bidding process. This good relationship helped Company B win the glazing contract on this project by offering the most competitive bid price among other glazing subcontractors. As a result, Company A's heavy commercial projected window system was chosen for the project.

5.3.2 WINDOW SYSTEM

Figure 5.3 Dual glazing projected windows in Project X

The aluminum-framed double-glazing projected window system was specified by the A/E, who had been hired by the Developer. Aluminum frames were selected because the projected windows have a lower price in comparison to other types of products in the same category, such as sliding or hung aluminum frame windows. While having an advantage of a lower price, this window system was equal in quality, function, and value in terms of insulation, ventilation, security, and aesthetics in comparison to other systems. In operation, projected windows may not be as convenient as sliding or hung windows, but this drawback is minor and it makes almost no adverse impact on the decision of home buyers as revealed by the Developer's project manager. In addition, the Developer has also used this type of window in previous developments and found no problem with it. The system had been found to be durable, as well as easy to maintain and replace.

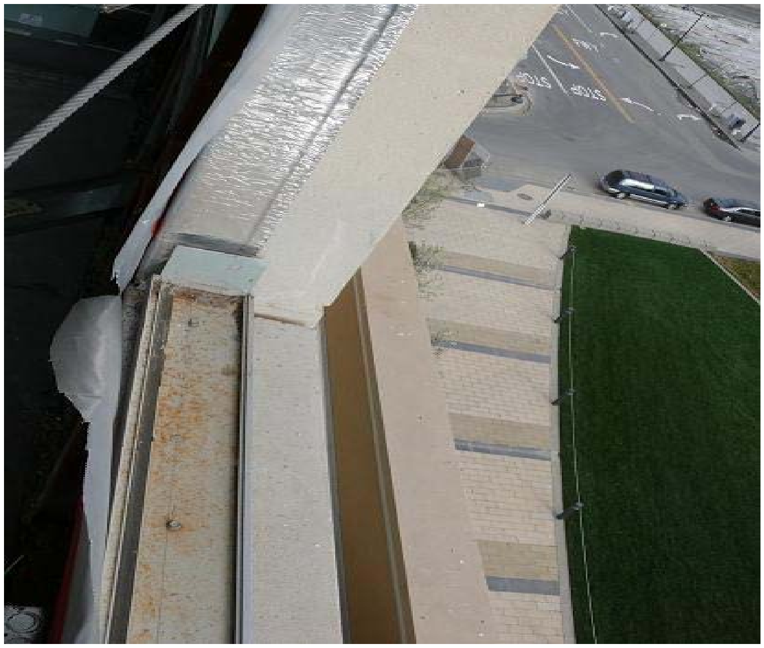


Figure 5.4 Bottom sill installed on the Glass Fiber Reinforced Concrete (GFRC)

Project X used 468 windows (including replacements for defect windows) with about 300 different types and variations. The variations were mostly in sizes, styles, hardware, and operations (i.e., the directions of opening a panel). Windows inside were glazed with an extruded aluminum, snap-in glazing bed. All windows were dual-glazing in 1/8" glass. Figure 5.3 shows some dual-glazing projected windows on the west facade of the Project X. The building structure was constructed of cast-in-place concrete with a GFRC exterior skin (Figure 5.4).

5.3.3 WINDOW SUPPLY CHAIN

Figure 5.5 illustrates a cross-functional diagram of the design, bidding, fabrication, delivery, and installation processes of the window system. It shows the interaction between the project players, namely the Developer, the Architect/Engineer (A/E), the General Contractor (GC), the window fabricator (Company A), and the window subcontractor (Company B).

The A/E developed the window specifications based on the owner’s requirements and characteristics of the Project X. The GC prepared the request for proposal and solicited bids from window subcontractors. Company B was selected as a window subcontractor. Company B chose Company A as the fabricator and supplier of the window system, and Company A prepared all window shop drawings.

The GC used a traditional bidding practice to select subcontractors. The advertised bid for glazing had a preliminary estimate of the cost it would take to procure and install the windows. This estimate was done in-house based on the GC’s historical cost data. This set the mark for other subcontractors to place their own bid price close to what the GC’s estimated price was for

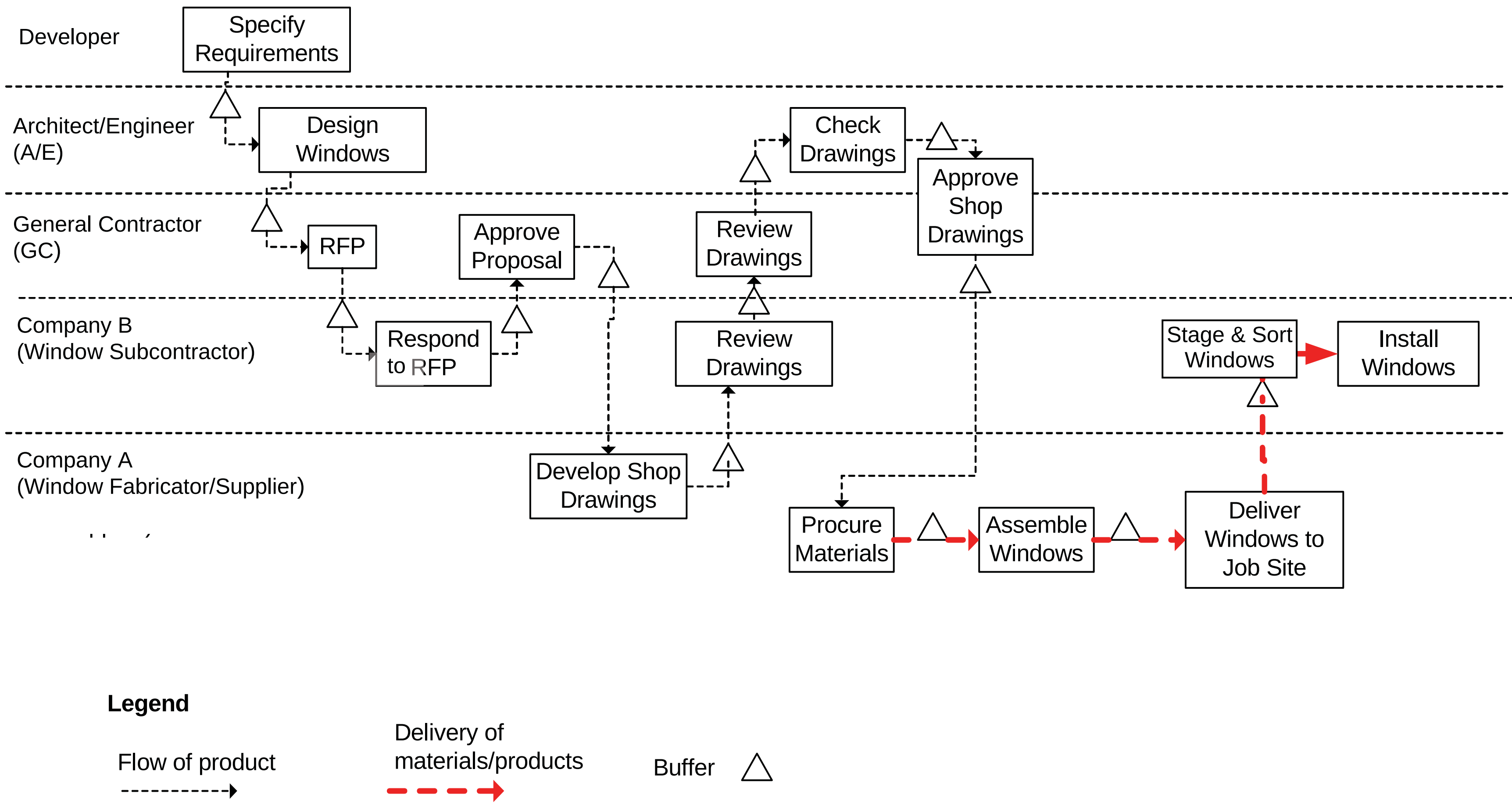


Figure 5.5 Cross-functional process map of window supply chain activities in Project X

the purchase of the windows plus a 10 percent markup for profit. The contract was awarded on a lump-sum basis to the lowest bidder, and therefore Company B was responsible for locating a fabricator and then installing the window system.

Company B checked all shop drawings issued by Company A and then submitted them to the GC. The GC reviewed shop drawings and then turned them over to the A/E for review. The A/E then confirmed that they reflected design intent. When the shop drawings and all specifications of these windows were found to be satisfactory, Company A purchased frames, glass, and auxiliaries from different suppliers (i.e., PPG, Pilkington, and Viracon for glass products; Kawneer, US Aluminum Corp, and Vistawall etc., for aluminum frames), and then windows were assembled, stored in Company A's warehouse, and shipped to the site. Next, Company B coordinated the installation schedule with the GC and installed the windows.

The approval process required a 15-minutes rain mock up test where 8 pound/square-foot of water pressure was used to test the waterproofing capability of the window system. Once the windows were installed in the building and installation work was approved by the GC, the liability for the windows was then transferred to the Developer.

In order to offload the material from the truck on site, the truck was staged in a plot located on the west side of the building site (Figure 5.6). The truck entered the staging site from the north side of the building. The staging area was left vacant in order for trucks to have easy site access.

13 truck loads were brought to the construction site with each truckload carried 35-40 windows. Company A brought a total of 468 windows included replacements for damaged windows or windows with wrong dimensions. Each truck load took approximately three to four days to arrive from Company A's fabrication shop to the job site. The windows were placed on wooden pallets to avoid damage and breakage. As per the written contract between the window subcontractor, Company B, and the window fabricator, Company A, it was agreed that Company A would bundle the window panes as specified in the window installation schedule which started from the first floor and went up to the seventh floor. Company B requested direct shipment from Company A to project site.

Although the windows were correctly labeled at the time of delivery, they were not bundled and organized accordingly. Many windows belonging to different work areas, i.e., different floors, were bundled and transported together. There were also several occurrences of mismatching, for example, window panes belonging to different window frames were packed together. Since it was necessary to unload the windows off the truck in a timely and organized fashion and deliver them to scheduled installation locations, a foreman of Company B had to devise a check list to overcome the unorganized bundling and mismatching of the window panes. His main goal was to place each window on the floor specified and then place each window as close as possible to its corresponding location without them getting in the way of the other trades working on those floors. According to the Company B's foreman, this description explains the extra steps of unloading and stocking up the windows, which took 1,220 man-hours to complete while he thought it would take less than 600 man-hours if windows were properly bundled.

Figure 5.6 Staging area located on the west side of the building

5.3.4 WINDOW INSTALLATION

A window-installation crew included one foreman and one journey man. They first installed each aluminum window frame into its wall opening and took approximately two hours to do so. The crew then installed the window panes in each the frame and took about one hour to do so.

Detailed steps for the window installation process are as follows:

- Install sub-sill
- Install sub-jambs
- Install sub-head
- Alcohol wipe end dams
- Alcohol wipe all screw heads
- Dry wipe
- Apply primer
- Caulk end dams at sills and head of compensation channels
- Caulk all screw heads
- Apply ramp seal over sill thermal break
- Apply interior and exterior bedding at sill
- Apply exterior bedding bead at head and jambs

- Check window joinery seals at sills and reseal or repair joinery if required
- Alcohol wipe face and sills of windows
- Install male leg of window frame
- Install male leg of window and install female leg of window
- Install drive gasket at sill and caulk sill’s full width
- Caulk over sill pressure gasket
- Install compensation jamb retainer
- Install compensation head retainer
- Clean off caulking drip at interior
- Check all joints for required seals

Company B’s only major equipment was a man lift, which they rented (Figure 5.7). Since the operation of a man lift does not require much space, the man lift could be easily maneuvered around the perimeter of the building. Figure 5.8 shows some hand tools used by the window installation crew.

Figure 5.7 Equipment used by Company B

Figure 5.8 Hand tools for window installation

(1) Bolt Gun, (2) Caulking gun, (3) Glass lift handle.

5.4 PROCESS MAPPING, INTERVIEWS, AND PROCESS SIMULATION

Sharif and I used process mapping with a time analysis technique to identify process inefficiencies. Next, I conducted interviews to validate findings as well as to identify areas containing process waste. I then used Discrete-Event Simulation (DES) to simulate the targeted process to quantify waste, and adjusted the simulated process according to lean production principles in order to quantify potential savings.

5.4.1 PROCESS MAPPING

Figure 5.9 illustrates the process map of the window supply chain with measurements of each activity's duration as well as the number of man-hours spent on each activity. The process map illustrates processes implemented by different parties. The process started when the GC issued a Request for Proposal to choose a window subcontractor and ended when the subcontractor had installed all windows. The whole process took about 21 months to complete. The process map covers the design, subcontractor selection, material procurement, fabrication, storage, transportation, and installation of windows. The average durations for completing each activity and the number of man-hours spent on each activity were collected based on interviews with the GC, the A/E, and the window subcontractor.

As illustrated in the process map, all shop drawings issued by Company A were checked by Company B and then submitted to the GC. The GC reviewed shop drawings and then turned them over to the A/E for review. A window consultant of the A/E checked the submittals for approval. When the shop drawings and all specifications of these windows were approved, Company A purchased frames, glass, and auxiliaries from suppliers. Company A then held purchased materials in its warehouse, where it assembled the windows, stored them in inventory, and delivered them to the job site for installation.

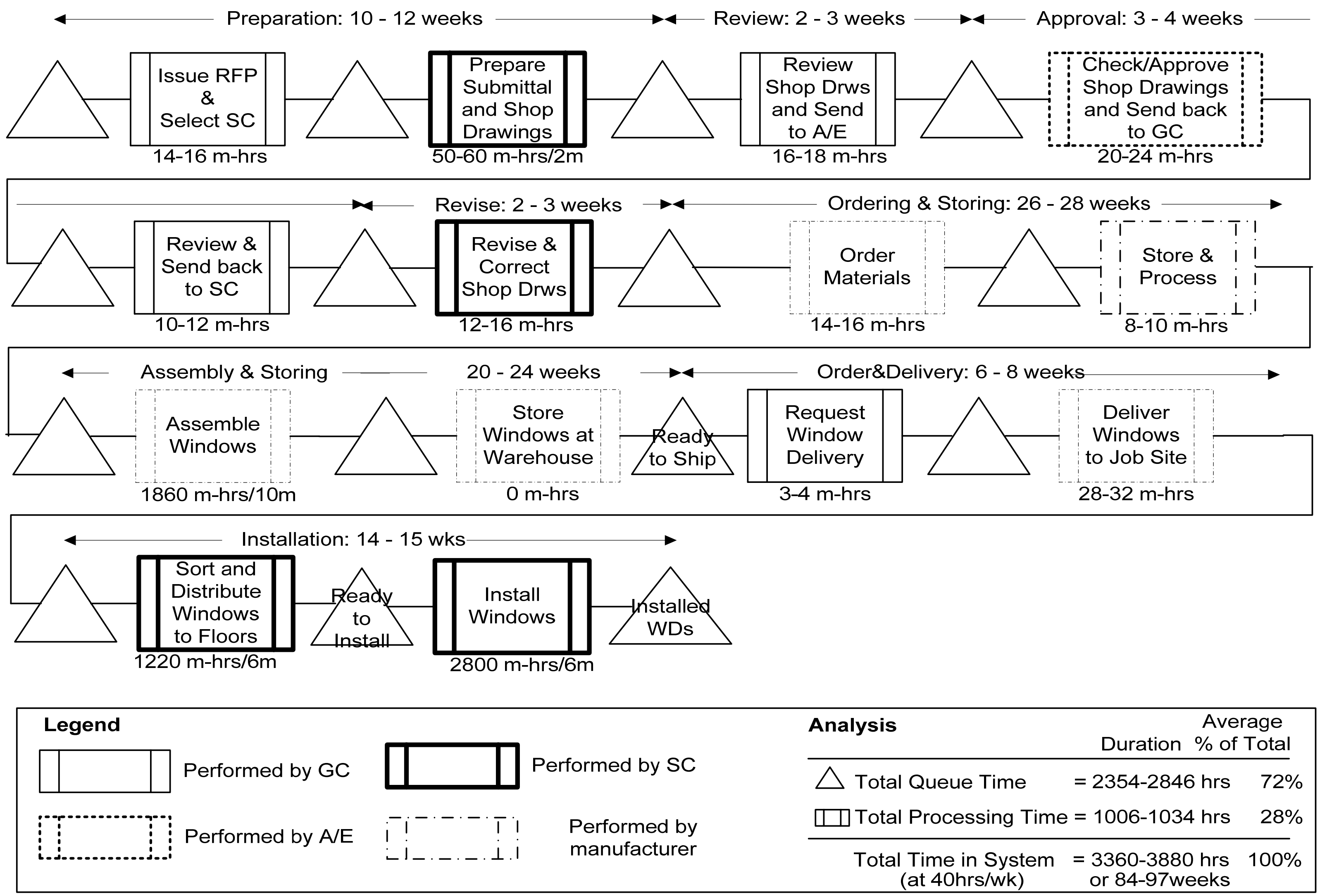


Figure 5.9 Process map of the window supply chain (Nguyen and Ahmad 2007)

Using this process map and a time analysis technique to analyze the whole delivery and installation process, inefficiencies were made explicit. The whole process took about 21 months. The total processing time (i.e., the time that the thing is being worked on) took only 28 percent of the period while total queue time (i.e., inventory and transportation time) took 72 percent of the period. The GC started selecting a window subcontractor after finishing the design. It took 10 - 12 weeks to select a subcontractor. Then the review, approval, and revision processes took about 7 - 10 week to complete. As demanded by the GC, Company B required Company A to procure and process materials and then to assemble windows way in advanced of the site installation. As a result, Company A had to inventory materials (aluminum, glass, and auxiliaries) and completed windows for a long time before they could transport them to the site (about 12 weeks for materials and 14 weeks for windows). This practice was to ensure the availability of windows once the installation started and to avoid fluctuation of material prices. However, it certainly increased inventory cost per window unit, increased cycle time, and increased the possibility of damage due to improper handling or lack of protection. In addition, the cost of capital frozen in idle material also increased the final cost of windows.

The line of balance chart in Figure 5.10 illustrates the actual timeline of the window supply chain as presented in the process map (Figure 5.9). This chart reveals time buffers between material order and window assembly, and between window assembly and site installation.

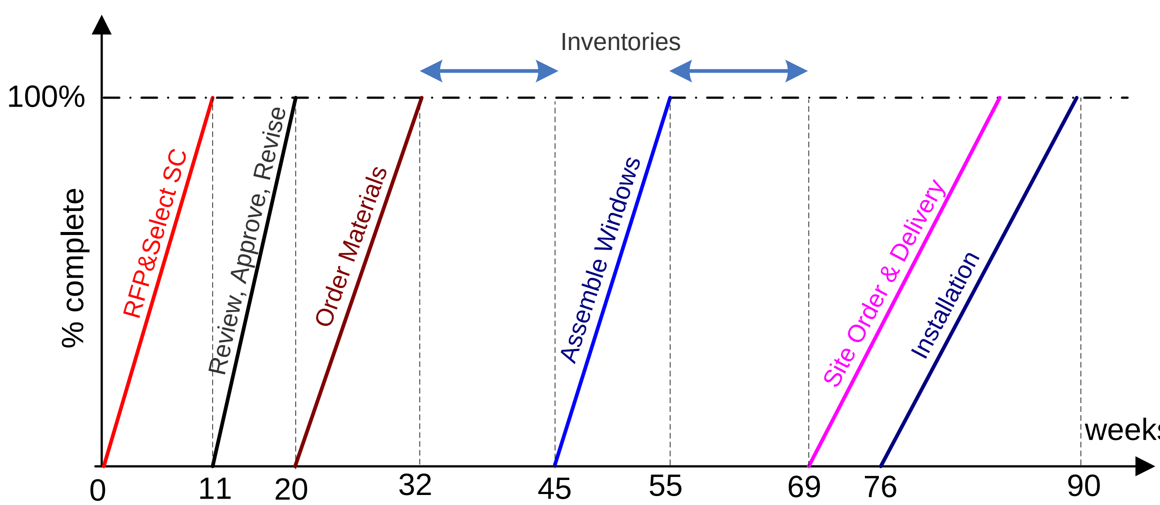


Figure 5.10 Line of balance chart of the window supply chain (Nguyen and Ahmad 2007)

5.4.2 INTERVIEWS

Interviews with the GC's project manager as well as with Company B's procurement manager, superintendent, and workers have revealed the following inefficiencies of the window supply chain:

- The A/E had specified an unusual number of window variations (over 300 different types of windows in a 110-unit residential development, many with only minor differences such as variations in size or the way a panel is opened). However, according to the window subcontractor, about half of the number of variations could have been eliminated without any significant impact to either functionality or aesthetics of the project.

- Cost overrun in window manufacturing due to the high level of customization in windows design. According to the window fabricator, the cost for the window system of this project could have been reduced significantly if unification in window design were achieved. This remark is in line with Tommelein's (2006) observation from pipe spool simulation experiments that standardization could improve production system performance and reduce the likelihood of mismatches.
- Windows were sometimes stacked on site at the wrong location, i.e., not near the wall opening where they should be installed. This error was due to workers' wrong interpretation of window types and locations and the specification thereof in project documents (e.g., drawings).
- Information regarding design changes was not often being communicated to the window fabricator in a timely manner. For example, due to some changes in the dimensions of some wall openings at least 5 windows did not fit their dedicated openings. In each case, the problem was recognized only after installation workers failed to put the window in. All these dimensionally wrong windows were discarded and the window subcontractor ordered new replacement windows, resulting in rework in fabrication, transportation, and installation, as well as physical waste products. This error originated from poor coordination between the A/E, the subcontractor, and the manufacturer.
- The long inventory period both in the fabricator's warehouse and on site caused higher storage cost and sometimes product damages.
- Deliveries from the fabrication facility to the construction site were not according to plan. For example, windows of different floors were packed and delivered together. The reason was that the fabricator optimized their productivity by grouping similar types of windows to fabricate in batches and then delivered windows in the order of fabrication. Arbulu et al. (2002) pointed out the effect of batch size on a supply chain's lead time: the bigger the batch size, the longer the lead time of the process overall. The local optimization in the fabricator's shop seriously affected the whole supply chain since the installation workers did not have the windows they needed when they needed them. Instead of installing windows according to the scheduled location, the window subcontractor had to plan their installation sequence according to the availability of delivered windows. That caused workspace conflict with the drywall subcontractor and the GFRC subcontractor in many locations. In addition, just the task of material handling at the job site alone took Company B about 1,220 man hours, as they had to unload trucks, sort windows, and place them in the correct installation position. This was so costly that Company B had to back charge the manufacturer 550 man-hours for their improper packaging practice.

As the accumulated result of all these inefficiencies, window installation was four months behind schedule. The installation was supposed to be finished by December 10, 2006 but it was actually finished at the end of April 2007.

Applying production system design principles of the LPDS™, Sharif and I provided the following recommendations to the various parties:

First, focusing on delivery (the pull of the customer, in this case) and handling of materials, windows of each floor should be packed together and delivered according to their sequence of installation on site. This would eliminate the sorting activity, eliminate the need for temporary site storage, and significantly reduce the duration of site distribution.

Second, focusing on window fabrication, that activity can be delayed and performed in parallel to site installation to take advantage of Just-In-Time principles, i.e., windows are assembled only shortly before when they are needed on site so that inventory in the fabrication shop and on site can be minimal. Company B should establish a feedback link from the construction site to inform Company A about product deficiencies, dimensions, tolerances, location, and quantities so that Company A could adjust the assembly line in a timely manner to match site demands.

Third, focusing on the design of the window system, the A/E should reduce the number of variations in windows. Standardization of window designs can significantly reduce the cost of design, assembly, and installation. This standardization also reduces potential for manufacturer's mistakes in packaging and delivering, which led to matching problems. Furthermore, better coordination of different trade contractors would reduce interruptions of the window installation activity.

Strategically, focusing on contractual relationships, the Developer could establish a multi-project partnership with members of the window supply chain including aluminum, glass and auxiliary parts suppliers, the window fabricator and the window subcontractor. This strategy might not work in all cases but could be feasible in this case as the Developer is a big developer, with a portfolio of ongoing projects. The partnership can eliminate the long lead time for selecting a subcontractor and the supply chain could choose to hold key materials (such as aluminum) upstream to avoid big time buffers and material inventories in the fabricator's warehouse. Besides, the GC, the A/E, the window subcontractor, and the window fabricator could work collaboratively to produce shop drawings and eliminate the lengthy iterative processes of reviewing, revising, and approving.

We summarized responses from the project's participants on the above recommendations as follows:

The GC's project manager and the window subcontractor's superintendent agreed that waste related to delivery and handling of materials was significant and apparent, and better coordination between the window fabricator and the window subcontractor could have eliminated at least some of that waste.

Company B's representative agreed that having a feedback link from the construction site to the fabrication shop would make it easier for them to adjust product tolerances and to have a better chance of avoiding product deficiencies in multiple products. However, according to Company B, matching the rate of window assembly at the fabrication shop with that of window installation on site may not be possible when using a 'typical' fabricator such as Company A. At any given time, Company A may have dozens of projects in their backlog, all of which essentially custom-built projects. Knowing their own production capacity, Company A typically inserts projects into a production slot in their schedule on a first-come first-served basis. They generally do not designate a portion of their production resources to any given project for the duration of that project in the field. This would require the upstream suppliers (such as the glass supplier) to respond in a similar manner, imposing upon them the same constraints as the window fabricator. This problem is typical in fragmented construction supply chains where sub-optimizations prevail. The problem can be alleviated to some degree once supply chain integration, continuous flow production and just-in-time with pull mechanism are fully applied.

Regarding the recommendation of arranging the GC, the A/E, the window subcontractor and the fabricator to work collaboratively in producing shop drawings. Company B's representative agreed that such collaboration could prove to be an excellent idea on a larger project. However, it would require a very early decision on the part of the GC regarding subcontractor selection. It would also require the budget for a given scope of work to be clearly defined, and defined early in the process. This would avoid the time-wasting exercise of value engineering and the cost of design and re-design that accompanies it. Company B's representative suggested that the GC should also anticipate paying the subcontractor for the time and resources spent while collaborating in the design process. It might even be worth considering extending the collaboration to include the subcontractor in a financial/partnering role in the actual development. In addition, Company B emphasized that unless the Developer was to standardize the window and glass specifications, and to award all of the projects in a given portfolio to the same subcontractor, it is doubtful that any cost savings could be realized through partnering or volume purchasing.

5.4.3 PROCESS SIMULATION

The results of process analysis and interviews show that activities of window transportation, site logistics, and window installation appeared to contain a significant amount of waste. Thus these processes were selected for further analysis using process mapping in more detail and DES to demonstrate a method of identifying and removing process waste for benchmarking future process cost estimates.

5.4.3.1 Process Description

Transportation: Company sent a total of 13 truckloads of widows to the job. Each truck had the capacity to load around 36 windows, give or take a few windows.

Site logistics: When a truck arrived at the site, six workers unloaded the truck. Company B ordered windows according to their installation schedule and expected windows to come when they were needed, where they were needed, but Company A failed to match this request. Windows were shipped in a random manner and an individual truck contained windows for different floors of the building. For that reason, material handling included unloading windows from the truck, unpacking windows, sorting them according to floor and work area, and distributing sorted windows to their designated installation location.

Installation: Each window installation crew comprised two glazing workers. Due to the nature of window installation and the weight of windows, at least two workers were needed to handle and install each window. Company B mobilized three crews, totaling six workers, for this job.

5.4.3.2 Illustration of Activities

Figure 5.11 Windows unpacked and sorted according to their corresponding floors

Figure 5.12 Windows distributed to their installation area

Figure 5.13 Window opening cleared for installation

Figure 5.14 Plastic spacers placed behind the aluminum frame to adjust and space the gap between the uneven concrete and the aluminum frame

Figure 5.15 Worker applying silicon paste to bottom sill

Figure 5.16 Worker smoothing the silicon paste to remove possible air bubbles

Figure 5.17 Worker applying silicon to window frame

Figure 5.18 Two workers lifting a window pane and placing it on the frame

Looking at the site logistics and site installation processes. As mentioned earlier, since it was necessary to unload the windows off the truck and move them to the room in which they would be installed, the window subcontractor had to implement extra steps to overcome the random packaging and the mismatching of the window panes. Those steps were: (1) unloaded window packages to a temporary storage area on site, (2) unpacked and sorted windows to group them according to designated floors, (3) distributed windows to their corresponding rooms.

5.4.3.3 Discrete-Event Simulation Model

Sharif and I developed an EZStrobe© (Martinez 1996) DES model to simulate the current state of the window installation process (Figure 5.19). The model simulates the activities of workers and the flow of materials from window transportation to the complete installation of about 468 windows. This model has five main activities, including transportation, unloading windows on site, unpacking and sorting windows, distributing windows to their corresponding floors, and site installation of windows.

Simulated activities:

Transport: Windows are transported to the site in 13 truck loads.

Unload: Workers unload window packages to a temporary storage area on site.

Unpack_Sort: Workers unpack and sort windows to group them according to designated floors.

Distribute: Workers distribute each window to its designated location. The fork was used to reflect the randomness of this distribution activity.

Install_(1-7): Workers install frames and windows into wall openings in floors from 1st to 7th according to installation schedule. Works were prioritized in the following floor orders: 1st and 2nd, then 3rd and 4th, then 5th and 6th, and finally 7th.

We collected the duration of each activity based on interviews with the window subcontractor's superintendent and by direct observation. When the simulation runs, upon the completion of one task the next task is activated and the simulation keeps track of the time taken for resources utilized for that task.

Figure 5.20 demonstrates the simulation model of an improved window installation process with an assumption that windows are packed and delivered according to floors. In addition, it is assumed that windows are delivered on a just-in-time basis, when the installation of the windows delivered by the previous truck load is finished, to eliminate the need for temporary storage and to avoid work interruption. In this manner, workers would only need to (1) unload window packages and (2) distribute windows to their designated locations. In this revised process the unpacking and sorting activities were eliminated and there is no need to arrange windows in a temporary storage area.

Simulated activities:

Transport: Windows are transported to the site in 13 truck loads.

Unload: Workers unload window packages from the truck.

Distribute: Workers distribute windows to their designated location.

Install: Workers install frames and windows into wall openings in floors from 1st to 7th according to the installation schedule.

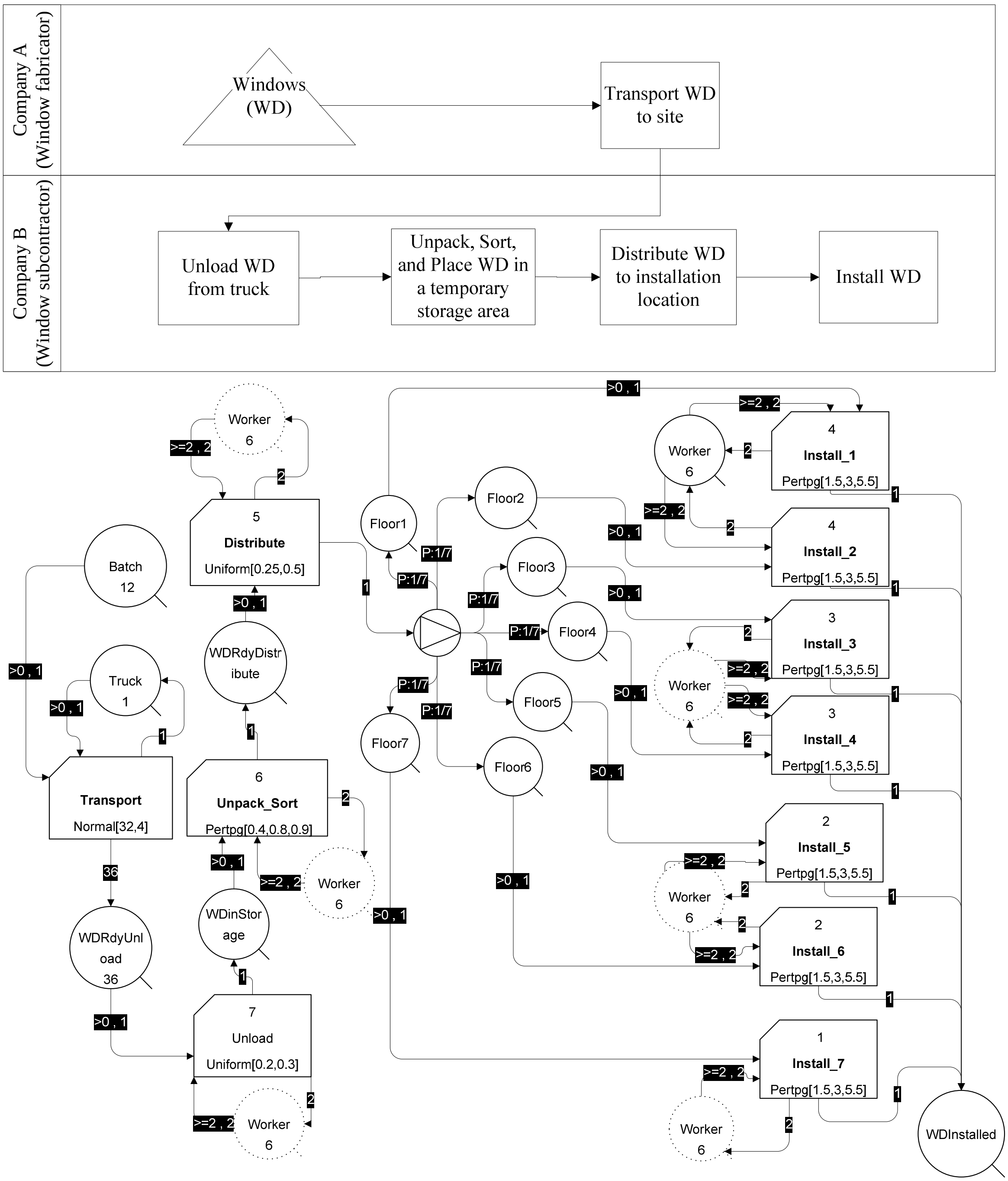


Figure 5.19 Current state map and current state simulation model of window site handling and installation processes

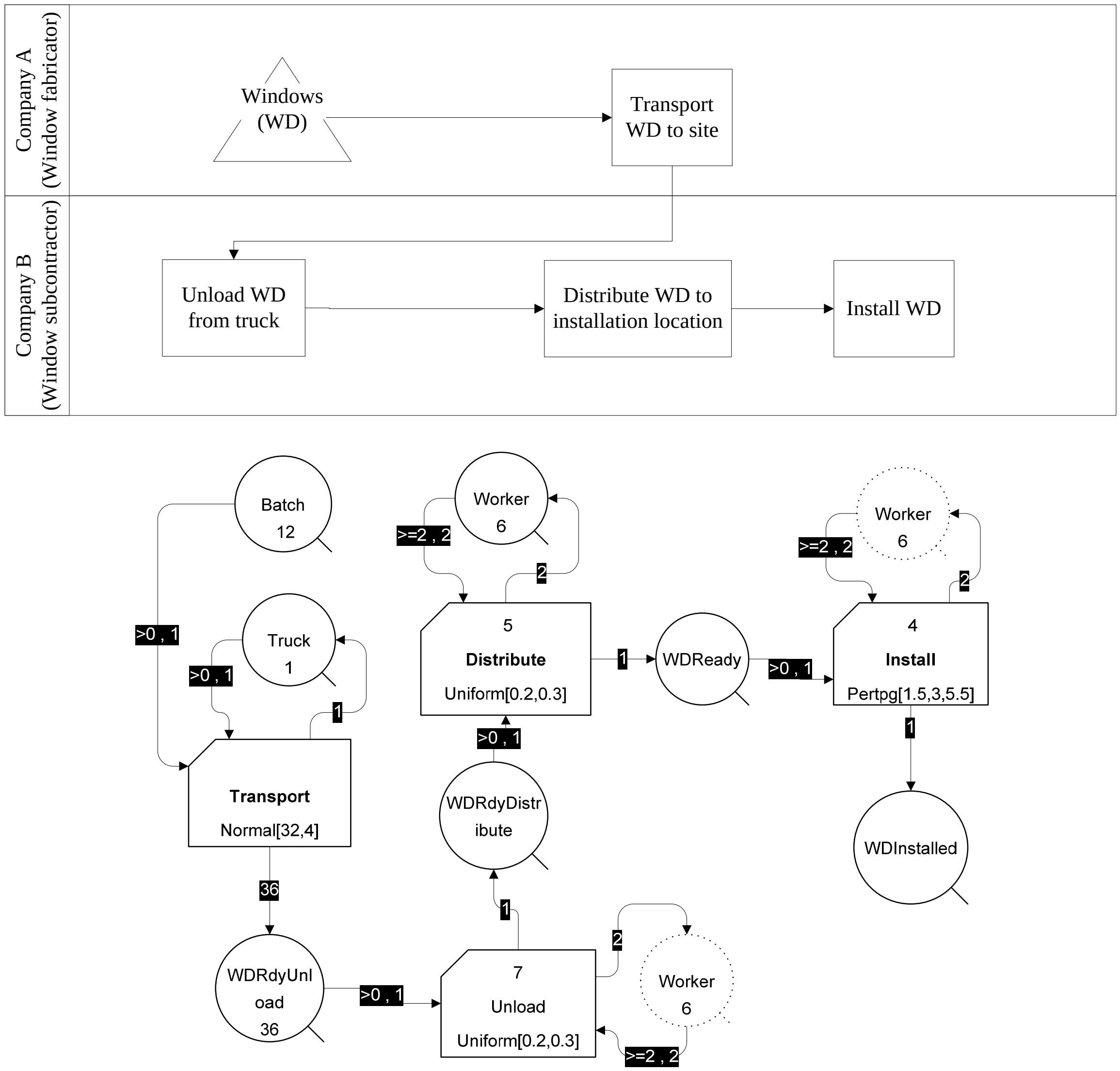


Figure 5.20 Future state process map and simulation model of window site handling and installation processes

5.4.3.4 Simulation Results and Process Cost Estimates

For the current state model presented in Figure 5.19, 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. The simulation result matches with the data collected from an interview with the superintendent of the window subcontractor.

The outcome from 1,000 replications of the revised model reveals that a total man-hour for unloading and distributing activities has a mean of 465 man-hours with a standard deviation of 1.63 man-hours. Results from the two simulation models reveal that a saving of 750 man-hours (or $37,500 assuming a $50/man-hour rate) can be achieved in reducing waste in site logistics of windows unloading and distributing activities. Follow up discussions with the window subcontractor on the simulation models' results and the waste reduction opportunity revealed that the results from the original model and the improved model were reasonable. Appendix B presents detailed simulation results for both models.

If the designers of the window system had been provided with this process information, they might 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 on the fabricator's side.

5.5 CASE-STUDY CONCLUSIONS AND LESSONS LEARNED

In this project, the estimate of the window system at the end of Design Development was used for budgeting and for controlling the window-subcontractor selection process. After finishing the Design Development phase, the Developer's cost estimator estimated the cost of the window system by counting the quantity of windows with the same type and multiplying that quantity with a composite unit cost from the Developer's internal cost database, which collected cost data from the Developer's completed residential projects. The composite unit cost was adjusted for time and location. This actually overlooked the impacts of product variation on the cost of the delivery- and installation process. Despite of the fact that inefficiencies and wastes prevailed in the window supply chain, according to the Developer's project manager, the final cost of this window system was "within budget". The reason may well be because this budget was inflated by the waste embedded in the historical database. As revealed from the results of the two simulation models, a waste of 750 man-hours (or $37,500 assuming a $50/man-hour rate) was embedded in material handling cost alone. If not quantified and separated from the total window installation cost, this waste would be included in a composite unit cost for window installation and become historical cost data. As suggested by the conventional cost estimating practice, the Developer may use the cost data of this window system as a benchmark to budget for a window system in a new development. That way, the new budget would include process inefficiencies and wastes such as the excessive labor and equipment cost for unpacking, sorting, and distributing windows in this case study.

In this project, since subcontractors and suppliers were selected after finishing the Design Development phase, the estimator had limited trade input to calculate process cost during design and had to rely on historical cost data. Any process coordination or request for trade inputs could be done only after bidding, when subcontractors and suppliers were on board. This transactional type of contractual relationship hindered early coordination and thus prevented estimators from providing a rational process cost estimate.

In this case study, the window fabricator and the window installation subcontractor could 'see' the waste in the material handling process. However, in conventional project delivery systems, such as DBB or DB, no channel exists to communicate this information to the architect or to the cost estimator. As shown in this case study, process mapping could help identify waste and a baseline process could be created by removing waste from the current state process map. This tool should be used to collect process data in order to separate real process cost and cost of process waste. This classification will help estimators make more reliable estimates on process costs and resource needs.

With the participation of subcontractors during design, using process mapping to make process cost explicit to the design team, process inefficiencies and wastes can be identified and thus eliminated by adjusting the design solution. If the A/E of this window system had been informed with the impacts of product variations as specified, they might have considered revising the product design solutions, e.g., reducing the number of window variations. This change in product design would help not only to reduce the cost of site logistics, as the simulation results suggested, but also to streamline the fabrication process in the manufacturer side.

CHAPTER 6. VISCOUS DAMPING WALL CASE STUDY

This chapter presents a proof of concept case study by applying the proposed PBCM framework to the process of estimating cost for the VDW system at the CHH project. The VDW system present a challenge for logistics and field operations (as will be detailed later) thus the IPD team at CHH wanted to further explore different schemes and solutions for their installation. The first objective of this case study is to demonstrate how the PBCM method including 4D simulation can assist cost estimating. The second objective is to demonstrate how CBA helps to make decisions when considering both cost and non-cost factors (i.e., comparative advantages between alternatives).

6.1 INTRODUCTION

Section 4.1 introduces the background of the CHH project. As described in section 4.2, to implement the TVD process, the cross-functional teams (referred as clusters at CHH) of designers and specialty contractors (referred as trade partners at CHH) structured meetings on a weekly basis to coordinate the design of major building components and systems. Continuous value analysis and cost updates took place within the clusters for monitoring estimated costs against Target Costs. The installation of the VDW system requires coordination of multiple specialists such as the structural engineer of record (SEOR), the VDW fabricator, a shipping company, and the structural steel installer. The VDW was a new product to the integrated project team and thus the team needed to examine alternatives for material handling and installation processes.

6.2 VISCOUS DAMPING WALL

A VDW consists of an inner steel plate connected to an upper floor girder, a steel tank connected to a lower floor girder, and a viscous fluid in the gap between them as shown in Figure 6.1.

During seismic excitation, the relative floor movement causes the inner steel plate to move inside the viscous fluid. The damping force from the shearing action of the fluid is dependent on the displacement and velocity of the relative motion. The VDW system is used to reduce seismic accelerations and wind induced vibration in a structure. Although it has been widely used in Japan, to my knowledge CHH is the first project in the United States to use a VDW system. The VDW system was selected because it provides better performance when compared to a conventional steel moment resisting system (Parrish et al. 2008). A VDW is connected to the structural frame along the base and top of the VDW unit, distributing the seismic forces evenly to the structure through a longer connection. The VDW system helps reduce the inter-story lateral floor movements and seismic accelerations, thereby reducing the overall quantity of structural steel required to resist such movements if using a conventional steel moment resisting frame. At the time I started this case study on March 2009, the CHH's structural design had 155 units of VDWs all of the same width of 7' but with three different heights of 9', 10', and 12' to match different floor to floor heights. Among 155 VDW units, there was 76 VDW 7'x9' units, 79 VDW 7'x12' units, and 0 (zero) VDW 7'x10'unit.

The VDW presented a challenge for logistics and field installation for reasons as follows: (1) the delivery and installation of VDWs required coordination of multiple project participants as described in section 6.4.1, (2) members of the IPD team had no previous experience in fabricating, transporting, and installing the VDW system, (3) as a seismic control device installed in between upper and lower girders, the sequence of installing the VDW system affected the sequence of installing the whole structural steel system, (4) CHH construction site was in downtown San Francisco, surrounded with busy streets, and with very limited storage area on site, (5) the large size and heavy weight of each VDW unit added risks to the installation process. In order to optimize the integration of product- and process design, the IPD team wanted to explore different schemes and solutions for VDW installation.

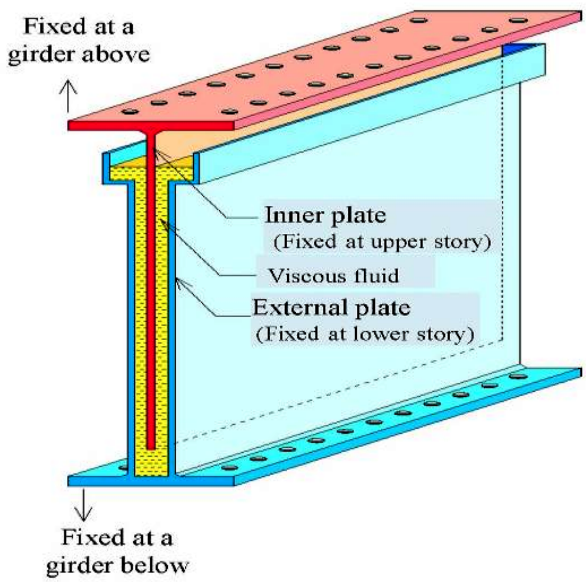


Figure 6.1 VDW composition (courtesy of DIS)

6.3 DATA COLLECTION

I participated as a member of the Virtual Design and Construction cluster at CHH over one year to help establish a framework for introducing model-based process simulation and PBCM to facilitate the design to target process. I collected data through observations, interviews, and document analysis while participating in the implementation of the model-based process simulation and PBCM experiments and helping to make adjustments to the experimental processes.

6.4 CASE-STUDY IMPLEMENTATION

6.4.1 IDENTIFYING PRODUCT AND PROCESS

The VDW system presented a challenge for logistics and field operations thus the IPD team at CHH wanted to further explore different schemes and solutions for its installation. The IPD team decided to select the installation process of the VDW system to experiment the PBCM method. The installation of the VDW system required coordination involving multiple trade partners, such as the SEOR, the VDW fabricator, and the structural steel installation trade partner.

6.4.2 Assembling a Cross-Functional Team

Participants of the PBCM meeting included representatives of companies involved in the design, fabrication, and installation of the VDW: Degenkolb Engineers (SEOR), Dynamic Isolation Systems Inc. (DIS) (design and fabrication of VDWs), Herrick Steel, Inc. (fabrication and installation of structural steel), Charles Pankow Builders, Ltd. (concrete works), and HerreroBoldt (General Contractor).

6.4.3 Process Visualization

6.4.3.1 Understanding Conventional VDW Installation Alternatives

The following descriptions and numbers in parentheses refer to Figure 6.2.

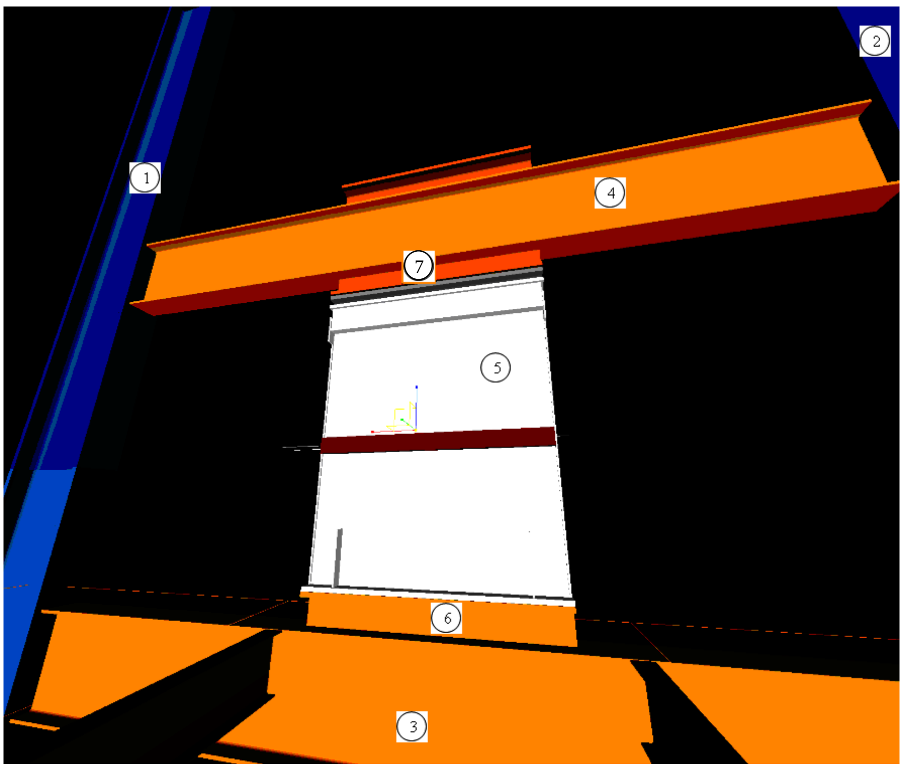


Figure 6.2 3D rendering of a VDW attached to structural steel

Captions: (1) and (2) columns; (3) lower girder; (4) upper girder; (5) VDW; (6) bottom and (7) top T-shaped steel serving as a connector between girders and the VDW

At the DIS' factory, the inner plate and the external plate of a VDW (Figure 6.1) are temporarily attached so that the height of the VDW is shorter than the distance between the surfaces of the T-shaped steels (6) and (7). The VDW is then filled with viscous fluid and transported to a storage area. At the Herrick's fabrication shop, the bottom (6) and the top (7) T-shaped steels are welded to the lower (3) and the upper (4) girders, respectively. By researching the installation of the VDW system in construction projects in Japan, the structural cluster figured out three different installation alternatives, as summarized in Table 6.1

Alternative 1: Pre-bolting

Once the lower girder (3), with the bottom T-shaped steel (6) welded on it, is in place on the steel structure, the VDWs are shipped to the jobsite. An upper girder is slowly set down on the top surface of a VDW unit and these are bolted together. The upper girder (4) and VDW unit (5) are lifted up with a crane and attached to the T-shaped steel (6) on the lower girder (3). The upper girder is temporarily fixed to columns. Since the inner plate and the external plate of the VDW are temporarily combined with a clearance designed to be smaller than the actual clearance needed to reach the surface of the lower girder, there will be a gap of about 1½" between the bottom of the VDW and the surface of the lower girder. As a result, there will be a sufficient clearance between the bottom of VDW and the surface of the lower girder to install the upper girder. It is then necessary to detach the inner plate and the external plate so that the external plate lowers slowly under the resistance of the viscous fluid, which enables a precise bolting of the external plate to the lower girder. DIS suggested using this method for the VDW installation.

Figure 6.3 VDW installation on concrete structure using sequential installation method in Japan (courtesy of DIS)

Alternative 2: Inserting

After columns (1) and (2), lower girder (3), and upper girder (4) are in place, the VDW (5) is inserted to the gap between the bottom (6) and the top (7) T-shaped steels and bolted to the bottom T-shaped steel (6) on the lower girder (3). The inner and the external plates of the VDW unit are then detached so that the inner plate can be lifted up gradually while it is bolted to the top T-shaped steel (7) on the upper girder (4).

Alternative 3: Sequential installation

After columns (1) and (2) and the lower girder (3) are in place, the VDW (5) will be installed on the bottom T-shaped steel (6) on the lower girder. Then the upper girder (4) will be erected. The inner and external plates of the VDW unit are then detached so that the inner plate can be lifted up gradually while it is bolted to the top T-shaped steel (7) on the upper girder (4).

Table 6.1 VDW installation alternatives

Alternative 1 **Pre-bolting**	**Alternative 2** **Inserting**	**Alternative 3** **Sequential Installation**
- Transport VDW from DIS to construction site - Transport columns and girders from Herrick to construction site - Erect columns (1) and (2) - Bolt VDW (5) to upper girder (4) on ground	- Transport VDW from DIS to construction site - Transport columns and girders from Herrick to construction site - Erect columns (1) and (2) - Erect upper girder (4)	- Transport VDW from DIS to construction site - Transport columns and girders from Herrick to construction site - Erect columns (1) and (2)
- Lift and install the upper girder (with VDW unit) to columns	- Lift and insert VDW unit to the gap between lower and upper girders - Bolt VDW to lower girder (3)	- Lift and bolt the VDW (5) unit on bottom T-shaped steel (6) on lower girder (3) - Erect upper girder (4)
- Detach inner plate and external plate - Bolt external plate to bottom T-shaped steel (6) on lower girder (3)	- Detach inner plate and external plate - Bolt inner plate to top T-shaped steel (7) on upper girder (4)	- Detach inner plate and external plate - Bolt inner plate to top T-shaped steel (7) on upper girder (4)

6.4.3.2 Acquire 3D Objects and Simulate VDW Installation Alternatives

Degenkolb (SEOR) used Autodesk Revit Structure 2009 to model the structural steel in 3D, including the VDW. I then converted this Revit model to the Navisworks Manage 2009 file format. 3D SketchUp 6.0 models of a tower crane and trucks were appended to the Navisworks model to allow the simulation of transportation and site hoisting operations. I discussed with representatives of the GC, the VWD fabricator, and the VDW installation contractor to understand what they would want to see in the 4D simulation and created a story board (Figure 6.4) to plan for scenes, objects, and processes that should be captured in the simulation. Then, I performed 4D simulations of the three installation alternatives using the Navisworks' Animator and Timeliner tools. The Animator allows simulating and capturing movements of objects in 3D space. The Timeliner allows 4D sequencing by connecting 3D objects to scheduling information so that objects will appear according to scheduled activities. It took about 12 hours for me to assemble 3D objects into a single 3D model and create 4D simulations of the three installation alternatives for this study. Figure 6.4 summarizes the inputs and tools used to create a process simulation using 3D product models.

The simulation shows the sequence of installation for all three mentioned alternatives. Truck movement and tower crane operations are also simulated to motivate discussion on transportation schedules and site logistics. Figure 6.5 presents a snapshot of the simulation.

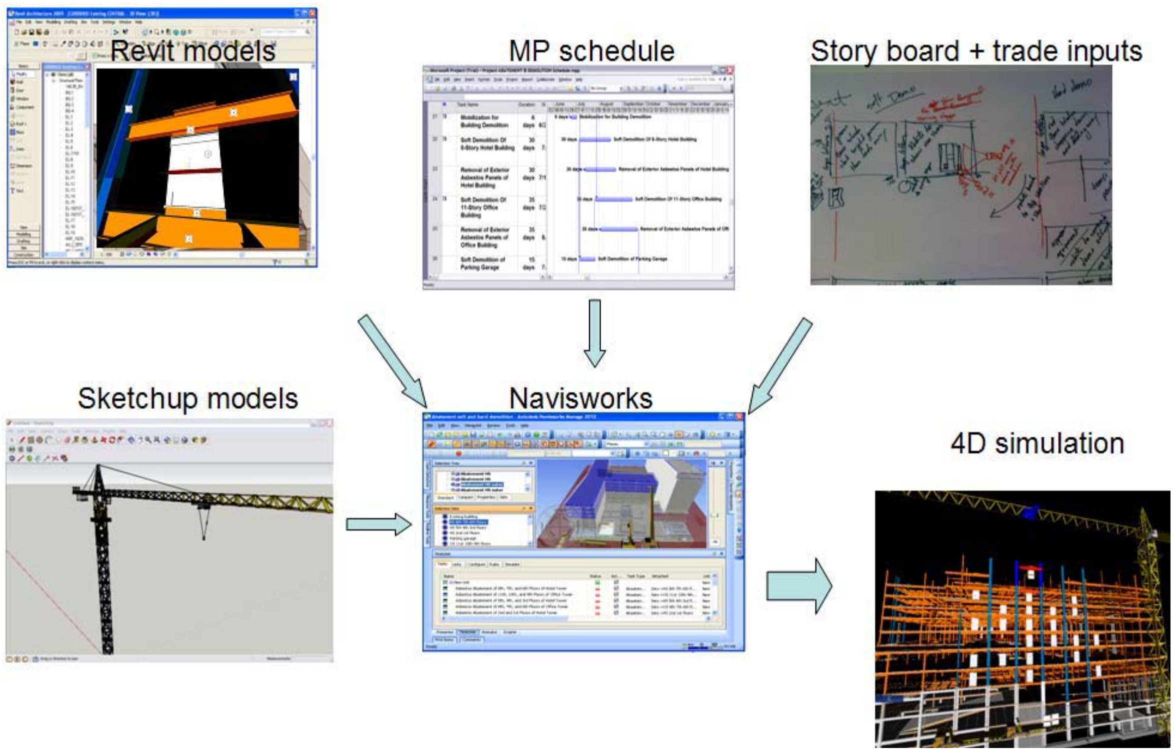


Figure 6.4 Inputs to 4D simulation

6.4.3.3 Present the 4D Simulations to a Cross-functional Team

4D simulations of the three installation alternatives were presented to the team. The simulations triggered a discussion on detailed operations and constructability issues. Table 6.3 summarizes key issues and questions raised by the team as well as solutions suggested. These are grouped in five categories: constructability, fabrication, transportation, site logistics, and installation. As a result of the discussion, the team came up with another alternative (alternative 4) which was similar to alternative 1 but instead of shipping the VDWs directly from the fabrication shop (DIS) to the site, they will be transported to the structural steel fabrication shop (Herrick) and then loaded on the same truck with adjacent columns and girders to be transported to construction site (Table 6.2). In addition, the team agreed to revise the design (i.e., revise patterns of bolts and raise the height of the T-shaped steel). The design decision to increase the T-shaped steel raised cost for Herrick due to additional material and fabrication work (estimated

$200/unit). However, this change allow better tool accessibility and this would generate a saving during site installation due to improved productivity. (Herrick estimated bolt tightening activities could be up to 30% faster, assuming that the team use alternative 4 for installation, resulting in saving of 30%*2hr*$900/hr = $540/unit). For the 155 VDW units, this decision alone resulted in an estimated total saving of 155units*($540/unit - $200/unit) = $52,700.

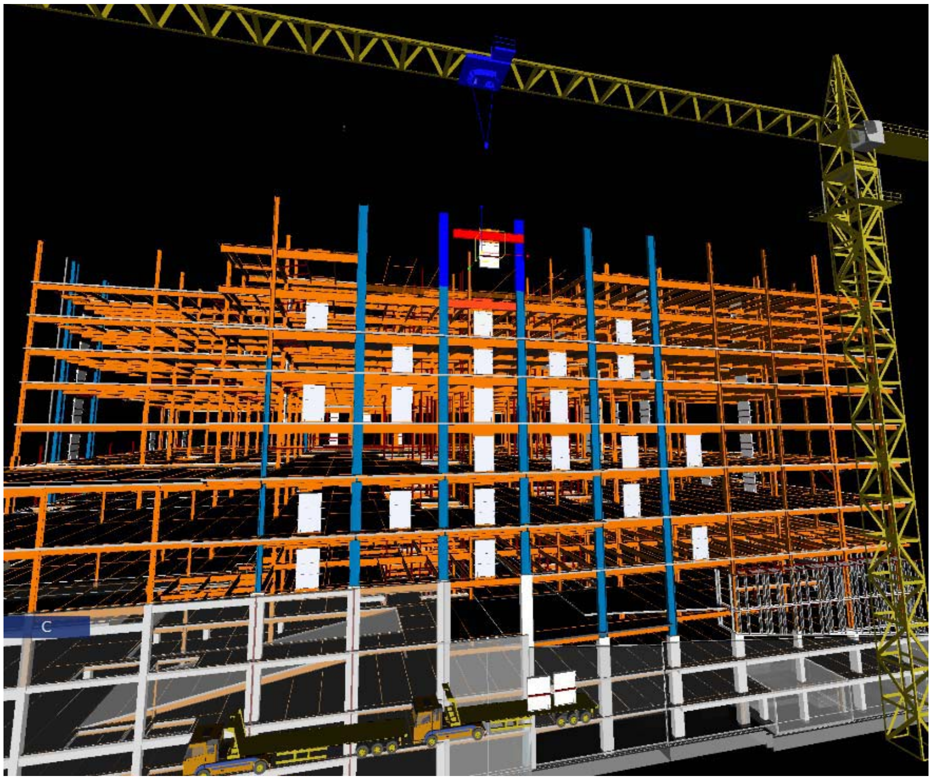


Figure 6.5 Frame in the 4D simulation of the VDW installation alternative 1

Table 6.2 Alternative 4

Alternative 4 **Pre-bolting with kitting**
- Transport VDWs from DIS to Herrick to kite VDW with columns
- Transport VDWs and adjacent columns and girders to construction site
- Erect columns (1) and (2)
- Bolt VDW (5) to upper girder (4) on ground
- Lift and install the upper girder (with VDW unit) to columns
- Detach inner plate and external plate
- Bolt external plate to bottom T-shaped steel (6) on lower girder (3)

Table 6.3 Discussion outcomes

Issues/questions	Suggestions/solutions
Category: Constructability	
Large dimension and density of bolts may prevent access for bolt tightening tools	Revise design to reduce diameter of bolts and/or reduce number of bolts. Test new bolts pattern and diameter on a new mock up
T-shaped steel with 10” in depth allow tight access for bolt tightening tools	Raise the height of T-shaped steel
Lost access to bolts after pouring concrete	Raise the height of T-shaped steel
Stiffeners under T-shaped steel may prevent tool access	Structural engineer to review positions of stiffeners. Consider horizontal bolting.
Some VDWs are close to walls of patient bathrooms	Coordinate with Interior Cluster group to ensure access to bolts
Category: Site logistics	
Two trucks, one with columns and girders and one with VWDs may cause traffic congestion on the street. Possible delay if VDW truck fails to come in time	May consider transporting VDW to Herrick shop and Herrick will bundle and transport columns, girders, and a VDW together on one truck to the site
Multiple lifts of VDW in windy condition	May consider shipping VDW in rack and lift the whole rack to installation area.
Site constraints	No storage area
Category: Transportation	
How many VDWs per truck?	Three for VDW size 7'x12', four for VDW sizes 7'x9' and 7'x10' are these are smaller and lighter than the VDW 7'x12'
Must VDW be kept strictly vertical at all time?	May swing up to 40 degree for a short time, keep vertical during transportation
Duration of transportation from manufacturing facility to site	Four to five hours
Distance of transportation from DIS to construction site	220 miles from Reno fabrication facility to San Francisco
Category: Fabrication	
Procuring of key materials	Viscous fluid imported from Japan and steel from US steel mill
Material lead time	DIS needs two months lead time from procuring materials to start production
Production rate	Three units per week

Issues/questions	Suggestions/solutions
Storage capacity at DIS fabrication shop	Up to 155 VDW units
VDW identification system	Use bar-chart ID tag for each VDW
Shipping schedule	Three units/week. Max 10 units/week. Able to match production rate to installation rate.
Category: Installation	
Rate of installation	Three units/day for alternative 1
	Up to ten units/day for alternative 3
Installation schedule	Alternative 1: requires close coordination with structural erection sequence.
	Alternative 3: requires less coordination.
Equipment for site installation	Tower crane, bolt tightening tools
Labor	crew of six workers
Impacts of different sizes of VDWs on installation	No significant impact

6.4.4 PROCESS MAPPING

Process Mapping is a management tool that can be used to understand how value is delivered; it captures knowledge about processes and then represents that knowledge using generally accepted signs such as boxes and arrows (Adams 2000). One benefit of process mapping is that it shows coordination processes across organizations. A cross-functional process map has the added advantage of representing hand-offs between trades (Damelio 1996). Therefore, the cross-functional process mapping was selected to map major steps of design, fabrication, transportation, and site installation of the VDW system.

The team determined that the process under study should include material handling, material transportation, and site installation of the VDW system; and the boundary for the process mapping exercise covered inventory at DIS, transportation, material handling on site, and site installation. Starting from alternative 1, trade partners used Post-It-Notes™ to identify process steps that belong to their own trades. Then the team together determined the sequence of steps and specified hand-offs between specialties. Figures 6.6, 6.7, 6.8, and 6.9 present the cross-functional process maps of installation alternatives 1, 2, 3, and 4 respectively.

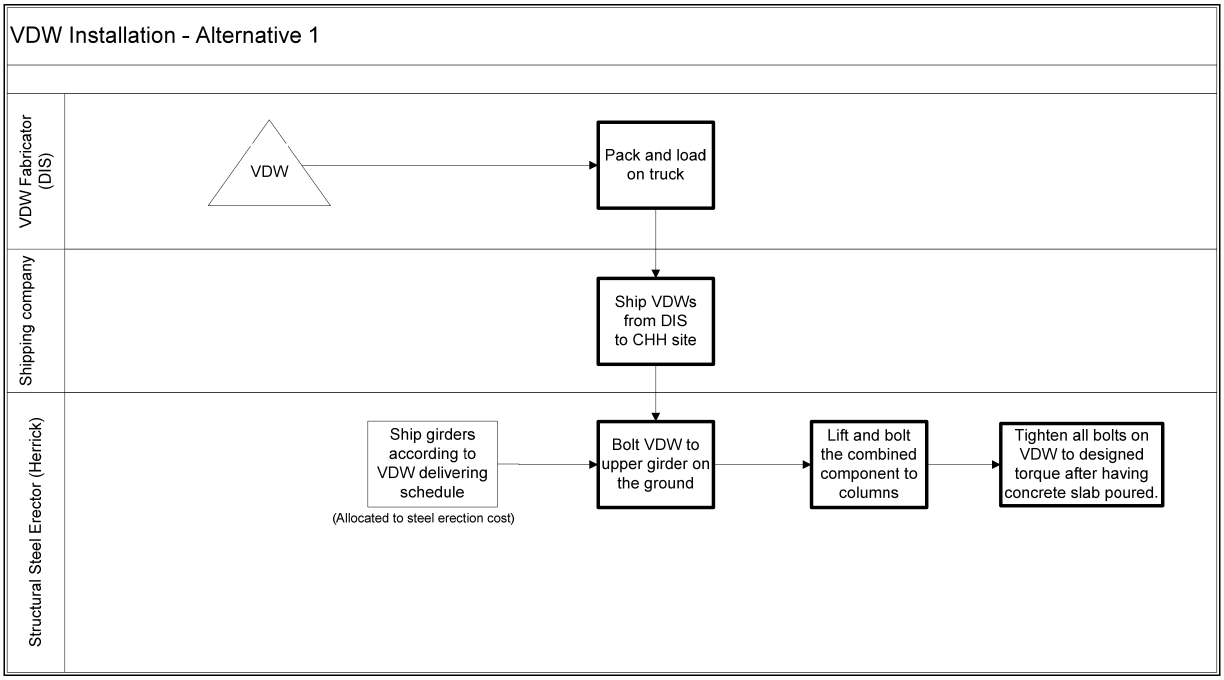


Figure 6.6 Cross-functional process map of installation alternative 1

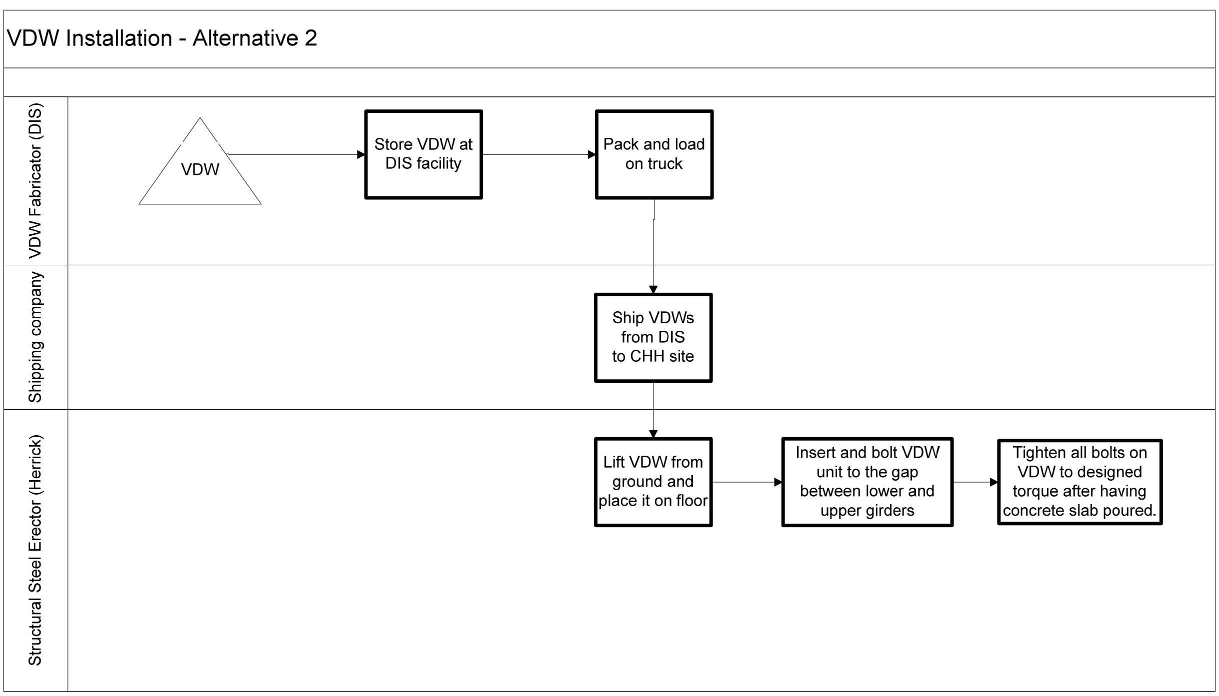


Figure 6.7 Cross-functional process map of installation alternative 2

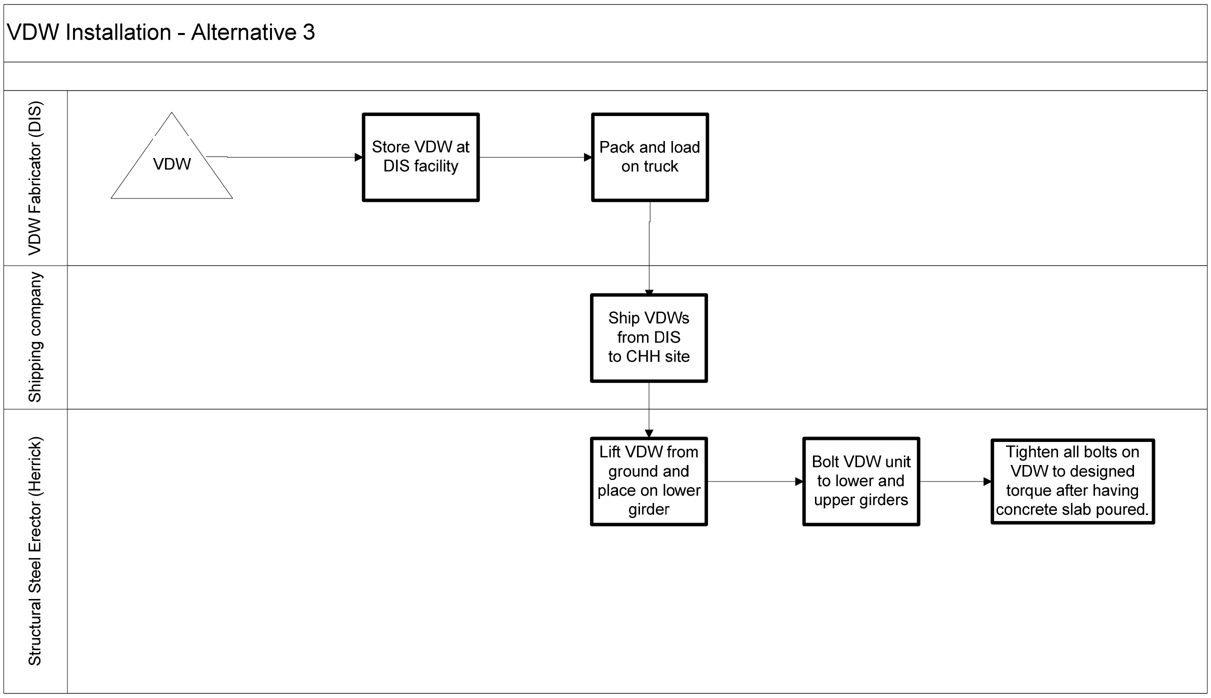


Figure 6.8 Cross-functional process map of installation alternative 3

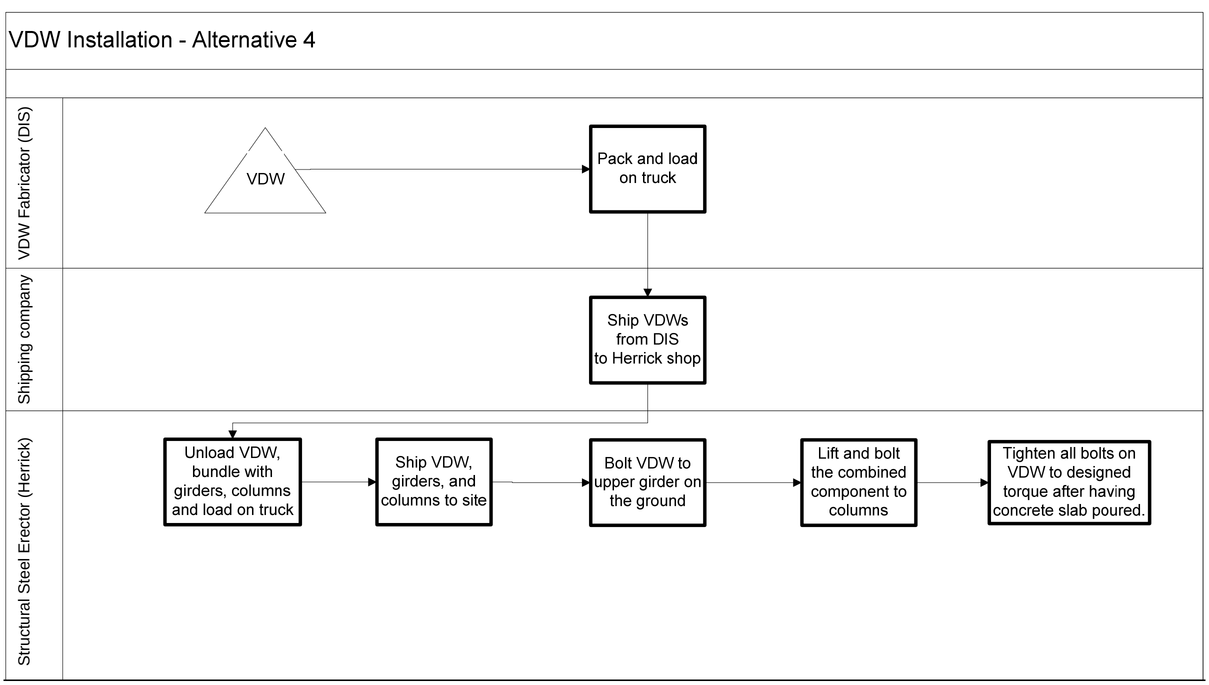


Figure 6.9 Cross-functional process map of installation alternative 4

6.4.5 PROCESS COST ESTIMATE

6.4.5.1 Identifying Activities for Estimating Process Cost

Almost all activities of the four alternatives contributed directly to the cost of delivering and installing a VDW, except for the activity “Ship girders according to VDW delivery schedule” in the alternative 1 (Figure 6.6), which was a ‘make ready’ activity to prepare for the next one “Bolt VDW to upper girder on the ground.” Since the cost of shipping girders had been included in the cost of structural steel erection, it was excluded from the process cost estimate for the VDW system in Figure 6.10.

6.4.5.2 Identifying Cost Drivers

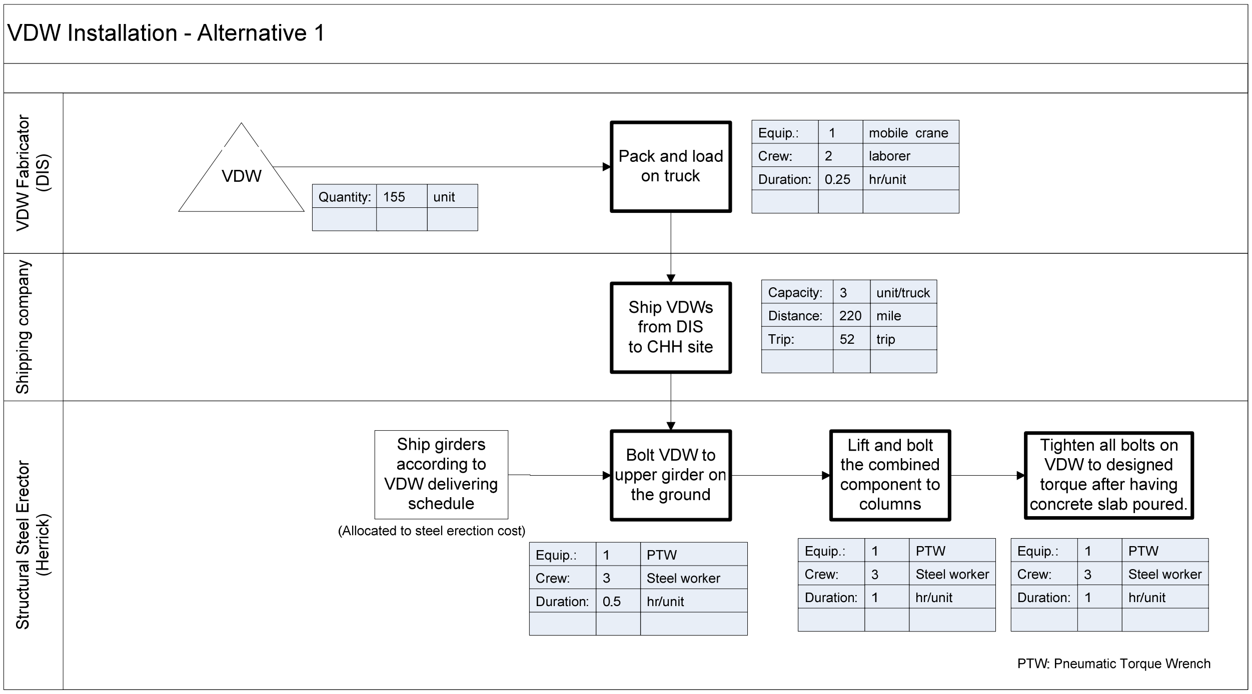
Table 6.4 lists cost parameters and cost drivers using for estimating and calculating process cost. A cost driver is a cost parameter that has a predominant effect on the cost of activity, for example an activity duration is often a cost driver for an installation activity.

Table 6.4 Cost parameters and cost drivers

Process	Cost parameters	Cost driver
Inventory	space occupied, utilities, security	sf/year
Transportation	truck capacity, number of trips, and distance	trip
Material handling and installation activities	crew composition, equipment, and duration	hour/unit

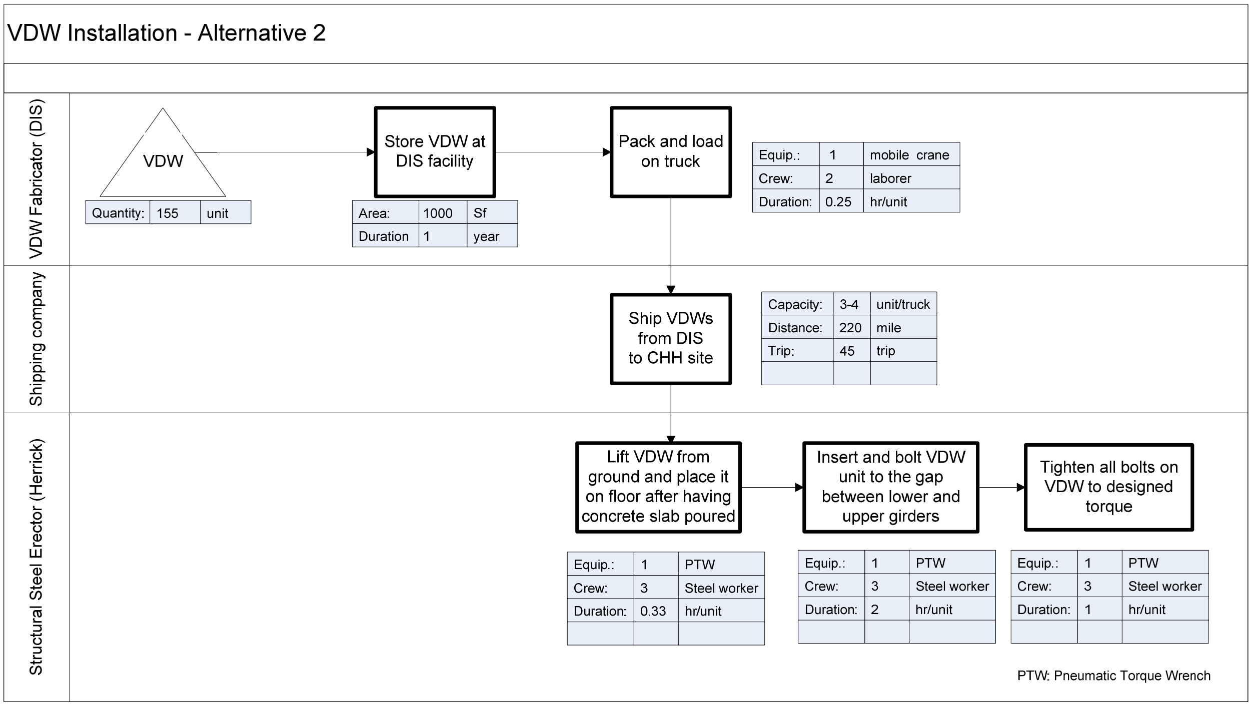
6.4.5.3 Providing Cost Data and Calculating Total Process Cost

The GC, designers, trade partners, suppliers, and cost estimators provided estimates such as distance, truck capacity, design quantities, crew composition, task duration, and estimated unit cost for cost parameters and cost drivers. Figures 6.10, 6.11, 6.12 and 6.13 summarized input data and results of process cost estimates for alternatives 1, 2, 3, and 4 consecutively. Appendix C presents detail calculation of allocating activity cost to each product unit (cost/unit values). All cost data presented in this case study has been multiplied by a factor to protect contractors’ private data.



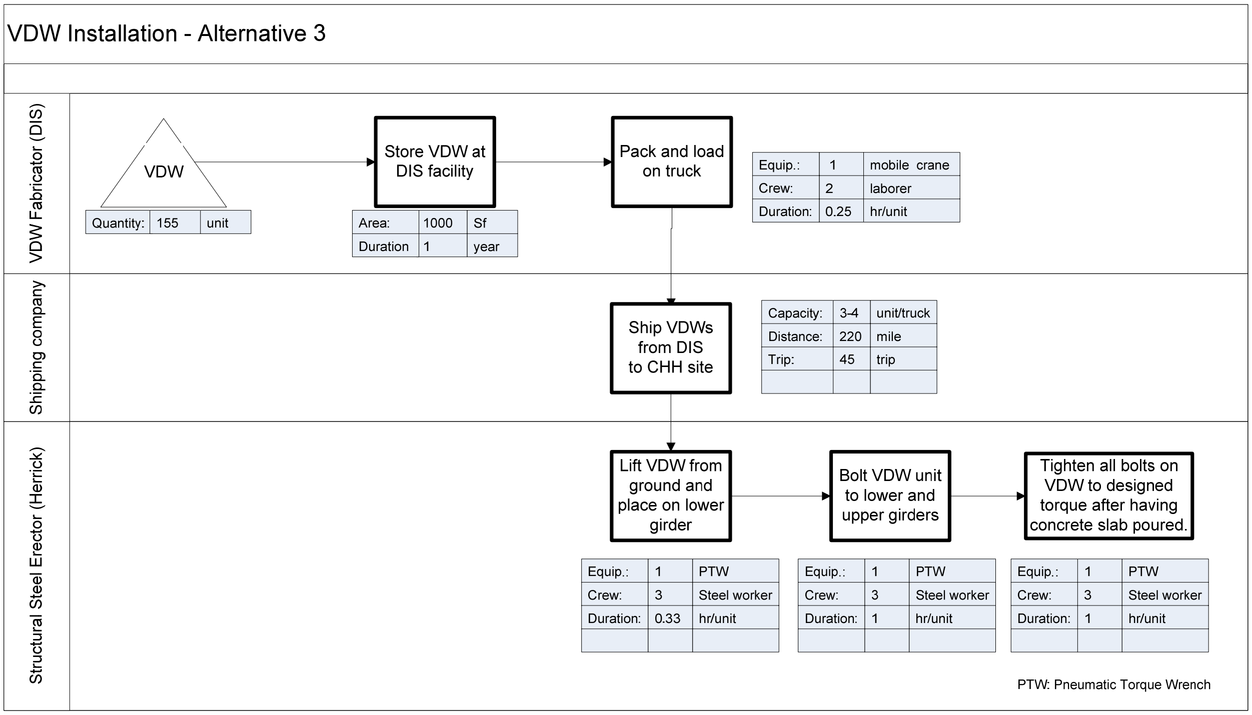
Alternative 1 - Pre-bolting	Quantity	Cost/unit	Cost
Material			
VDW size 7' x 9'	76	$30,600	$2,325,600
VDW size 7' x 12'	79	$40,500	$3,199,500
Material cost			*$5,525,100*
Activities			
Store VDW at DIS	155	$0.00	$0
Pack and load on truck	155	$22.50	$3,488
Ship VDWs from DIS to site	155	$704.52	$109,200
Bolt VDW to upper girder on the ground	155	$450.00	$69,750
Lift and install the combined component to lower girder	155	$900.00	$139,500
Tighten all bolts on VDW to designed torque after having concrete slab poured.	155	$900.00	$139,500
Process cost			*$461,438*
Total cost alternative 1:			**$5,986,538**

Figure 6.10 Process-Based Cost Model of alternative 1



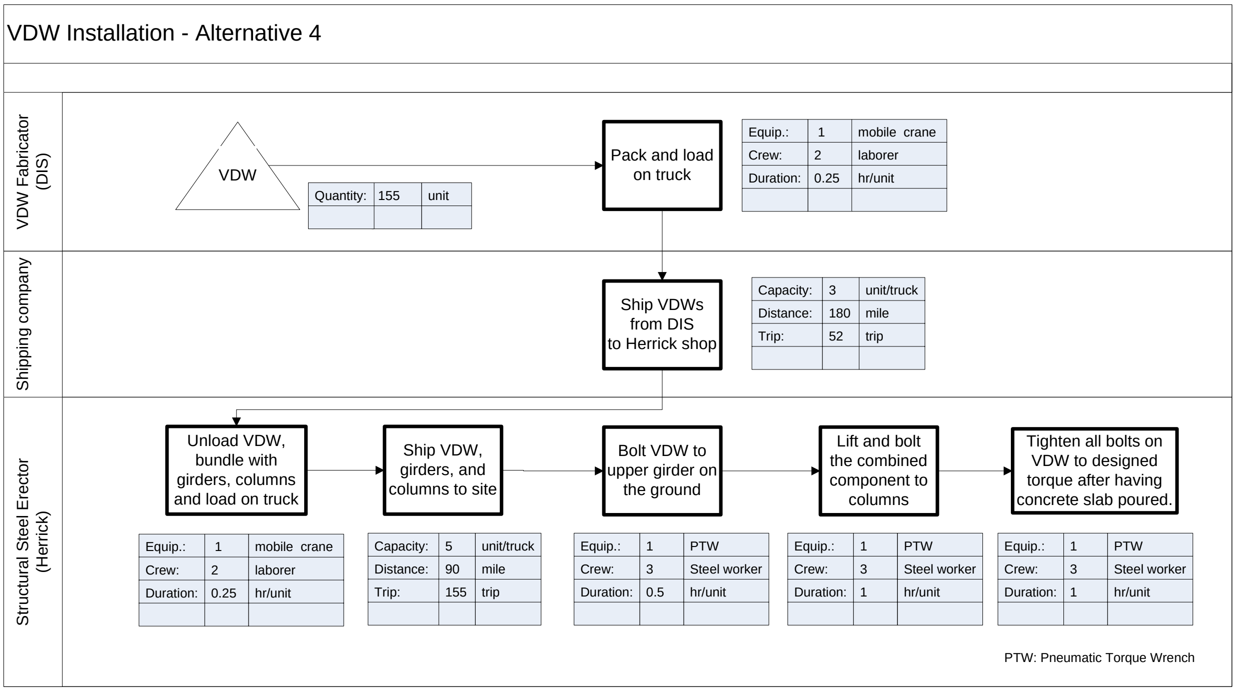
Alternative 2 - Inserting	Quantity	Cost/unit	Cost
Material			
VDW size 7' x 9'	76	$30,600	$2,325,600
VDW size 7' x 12'	79	$40,500	$3,199,500
Material cost			*$5,525,100*
Activities			
Store VDW at DIS	155	$167.74	$26,000
Pack and load on truck	155	$22.50	$3,488
Ship VDWs from DIS to site	155	$609.68	$94,500
Lift VDW from ground and place it on floor on a roller after having concrete slab poured	155	$297.00	$46,035
Insert and bolt VDW unit to the gap between lower and upper girders	155	$1,800.00	$279,000
Tighten all bolts on VDW to designed torque.	155	$900.00	$139,500
Process cost			*$588,523*
Total cost alternative 2:			**$6,113,623**

Figure 6.11 Process-Based Cost Model of alternative 2



Alternative 3 - Sequencing	Quantity	Cost/unit	Cost
Material			
VDW size 7' x 9'	76	$30,600	$2,325,600
VDW size 7' x 12'	79	$40,500	$3,199,500
Material cost			*$5,525,100*
Activities			
Store VDW at DIS	155	$117.42	$18,200
Pack and load on truck	155	$22.50	$3,488
Ship VDWs from DIS to site	155	$609.68	$94,500
Lift VDW from ground and place on lower girder	155	$297.00	$46,035
Bolt VDW unit to lower and upper girders	155	$900.00	$139,500
Tighten all bolts on VDW to designed torque after having concrete slab poured.	155	$900.00	$139,500
Process cost			*$441,223*
Total cost alternative 3:			**$5,966,323**

Figure 6.12 Process-Based Cost Model of alternative 3



Alternative 4 - Pre-bolting with kitting	Quantity	Cost/unit	Cost
Material			
VDW size 7' x 9'	76	$30,600	$2,325,600
VDW size 7' x 12'	79	$40,500	$3,199,500
Material cost			*$5,525,100*
Activities			
Pack and load on truck	155	$22.50	$3,488
Ship VDWs from DIS to Herrick shop	155	$637.42	$98,800
Unload VDW, bundle with girders, columns and load on truck	155	$22.50	$3,488
Ship VDW, girders, and columns from Herrick to site	155	$187.50	$29,063
Bolt VDW to upper girder on the ground	155	$450.00	$69,750
Lift and bolt the combined component to columns	155	$900.00	$139,500
Tighten all bolts on VDW to designed torque after having concrete slab poured.	155	$900.00	$139,500
Process cost			*$483,588*
Total cost alternative 4:			**$6,008,688**

Figure 6.13 Process-Based Cost Model of alternative 4

6.4.6 MAKING DECISIONS USING CHOOSING BY ADVANTAGES (CBA)

The IPD team at CHH used the CBA Decisionmaking System (Suhr 1999) to make decisions. The CBA system is based on several key principles including: “Decisions must be anchored to the relevant facts” and “Decisions must be based on the importance of advantages” (Suhr 1999). In the CBA terminology, a *Factor* is a container of information and data. It contains the criteria, specific attributes of the alternatives and consequential advantages. A *Criterion* is a decision rule or guideline established by the decision maker. A criterion can be expressed as a must (mandatory) or a want (desirable). An *Attribute* is a characteristic, quality or consequence of one alternative. An *Advantage* is a beneficial difference between two attributes (Koga 2008).

Given various factors that need to be considered in selecting an installation option, the cross-functional team decided to use CBA to analyze advantages of the identified alternatives. Assuring safety, reliability, and ease of installation were determined as factors containing ‘must’ criteria. Minimizing unnecessary transportation, movements, temporary storage, and waiting for materials, equipment, and labors were determined as factors containing ‘want’ criteria. By the time of writing of this dissertation, the CBA table has not been completed because the team continues to gather data and it is not the last responsible moment for making this decision. The last responsible moment for this decision is anticipated to occur when the steel erection plan gets finalized in early 2010. Figure 6.14 presents CBA analysis results. When the importance of the advantage, “Much more ease of installation” was weighed against the importance of the other advantages, it was deemed to be the paramount advantage. It was placed at the top of the importance scale in position 100. All other advantages were individually weighted by the team on the same scale of importance relative to the paramount advantage and one another. Alternative 2 was eliminated since it does not pass the must criterion on ‘ease of installation’.

LEGEND Underline Least Preferred Attribute Yellow cell = most important Advantage in Factor Blank = no advantage Circle = paramount advantage	Alternative 1 Pre-bolting		Alternative 2 Inserting		Alternative 3 Sequential installation		Alternative 4 Pre-bolting with kitting	
Installation Cost	$ 348,750		$ 464,535		$ 325,035		$ 348,750	
Storage cost	$ -		$ 26,000		$ 18,200		$ -	
Transportation cost	$ 109,200		$ 94,500		$ 94,500		$ 131,350	
TOTAL	$ 457,950		$ 585,035		$ 437,735		$ 480,100	
Factor: **Interference** *Criterion:* Cause work stoppage/ interference/ productivity losses to related activities or other trade partners. Less is better. *Attribute:*	Interferes with the structural steel installation activity. Steel workers and tower crane need to shift between structural steel and VDW		Could install a large batch of VDWs after finishing structural steel of one floor or more		Could install a batch of VDWs after finishing structural steel of one floor level		Interferes with structural steel installation activity. Steel workers and tower crane need to shift between structural steel and VDW	
Advantage:	!	0	Much less interference	50	Less interference	41	!	0
Factor: **Reliability** *Criterion:* Assure reliability of the method. More is better. *Attribute:*	This method is used widely in Japan. Very good for handling tolerance issues		Rarely used. Tolerance may be a problem.		This method is used in Japan. Tolerance may be a problem		This method is used widely in Japan. Very good for handling tolerance issues	
Advantage:	Much more reliability	90	!	0	More reliability	72	Much more reliability	90
Factor: **Coordination effort between trades.** *Criterion:* Reduce the coordination effort required between trades. Less is better. *Attribute:*	Tight coordination needed between DIS, shipping companies, and Herrick for just-in-time delivery of columns, girders, and VDWs		VDWs could arrive after finishing installation of structural steel on one or several levels		VDWs could arrive after finishing installation of structural steel on a portion of one level		VDWs shipped to Herrick fabrication shop and then shipped to site with columns and girders	
Advantage:	!	0	Much less coordination	65	Less coordination	55	Less coordination	55
Factor: **Street congestion** *Criterion:* Less is better. *Attribute:*	Two trucks on street during installation		One truck at a time, unload quickly		One truck at a time, unload quickly		One truck on street during installation	
Advantage:	!	0	Much less congestion	70	Much less congestion	70	Much less congestion	70
Factor: **Tower crane usage** *Criteria:* Reduce occupancy of tower crane or other handling equipments. Less is better *Attribute:*	May need one lift for every combined VDW+upper girder		Could lift a rack containing three to four VDWs and place it on structural steel		Could lift a rack containing three to four VDWs and place it on structural steel		May need one lift for every combined VDW+upper girder	
Advantage:	!	0	Less crane usage	44	Less crane usage	44	!	0
Factor: **Temporary space** *Criterion:* Minimize temporary space usage for VDW handling and movement. Less is better. *Attribute:*	No temporary space needed		Need to temporarily place VDWs on structural steel		Need to temporarily place VDWs on structural steel		No temporary space needed	
Advantage:	Much less temporary space	40	!	0	!	0	Much less temporary space	40
Factor: **Labor safety** *Criterion:* Assure safety for workers. More is better. *Attribute:*	VDW and upper girder bolted on ground.		All connections performed on structural steel		All connections performed on structural steel		VDW and upper girder bolted on ground.	
Advantage:	Much more safe	60	!	0	!	0	Much more safe	60
Factor: **Ease of installation** *Criterion:* Ease for worker's operations and equipment operations during installation. More is better *Attribute:*	The resistance of viscous fluid allows external plate of the VDW lowering down slowly, which enables a precise installation of the external plate on the lower girder.		Given the large size and weight of VDWs, the team has not figured out exactly how the VDW could be inserted into the gap between girders		Need to tighten up upper bolts in a certain sequence for the inner plate to raise up		The resistance of the viscous fluid allows external plate of the VDW to lower down slowly, which enable a precise installation of the external plate on the lower girder.	
Advantage:	Much more ease of installation	100	!	0	More ease of installation	75	Much more ease of installation	100
		290		**229**		**357**		**415**

Figure 6.14 Choosing By Advantages decision study

When the CBA is used to consider alternatives having unequal costs, a bar chart is prepared (Figure 6.15). The height of each bar represents the summed total importance of the advantages of each alternative. Each bar is positioned to represent its cost using the x-axis like a number line. The spacing must be correctly proportional to represent the situation thus the numbers along the x-axis server as a scale to position each bar according to the cost of each alternative. The CBA chart helps the decision maker to have a sensory-rich perception of the decision scenario and consider the incremental differences.

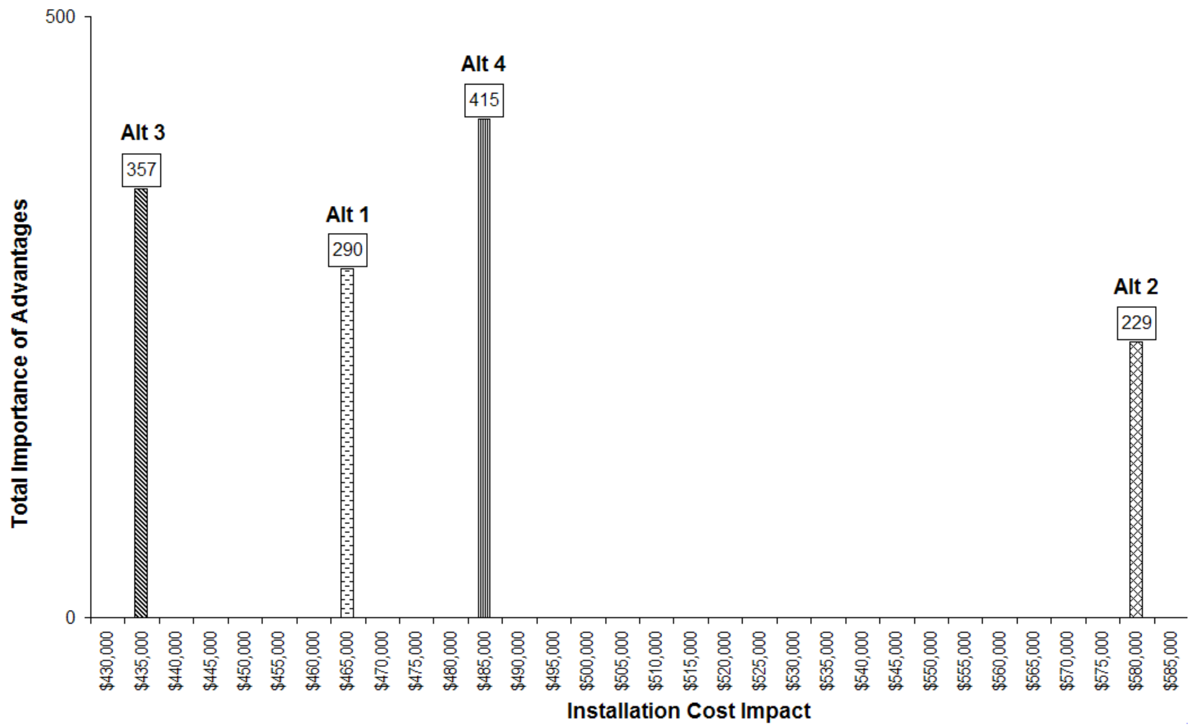


Figure 6.15 Total importance of advantages relative to total cost

In this example, alternative 1 would be rejected since it is $30,000 more expensive but has 67 units of importance less than alternative 3, likewise alternative 2. Although alternative 4 costs $52,000 more than alternative 3, it ranked highest, in terms of the total importance of advantages, at 415. In addition, it is better than alternative 3 in all three ‘must’ criteria. The team may decide to select alternative 4 to install the VDW system if they would together decide that the total increment in the total importance of advantages outweighs the increment in cost, or vice-versa.

6.5 CASE-STUDY CONCLUSIONS AND LESSONS LEARNED

Right from the Design Development phase, an integrated team of designers, engineers, and specialty contractors could examine construction operations in a virtual environment to achieve a common understanding of coordination, logistics, and construction/installation processes. Based on that, they can bring their experience and ideas to investigate alternative ways of doing the work or to suggest design changes to improve constructability. In addition, collaboration tools such as process mapping and CBA helped the cross-functional team generate ideas, communicate design and construction knowledge, evaluate advantages and costs of each alternative, and consider alternatives for Work Structuring.

Process mapping made the logistics and installation activities of the VDW system explicit to the cross-functional team. Each trade partner understood the work of others as well any coordination effort required for producing successful hand-offs.

The team approach to cost estimating, with the participation of people who will actually perform the fabrication and installation work of the VDW system, provided quick and reliable estimates of process data such as capacity, activities, duration, and resources. These data was used to produce process cost estimates which helped evaluate saving as well as additional cost to assist decision making.

CBA helped the team establish factors (representing target values) through selecting ‘must’ and ‘want’ criteria, and provided a sound method for evaluating alternatives according to those targets. During the evaluation process, the team explicitly identified differences between alternatives and recognized the importance of those differences.

The aim of TVD is not to minimize project cost but to maximize value generation while remaining within the Target Cost. This effort may result in shifting costs from the site installation process to product fabrication and logistics, or between trade partners. In this case study, the design decision to increase the height of the T-shaped steel raised material and fabrication cost but it allowed a net saving of $52,700 for the site installation of the VDW.

Alternative 4 offers the best value to the project since it ranked highest, in terms of total importance of advantages, at 415. It meets ‘must’ criteria and allowed additional value such as much more reliability, much less temporary space for material handling, much safer for installation worker, and much more ease of site installation. In terms of cost, it costs about $52,000 more than the lowest cost option, alternative 3. However, the saving of $52,700 in installation cost allowed the team to pursue alternative 4 as it offset the cost difference of $52,000 between alternative 4 and the lowest cost option. Overall, by working collaboratively, using CBA, and by having immediate process cost feedback the team was able to come up with a new alternative that brings the most value to the project at a cost equal to that of the lowest cost option. The risk and profit sharing term and the collaborative working environment enabled by the IFOA made this coordination effort possible.

This chapter introduces a proof of concept case study which applied the proposed PBCM framework to support the process of design to target at CHH. The implementation of PBCM facilitated the coordination between specialists, assisted look-ahead planning, integrated product- and process design, and yielded reliable estimates of manpower and process-related cost. The estimates were reliable since the people who actually perform the work provided input data for estimates. By early coordination, the team eliminated major assumptions about work performed by others as well as hand-offs received from or produced by others. In addition, contingencies are not included in the cost estimate and they are identified and managed separately. In addition, 4D visualization, process mapping, and CBA were key collaboration tools to support the implementation of the PBCM framework. As a result, the structural cluster team successfully coordinated companies across the VDW supply chain and incorporated their innovative ideas in the evaluation of the VDW installation alternatives.

CHAPTER 7. INTEGRATING PROCESS- AND COST DATA IN A PRODUCT MODEL

This case study demonstrates a mechanism of linking a product model with process- and cost data to provide rapid cost feedback to designers and to support model-based cost estimating during the design process. The objectives of this case study are to (1) demonstrate the technical feasibility of PBCM; (2) propose a method to connect BIM object family with process- and cost data; (3) provide an interface for adjusting process- and cost data through process maps; and (4) suggest a framework for establishing and utilizing process database.

7.1 INTRODUCTION

Autodesk Revit provides an Application Programming Interface (API) (Autodesk 2009b) that allows users and external application developers to integrate their applications with it. Programmed as an API, LeanEst works as an Add-In to an existing BIM tool, Autodesk Revit Architecture 2010. I jointly developed LeanEst with Harmony® Soft Company (Company's website: http://www.harmonysoft.com.vn/en/index.php). Before discussing the LeanEst workflow in detail, it is important to present the basics of Autodesk Revit families and their definition. Appendix D defines some key Autodesk Revit terminology used in this chapter.

Autodesk Revit-based products are parametric modeling tools. Parametric modeling uses parameters to define the size and geometry of features and to create relationships between features (Eastman et al. 2008). In Revit, parametric objects can be 3D objects such as columns or beams or 2D drafting objects. These objects are classified into three different classes of families including system, loadable, and in-place families (Autodesk 2009a):

- System families are predefined and stored in the project template. System families are used to create basic building elements such as walls, roofs, ceilings, floors, and other elements that would be assembled on a construction site.
- Loadable families are defined externally in freestanding '.rfa' files. Loadable families create the building components that would usually be purchased, delivered, and installed in and around a building, such as windows, doors, casework, fixtures, furniture, and planting. Due to their highly customizable nature, loadable families are the families that Revit users most commonly create and modify. In this example, the VDW system is a loadable family and it has three family types corresponding to three different sizes used on CHH: VDW 7'x9', VDW 7'x10', and VDW 7'x12'.
- In-place families are created for unique components that are specific to the current project. An in-place family contains a single family type.

A 'family' is a group of elements with a common set of properties, called parameters, and a related graphical representation. Different elements belonging to a family may have different values for some or all of their parameters, but the set of parameters (their names and meanings) is the same. These variations within the family are called 'family types' or 'types'.

Figure 7.1 shows the mechanism of linking a product model with process- and cost data to provide rapid cost feedback and support model-based cost estimating during the design process. The mechanism includes three data links:

Data link (1): Using the Open Data Base Connectivity (ODBC) to link each activity in a process map to its data record in a process- and cost database.

Data link (2): Using the LeanEst Revit Add-In to link a BIM object to cost and process data.

Data link (3): Using the Uniform Resource Locator (URL), as a built-in parameter of a BIM object, to link that BIM object to its process map.

This mechanism is designed to make process- and cost data from the supplier and specialty contractor explicit and visual in order to create a common understanding of processes and costs between team members. The design team may choose to revise the process design, usage of resources, and cost information on the process map, or on the process- and cost database, or on the product model

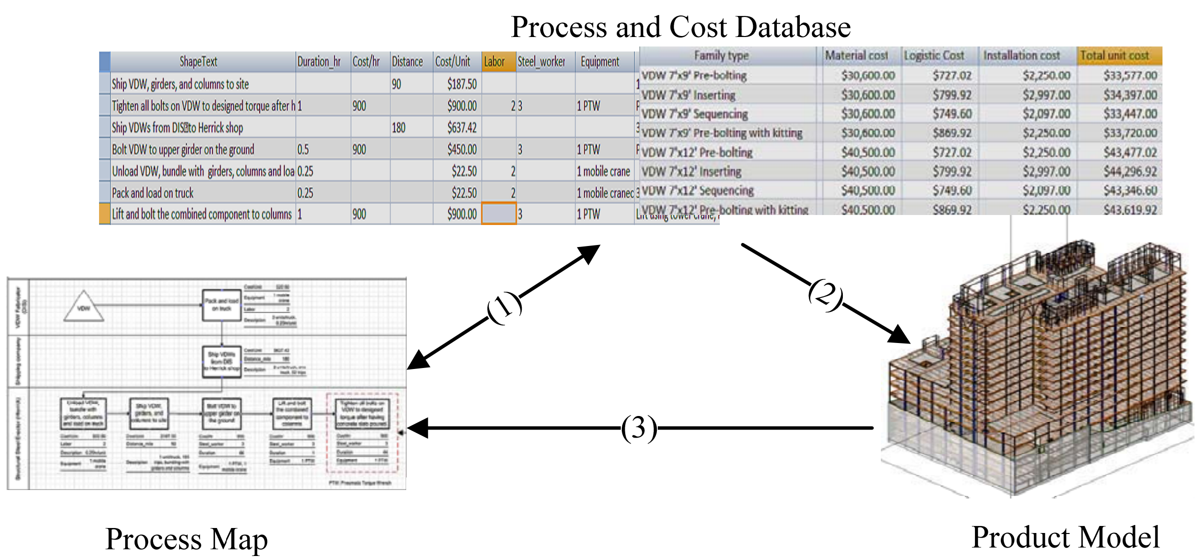


Figure 7.1 Connecting data between a database, a BIM model, and a process map

7.2 DATA LINK (1): CONNECT PROCESS- AND COST DATA TO A PROCESS MAP

The Open Data Base Connectivity (ODBC) is a standard, written by Microsoft, for sharing database information between applications under the Windows operation system. ODBC creates a mechanism to link Microsoft Visio shapes to database records. This way, the user can pass information back and forth between Visio and the database and keep the two versions of the data synchronized.

Almost all Windows-based database programs allow users to convert their proprietary data format to the ODBC format. Some examples are Access, Alpha Four, Oracle, Paradox, and SQL

Server. In this demonstration, I use Microsoft Access 2007 to store process- and cost data and I use ODBC to connect the Access database to a flowchart in Microsoft Visio 2007.

A row in the Access database is called a record. Each row contains data for an activity that is represented as a shape in Visio. When the user connects Visio with a database file, shapes in Visio are connected to specified rows in the database table. The user may specify a data connection using a shape's name or a shape's ID. Visio keeps track of the link between shapes in Visio and rows in the database and the ODBC transfers data back and forth. This is a bi-directional data connection.

Figure 7.2 shows a cross-functional process map in Visio before it is populated with data. Figure 7.3 shows a table containing process- and cost data in Microsoft Access 2007. The activity "Tighten all bolts on VDW to designed torque after having concrete slab poured" has various process- and cost data associated with it, such as its duration, cost per hour, and the number of workers and laborers. Figure 7.4 shows the Visio process map after it is populated with data. The user may select which data to display beside each activity in the process map.

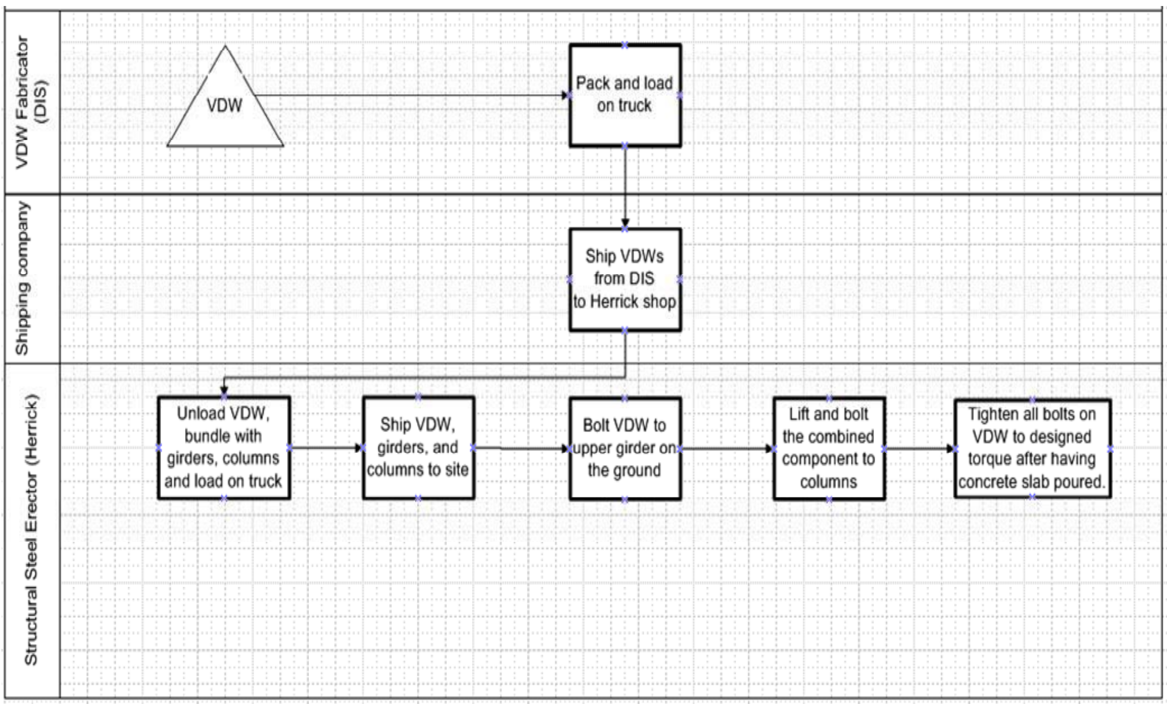


Figure 7.2 Cross-functional process map in Visio before populated with data

VDW Pre-bolting with kitting

ShapeText	Duration_hr	Cost/hr	Distance	Cost/Unit	Labor	Steel_worker	Equipment	Description
Ship VDW, girders, and columns to site			90	$187.50				1 unit/truck, 155 trips, bundling with g
Tighten all bolts on VDW to designed torque after h	1	900		$900.00	2	3	1 PTW	PTW: Pneumatic Torque Wrench
Ship VDWs from DIS to Herrick shop			180	$637.42				3 units/truck, one truck, 52 trips
Bolt VDW to upper girder on the ground	0.5	900		$450.00		3	1 PTW	PTW: Pneumatic Torque Wrench
Unload VDW, bundle with girders, columns and loa	0.25			$22.50	2		1 mobile crane	
Pack and load on truck	0.25			$22.50	2		1 mobile cranec	3 units/truck
Lift and bolt the combined component to columns	1	900		$900.00		3	1 PTW	Lift using tower crane, PTW: Pneuma

Figure 7.3 Process- and cost data in Microsoft Access 2007

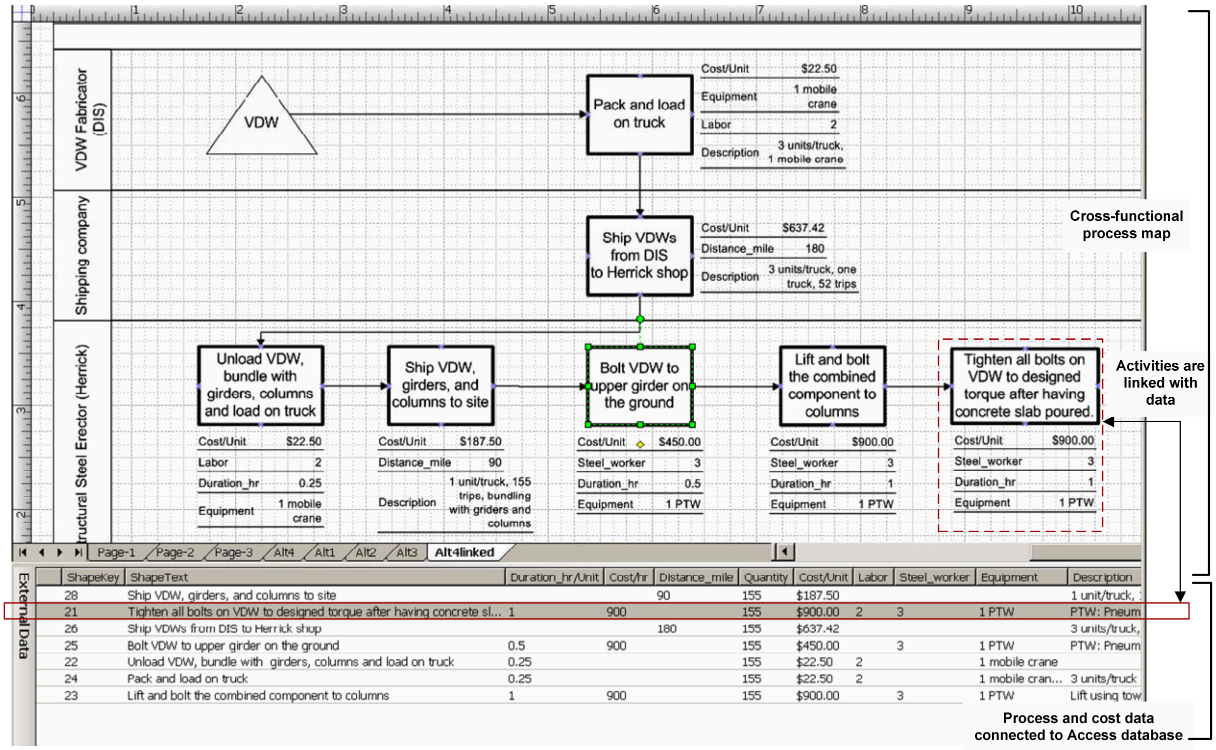


Figure 7.4 Shapes in a process map in Microsoft Visio 2007 link to process- and cost data in Microsoft Access 2007 using ODBC

By linking to a process map, data are more comprehensible to a design team than when they are presented in a conventional spreadsheet. The process map becomes a visual interface for the design team to access and adjust process data.

7.3 DATA LINK (2): CONNECT DATA TO BIM MODEL USING LEANEST REVIT ADD-IN

When installed, LeanEst adds customized commands to the External Tools panel in Revit Architecture 2010. LeanEst automates the process of creating and attaching multiple shared parameters to a Revit object family and links those parameters to cost data in an external database. Figures 7.5 to 7.8 illustrate the LeanEst user interface in Autodesk Revit Architecture 2010. The LeanEst Add-In creates a menu in Revit's External Tools. This menu includes three functions: (1) AddSharedParameters that pull in a pre-defined set of shared parameters to a new Autodesk Revit project, (2) AddParamsToFamily that adds shared parameters to a selected family type, and (3) LinkCostData that writes values from a Microsoft Access 2007 database to the created shared parameters.

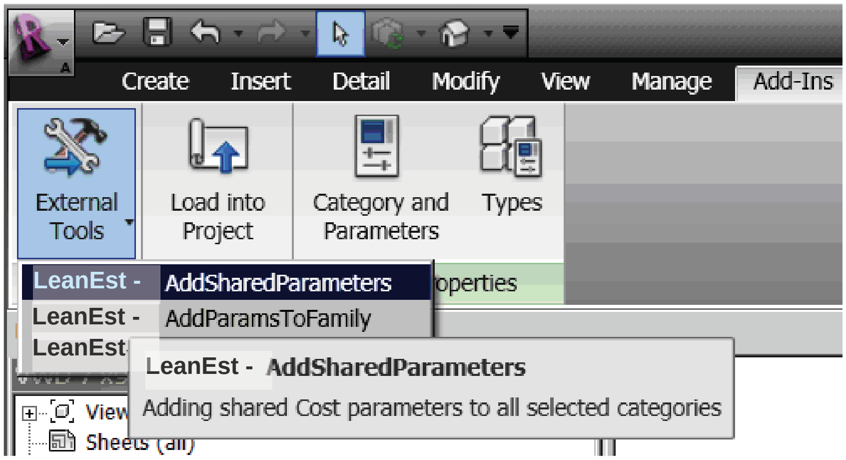


Figure 7.5 AddSharedParameters function

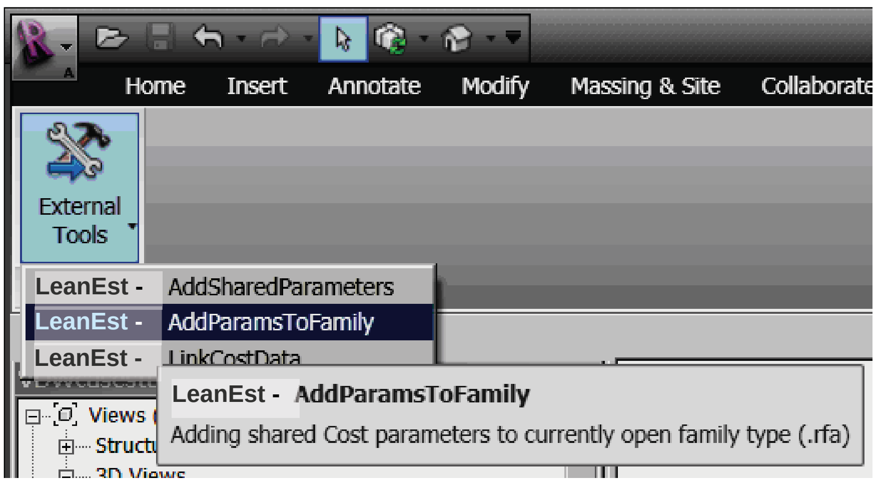


Figure 7.6 AddParamsToFamily function

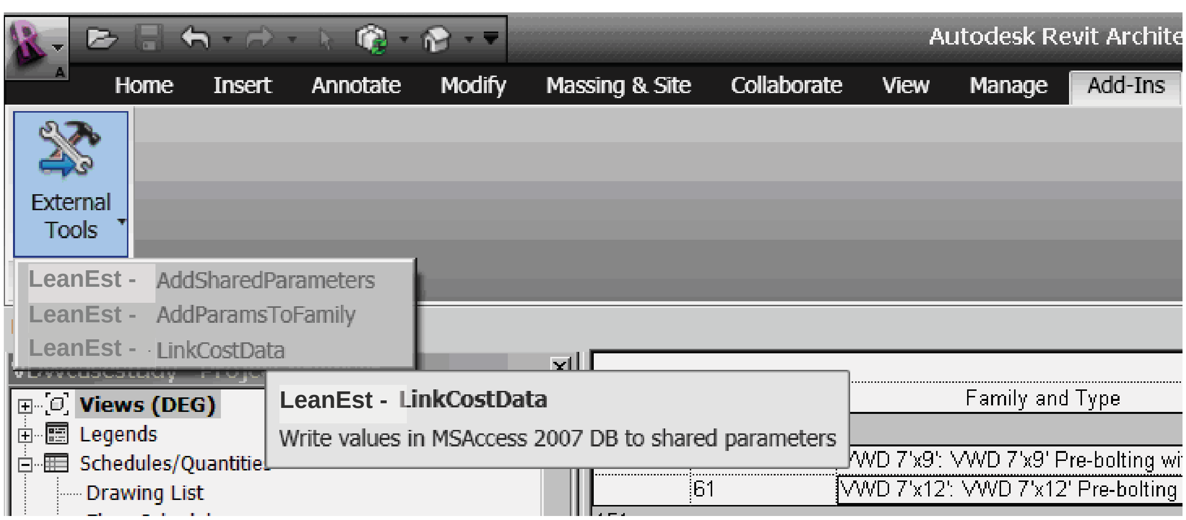


Figure 7.7 LinkCostData function

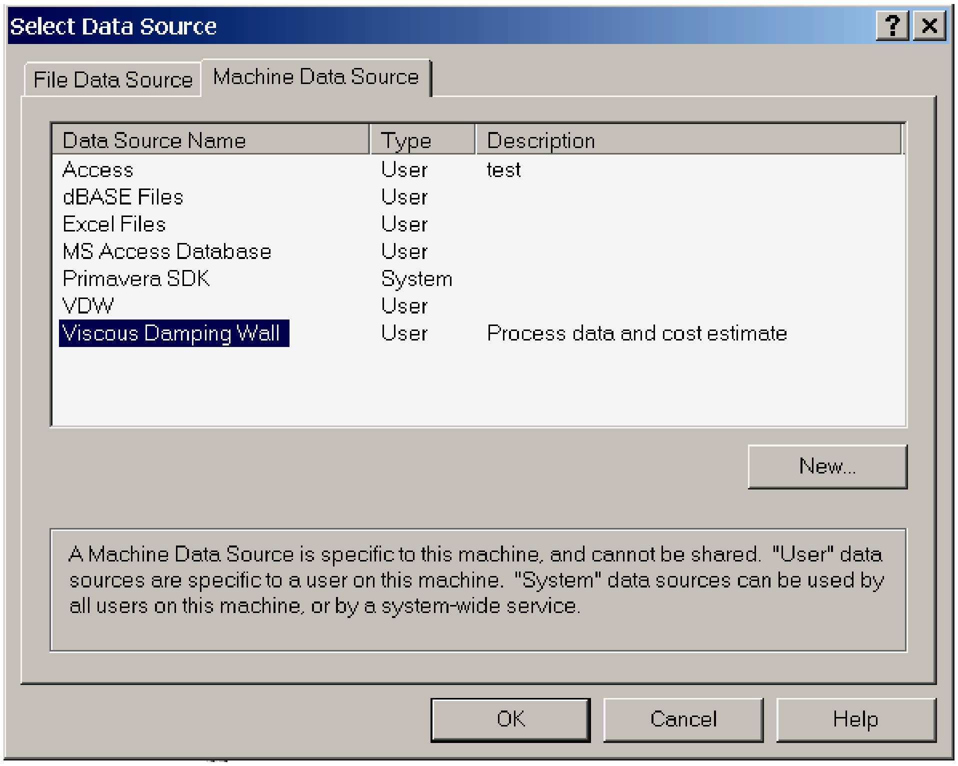


Figure 7.8 Option for specifying data source to connect using LinkCostData function

In this example, I use the AddSharedParameters tool to add the pre-defined shared parameters, shown in Table 7.1 representing product and process costs to the structural steel model in Autodesk Revit:

Table 7.1 Shared parameters and data type

Shared Parameters	**Data Type**
Logistic Cost	Cost
Installation Cost	Cost
Material Cost	Cost
Total Unit Cost	Cost
Total Cost	Cost

Then I use the AddParamsToFamily function to add the created shared parameters to all VDW family types.

SI	Family type	Description	Material cost	Logistic Cost	Installation cost	Total unit cost
1	VDW 7'x9' Pre-bolting	Viscous Damping Wall 7'x9' - Pre-bolti	$30,600.00	$727.02	$2,250.00	$33,577.00
2	VDW 7'x9' Inserting	Viscous Damping Wall 7'x9' - Inserting	$30,600.00	$799.92	$2,997.00	$34,397.00
3	VDW 7'x9' Sequencing	Viscous Damping Wall 7'x9' - Sequenci	$30,600.00	$749.60	$2,097.00	$33,447.00
4	VDW 7'x9' Pre-bolting with kitting	Viscous Damping Wall 7'x9' - Pre-bolti	$30,600.00	$869.92	$2,250.00	$33,720.00
5	VDW 7'x12' Pre-bolting	Viscous Damping Wall 7'x12' - Pre-bol	$40,500.00	$727.02	$2,250.00	$43,477.02
6	VDW 7'x12' Inserting	**Viscous Damping Wall 7'x12' - Insertin**	$40,500.00	$799.92	$2,997.00	$44,296.92
7	VDW 7'x12' Sequencing	Viscous Damping Wall 7'x12' - Sequen	$40,500.00	$749.60	$2,097.00	$43,346.60
8	VDW 7'x12' Pre-bolting with kitting	Viscous Damping Wall 7'x12' - Pre-bol	$40,500.00	$869.92	$2,250.00	$43,619.92
9	VDW 7'x10' Pre-bolting	Viscous Damping Wall 7'x10' - Pre-bol	$34,100.00	$727.02	$2,250.00	$37,077.00
10	VDW 7'x10' Inserting	Viscous Damping Wall 7'x10' - Insertin	$34,100.00	$799.92	$2,997.00	$37,897.00
11	VDW 7'x10' Sequencing	Viscous Damping Wall 7'x10' - Sequen	$34,100.00	$749.60	$2,097.00	$36,947.00
12	VDW 7'x10' Pre-bolting with kitting	Viscous Damping Wall 7'x10' - Pre-bol	$34,100.00	$869.92	$2,250.00	$37,220.00

Figure 7.9 VDW cost data in Microsoft Access 2007

Figure 7.9 shows records of cost data for the VDW family types in Microsoft Access 2007. I use the LinkCostData function to write values in the Microsoft Access database to the created shared parameters. Once these data are linked to the corresponding VDW family types in Revit, when right-clicking on the family type to see object properties, this cost information is included in the object property list as illustrated in figure 7.10.

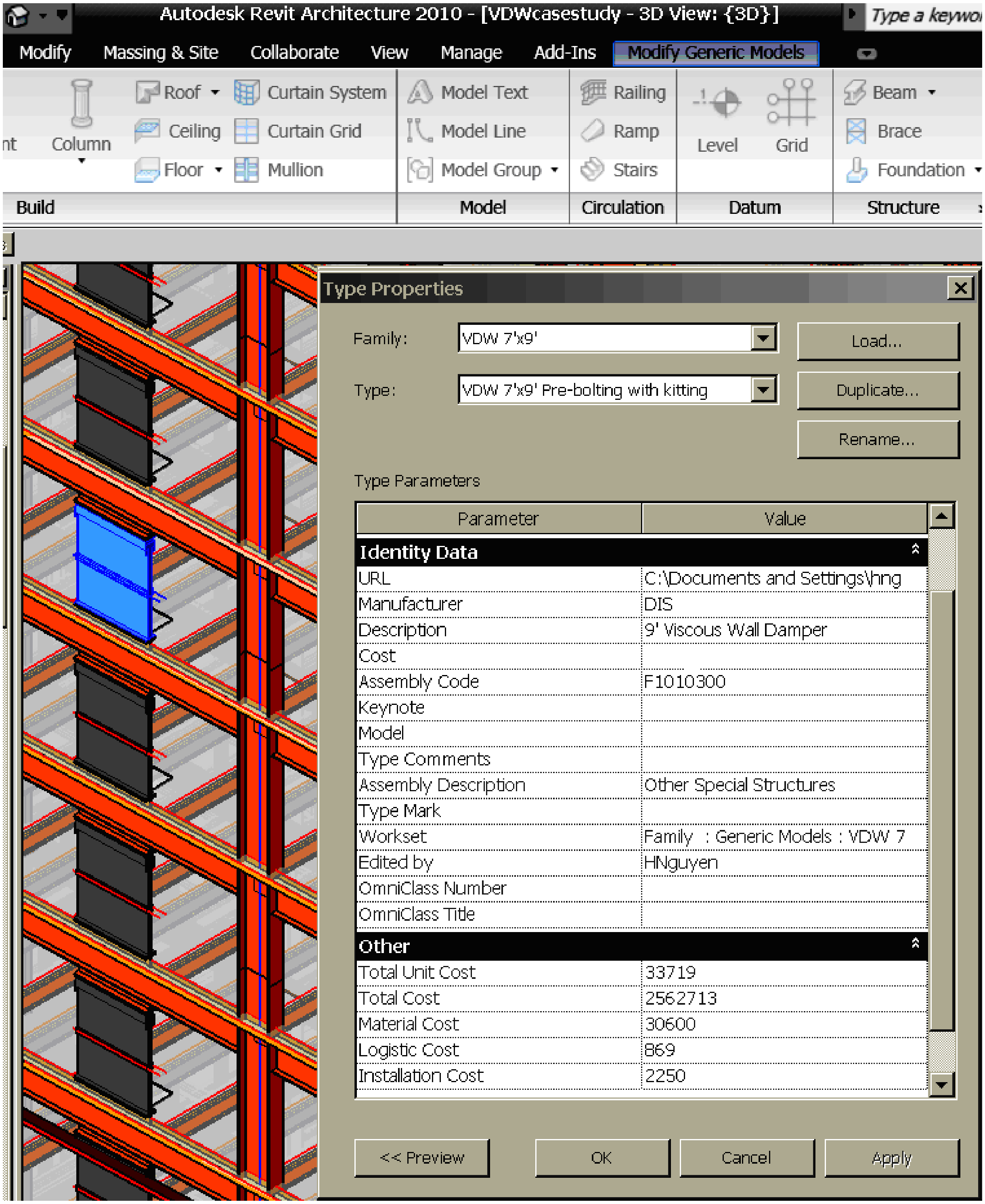


Figure 7.10 Cost data is linked to BIM object and displayed on the object property list

This cost information can be included in a quantity schedule within Autodesk Revit to provide cost feedback to the design team when product or process alternatives are being selected.

Information such as VWD counts can be extracted from the Revit model to calculate a total cost as illustrated in figure 7.11.

Viscous Damping Wall								
Family and Type	Description	Material Cost	Installation Co	Logistic Cost	Total Unit Cost	Count	Total Cost	Manufacturer
VDW 7'x9': VDW 7'x9' Pre-bolting with k	9' Viscous	30600	2250	869	33719	76	2562713	DIS
VDW 7'x12': VDW 7'x12' Pre-bolting wit	12' Viscous	40500	2250	869	43619	79	3445973	DIS

Figure 7.11 Cost feedback for 'Pre-bolting with kitting' installation alternative

Figure 7.11 depicts a VDW schedule view in Autodesk Revit: two VDW family types are used in this design including 76 units of VDW 7'x9' and 79 units of VDW 7'x12'. The selected method of installation is 'Pre-bolting with kitting'. Given the selected family types, the method of installation, and the quantities of VDW extracted from the design model, the total estimated cost for this design alternative is $2,562,713 + $3,445,973 = $6,008,686. This result matches with the manual PBCM calculation presented in Figure 6.13, Chapter 6.

Figures 7.12, 7.13, and 7.14 illustrate examples when the design team considers other alternatives of installing the VDW. From the drop down list, a designer may replace the object family type 'Pre-bolting with kitting' with 'Sequencing', 'Inserting', or 'Pre-bolting' installation method to see how cost will be effected. Values in related fields such as material cost, installation cost, or total cost, etc. will change to reflect the choice of installation method.

Viscous Damping Wall								
Family and Type	Description	Material Cost	Installation Co	Logistic Cost	Total Unit Cost	Count	Total Cost	Manufacturer
VDW 7'x9': VDW 7'x9' Sequencing	9' Viscous	30600	2097	749	33446	76	2541941	DIS
VDW 7'x12': VDW 7'x12' Sequencing	12' Viscous	40500	2097	749	43346	79	3424381	DIS

VDW 7'x10': VDW 7'x10' Pre-bolting with kitting
VDW 7'x10': VDW 7'x10' Sequencing
VDW 7'x12': VDW 7'x12' Inserting
VDW 7'x12': VDW 7'x12' Pre-bolting
VDW 7'x12': VDW 7'x12' Pre-bolting with kitting
VDW 7'x12': VDW 7'x12' Sequencing

Figure 7.12 Cost feedback for 'Sequencing' installation alternative

Viscous Damping Wall								
Family and Type	Description	Material Cost	Installation Co	Logistic Cost	Total Unit Cost	Count	Total Cost	Manufacturer
VDW 7'x9': VDW 7'x9' Inserting	9' Viscous	30600	2997	799	34396	76	2614165	DIS
VDW 7'x12': VDW 7'x12' Inserting	12' Viscous	40500	2997	799	44296	79	3499456	DIS

VDW 7'x10': VDW 7'x10' Pre-bolting with kitting
VDW 7'x10': VDW 7'x10' Sequencing
VDW 7'x12': VDW 7'x12' Inserting
VDW 7'x12': VDW 7'x12' Pre-bolting
VDW 7'x12': VDW 7'x12' Pre-bolting with kitting
VDW 7'x12': VDW 7'x12' Sequencing

Figure 7.13 Cost feedback for 'Inserting' installation alternative

Viscous Damping Wall								
Family and Type	Description	Material Cost	Installation Co	Logistic Cost	Total Unit Cost	Count	Total Cost	Manufacturer
VDW 7'x9': VDW 7'x9' Pre-bolting	9' Viscous	30600	2250	727	33577	76	2551853	DIS
VDW 7'x12': VDW 7'x12' Pre-bolting	12' Viscous	40500	2250	727	43477	79	3434684	DIS

Figure 7.14 Cost feedback for ‘Pre-bolting’ installation alternative

When the quantity and the type of VDW get changed during design, this information will be immediately updated in the Autodesk Revit schedule view, and a new total cost will be calculated automatically. Figure 7.15 illustrates the situation where 9 units of VDW 7’x12’ are replaced by 9 units of VDW 7’x10’ using the ‘Pre-bolting with kitting’ installation alternative. Designers can see the change in quantity in the ‘Count’ column and the change in cost in the ‘Total Cost’ column.

Viscous Damping Wall								
Family and Type	Description	Material Cost	Installation Co	Logistic Cost	Total Unit Cost	Count	Total Cost	Manufacturer
VDW 7'x9': VDW 7'x9' Pre-bolting with k	9' Viscous	30600	2250	869	33719	76	2562713	DIS
VDW 7'x10': VDW 7'x10' Pre-bolting wit	10' Viscous	34100	2250	869	37219	9	334979	DIS
VDW 7'x12': VDW 7'x12' Pre-bolting wit	12' Viscous	40500	2250	869	43619	70	3053394	DIS

Figure 7.15 Cost feedback when design changes

Cost information contained in shared parameters can be exported to other applications such as Microsoft Excel or cost estimating applications for producing cost reports. It is also possible to extract a family with its shared parameters out of a project and store it into an external family file for usage in future projects.

Although developed for Autodesk Revit Architecture 2010, with some minor modifications, LeanEst can also be used with Autodesk Revit Structure 2010 and Autodesk Revit MEP 2010.

With LeanEst, users can connect any type of data contained in the process- and cost database to a BIM object. As illustrated in the example in Figure 7.16, durations, costs per unit, and activity descriptions to install a VDW 7’x12’ using the ‘Pre-bolting with kitting’ method are displayed as properties of the VDW 7’x12’ ‘Pre-bolting with kitting’ family type.

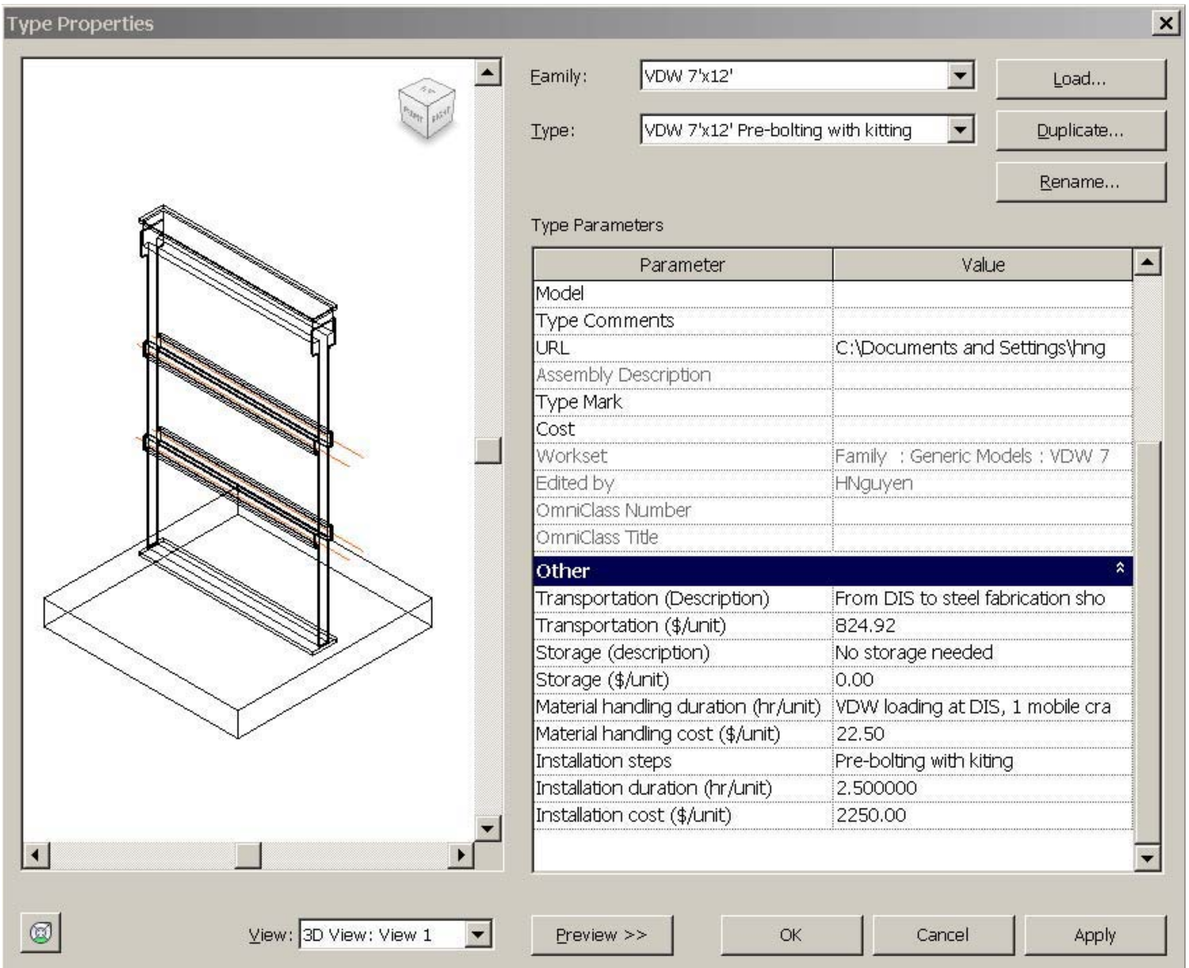


Figure 7.16 Connect detailed process- and cost data to an object family type

7.4 DATA LINK (3): LINK PROCESS MAP TO BIM OBJECT

A Uniform Resource Locator (URL) is a built-in parameter of a BIM object. A URL can be used to link a BIM object to its process map stored on a project server or a web page. To create the link, Autodesk Revit users may enter a URL link as a BIM object's property as illustrated in Figure 7.17. In Autodesk Revit's Schedule View, the user can click on the URL field to open a process map as illustrated in Figure 7.18.

When opened, the user will see the process map and process- and cost data populated with it as presented in Figure 7.4. This link makes process information accessible and visual to the design team.

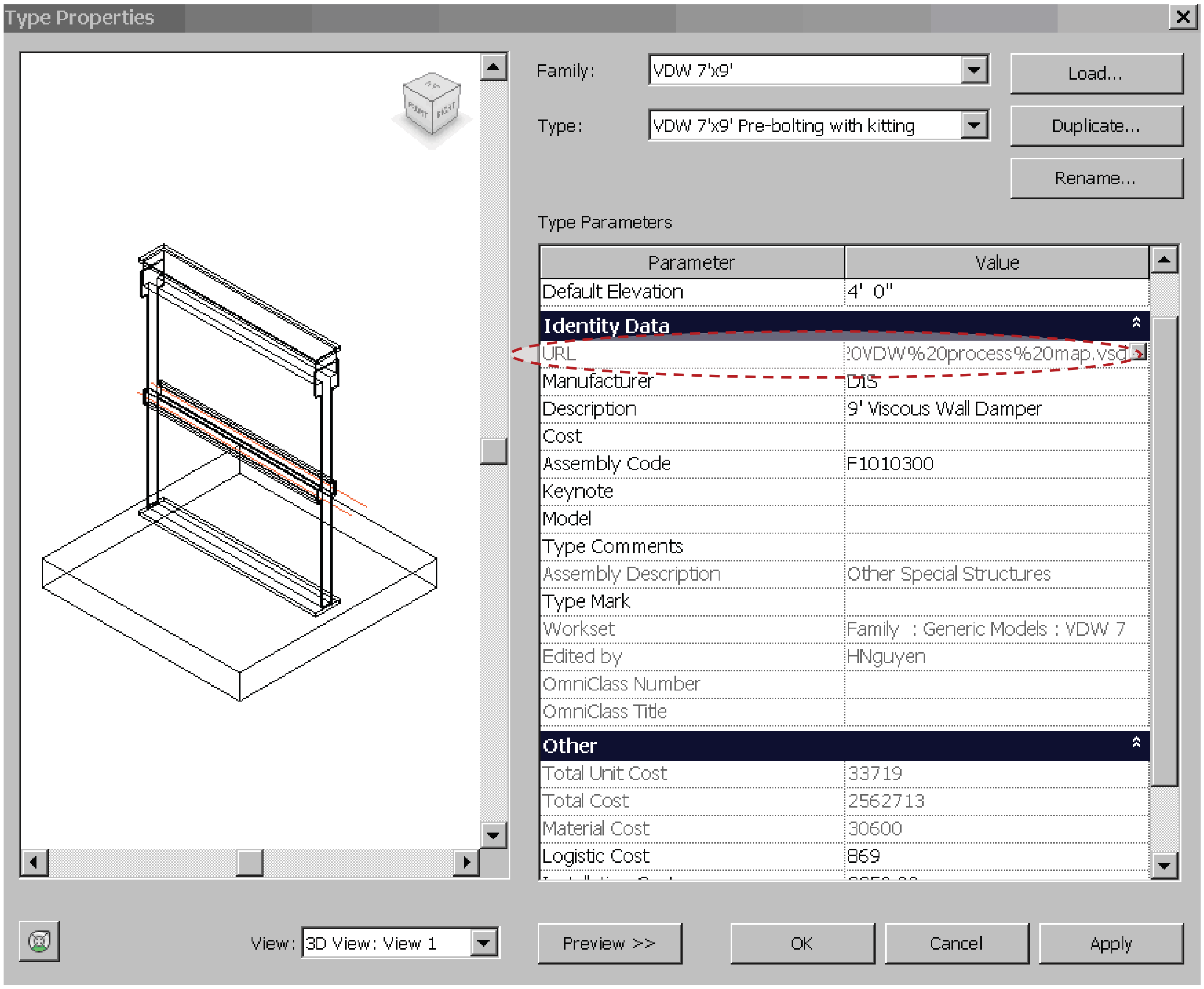


Figure 7.17 Enter a URL link as a BIM object's property

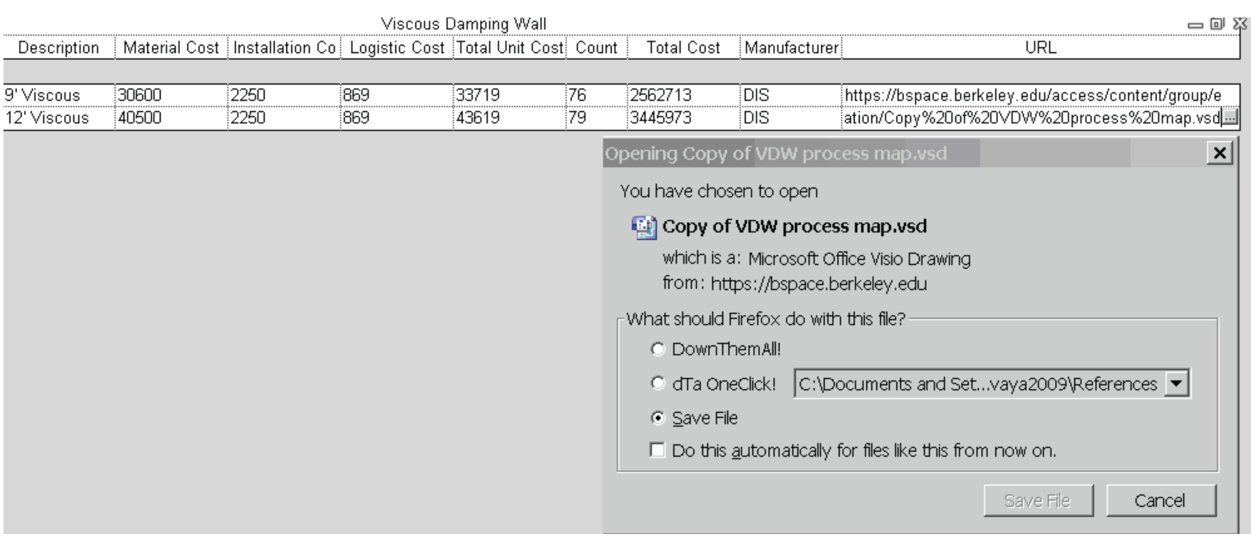


Figure 7.18 Open a process map from Autodesk Revit's Schedule View

7.5 PRACTITIONERS' FEEDBACK ON LEANEST

The advantage of LeanEst is in linking cost directly to BIM objects and displaying cost information within the modeling software. This linking mechanism makes cost information instantly available to the design team (Krumenacker 2010; Kothari 2010; Hofmann 2010).

The timing of providing cost feedback is important in avoiding wasted effort in design. The current cost estimating process on CHH takes days or even weeks to provide feedback to designers and that often causes rework in design (Krumenacker 2010).

The LeanEst tool may require a lot of data input, but some trade partners already have had in-house process- and cost database. The problem may lie in how to encourage them to share that database with the design team (Modrich 2010).

The data links allow transparency in adjustment of process- and cost data (Hofmann 2010; Sparapani 2010; Kothari 2010).

The data links add intelligence to the product model, they help to integrate the product model and the cost model (Lostuvali 2010; Modrich 2010; Krumenacker 2010).

The database takes into account the cost implications of alternatives of logistic and installation activities, revealing how design changes lead to changes in product and process cost (Lostuvali 2010).

When budget is calculated base on trade partners' inputs on their work sequence, duration, productivity, and unit cost, they would be more committed to deliver their work within that budget (Hofmann 2010).

7.6 CONCLUSION

LeanEst provides a link between a family type and its related cost and process data. This link enables designers to have immediate product and process cost feedback during design. LeanEst is most useful in informing the decision-making process when it contains cost and process information provided by the specialty contractors who will actually implement the work.

A process-based cost estimating method used in connection with BIM can provide more useful data in comparing design solutions than traditional cost models do. In addition, process cost data that comes out of the PBCM can be entered to BIM as properties of an assembly or a system, so that designers will instantly have cost feedback on how total cost is affected by their changes in product design or process design.

CHAPTER 8. CONCLUSIONS

This chapter highlights the research findings, presents contributions to knowledge, and specifies directions for further research. Section 1 summarizes answers to research questions presented in Chapter 1. Section 2 lays out the contributions to knowledge of the dissertation. Section 3 presents cross case-study conclusions. Finally, Section 4 recommends further research in this field.

8.1 RESEARCH FINDINGS

This dissertation involved literature review, case studies, and action research. In this section I present answers to the research questions raised in Chapter 1.

8.1.1 HOW COULD PROCESS-BASED COST MODELING SUPPORT TARGET VALUE DESIGN IN THE LEAN PROJECT DELIVERY SYSTEM™?

A PBCM helps to make both process cost and product cost explicit to designers when they are in the process of analyzing design alternatives. The aim of TVD is not to minimize project cost but to maximize value generation while remaining within the allowable budget. This effort may result in shifting costs from the site installation process to product fabrication- and logistics processes, or between project participants. The application of TVD often results in multiple design alternatives with different product costs, process costs, as well as product and process features. Thus, the challenge of the application of TVD is to evaluate multiple design alternatives to come up with a most preferred design solution. As pointed out in Chapters 1 and 3, traditional cost modeling methods are insufficient to make trade-offs between multiple alternatives of product- and process design in order to support TVD. In contrast, as revealed from results of the VDW case study (Chapter 6) and the software demonstration (Chapter 7), a PBCM is able to specify: (1) cost changes due to changes in product design (i.e., changes in materials, shapes, or dimensions), and (2) cost changes due to changes in process design (i.e., changes in sequencing, logistics processes, or construction processes). Thus, PBCM is more effective in supporting product- and process design integration in TVD than traditional cost models are.

The VDW case study (Chapter 6) reveals that PBCM facilitates the coordination between specialists, assists in look-ahead planning, integrates product- and process design, and yields reliable estimates of manpower and process-related cost. Estimates are reliable because (1) the people who actually perform the work provide up-to-date input data for estimates, logistics and construction processes are well defined and those in combination lead to less process uncertainty, (2) the IFOA allows trade partners be paid according to the actual cost incurred during construction, not to the estimated lump-sum as in traditional types of contract, e.g., DBB. In addition, trade partners are awarded with incentives if the project cost is less than the EMP. With this arrangement, trade partners are not held accountable to their estimates hence they can provide cost data without adding ‘fat’ to them, (3) estimators can minimize or eliminate their assumptions on logistics and installation processes by communicating with the cross-functional team, (4) inefficiencies and wastes are excluded from process- and cost data, (5) contingencies are managed separately in lieu of being hidden in cost data, (6) the link of process- and cost data to a process map makes process- and cost data explicit to estimators and the design team overall so that any adjustment is transparent and justifiable to the team. In addition, collaboration tools such as process mapping, model-based process simulation, and CBA helped the cross-functional team generate ideas, communicate design and construction knowledge, evaluate advantages and costs of each alternative, and decide on an alternative that best delivers target values as specified by the TVD team.

By linking cost data to a product model (BIM), a PBCM provides rapid cost feedback to designers and lessens the time required to assemble cost updates that are to inform TVD. By integrating process- and product cost data with BIM, an integrated product/process/cost model helps to streamline the design process and reduce rework in the design/estimate/re-design iteration. In addition, the implementation of the PBCM method helps the IPD team to maintain a knowledge database of product design, process design, and their costs for future projects.

Figure 8.1 summarizes the attributes of PBCM in supporting TVD in comparison to other cost estimating methods that are commonly used during Design Development, including Parametric Cost Estimating (explained in section 3.3.2.2), Assembly and System Estimating (explained in section 3.3.2.4), and Unit Price and Schedule Estimating (explained in section 3.3.2.5). The Area and Volume Estimating method is not considered since it is rarely used during Design Development (explained in section 3.3.2.3). I present the comparison of attributes using a CBA format. For the cost estimating methods to be comparable, I establish a context of comparison in the Design Development phase and in the TVD setting. Figure 8.1 presents factors, criteria, attributes, and advantages of each cost estimating method. Factors considered are (1) suitability for Design Development, (2) ease of implementation during Design Development, (3) feedback time, (4) reliability of input data, (5) transparency, (6) relative accuracy, and (7) trade-off analysis. In Figure 8.1, the underlined text represents the least preferred attributes.

When the importance of the advantage, 'Much more facilitation' was weighed against the importance of the other advantages, it was deemed to be the paramount advantage. It was placed at the top of the importance scale in position 100. All other advantages were individually weighted on the same scale of importance relative to the paramount advantage and one another. The bottom row of Figure 8.1 lists the total importance of advantages of each alternative. PBCM has a total importance of 444, higher than that of other estimating methods used in Design Development and it is the preferred alternative based on my rationale.

LEGEND Underline Least Preferred Attribute Yellow cell = most important Advantage in Factor Blank = no advantage Circle = paramount advantage	PBCM		Parametric Cost Estimating		Assembly and System Estimating		Unit Price and Schedule Estimating	
Factor: **Suitability for Design Development** *Criterion:* Suitable to the level of detail used in Design Development. More is better. *Attribute:*	Is best used to perform Intermediate Estimate during Design Development		Is best used to perform Preliminary Estimate during Conceptual Design. May be used in early Design Development		Is best used to perform Intermediate Estimate during Design Development		Is best used to perform Detail Estimate during Construction Document. May be used in late Design Development	
Advantage:	Much more suitable	88	!	0	Much more suitable	88	Somewhat more suitable	65
Factor: **Ease of implementation during Design Development** *Criterion:* More is better *Attribute:*	Needs training to establish and maintain a database, estimators should be familiar with BIM applications.		Requires defined mathematical formula for the cost function that best fits the available historical data		Estimators are very familiar to the use of this method during Design Development.		Estimators sometimes use this method during Design Development.	
Advantage:	!	0	!	0	Much more ease of implementation	96	More ease of implementation	86
Factor: **Feedback time** *Criterion:* Minimize the time it takes to provide cost feedback to designers when design changes. Less is better. *Attribute:*	Hours		Hours		Days		Weeks	
Advantage:	Much less time	95	Much less time	95	Less time	77	!	0
Factor: **Reliability of input data** *Criterion:* More is better. *Attribute:*	Uses process and cost inputs from people who will actually perform the work. Process and cost data are specific to project conditions. Inefficiencies and wastes are excluded from the collected process and cost data		Uses cost data from previous projects, whose conditions may vary. Data are in project or system level. Very limited information on logistics and installation processes		Uses historical cost data from previous projects, whose conditions may vary. Data are in system level. Limited information on logistics and installation processes		Uses historical cost data from previous projects, whose conditions may vary. Data are in elemental level. Data may contain process wastes and inefficiencies	
Advantage:	Much more reliability	90	!	0	More reliability	75	More reliability	75
Factor: **Transparency** *Criterion:* Ensure adjustments of source data are transparent and justifiable. More is better. *Attribute:*	Process and cost data are presented according to activities on process maps, that makes process and cost data explicit to design team		Estimators adjust mathematical formula to address changes in design		Estimators rely on historical data, the estimators own past experience, previous experience of others, and gut felling.		Estimators rely on historical data, the estimators own past experience, previous experience of others, and gut felling.	
Advantage:	Much more transparency	89	!	0	More transparency	79	More transparency	79
Factor: **Relative accuracy** *Criterion:* More is better. *Attribute:*	Within 10% accuracy		Within 20% accuracy		Within 10% accuracy		Within 5% accuracy	
Advantage:	More accurate	70	!	0	More accurate	70	Much more accurate	80
Factor: **Trade-off analysis** *Criterion:* Facilitate trade-off between alternatives of integrating product design and process design. More is better. *Attribute:*	Process cost and product cost are explicit to designers when they are in the process of analyzing design alternatives		No separation of process cost and product cost		May have limited separation of process cost and product cost		May have some separations of process cost and product cost	
Advantage:	Much more facilitation	100	!	0	Somewhat more facilitation	5	More facilitation	60
		444		**95**		**306**		**294**

Figure 8.1 Comparison of cost estimating methods to support TVD during Design Development

8.1.2 WHAT COULD A PBCM LOOK LIKE?

The PBCM proposed in this research is not intended to replace traditional cost models. While traditional models focus on the "what" of cost, PBCM focuses on the "how." The PBCM is intended to supplement traditional cost models by making process information explicit to designers and cost planners. As pointed out in Chapters 6 and 7, the PBCM makes both process-related cost and product cost explicit to designers when they are in the process of analyzing design alternatives. Process-related cost may include the cost of material handling, transportation, site logistics, and site installation depending on the scope of cost estimating. Chapter 4 presents key steps of PBCM including three phases: (1) capturing process cost data, (2) attaching cost data to a BIM object family, and (3) providing cost feedback to designers.

Chapter 4 presents two methods of collecting process- and cost data in two scenarios: (1) for products that have standard process designs, and (2) for products that require new process designs. In both scenarios, process- and cost data are collected according to activities on a process map. Process data may include activities' names and descriptions, activities' sequences, durations of activities, crew composition, number of man-hours to complete each activity, equipment utilization, inventory space needed, and transportation distance, etc. Cost data may include material cost, crew cost, equipment cost, inventory cost, and transportation cost, etc. For products that have standard process designs, process data can be collected by direct observation of actual processes, by interviewing field personnel, or by combining both methods as demonstrated in the window case study (Chapter 5). Techniques for collecting data may include: videotaping, tracking time, and getting input from the work crew, superintendent, project engineer, and project manager. For products that require new process designs as demonstrated in the VDW case study (Chapter 6), it is necessary to assemble a cross-functional team and to have the team together map out process design alternatives. Model-based process simulation helps the team in achieving common understanding of process design alternatives. Process maps serve as a platform for the team to provide input data such as activities, sequencing alternatives, estimated duration of each activity, estimated number of man-hours to complete each activity, equipment, inventory, constraints, and coordination requirements from each party. The GC, designers, trade partners, suppliers, and cost estimators provide data relating to each activity in the process map such as distance, resource capacities, design quantities, crew compositions, activity durations, and estimated unit costs. Process cost is calculated using process data and rates for labor, equipment and materials provided by the team. A process cost database contains cost of each activity allocated to a unit of a product.

To attach cost data from a database to an object family in a product model, a software tool I developed jointly with Harmony® Soft Company named LeanEst (Chapter 7) creates additional object properties that can contain cost data. The software also produces a link between the created object properties and values in the cost database so that these values are displayed as properties of an object family. Chapter 7 illustrates the data linking mechanism.

To provide cost feedback to designers, when the IPD team considers a change in product (i.e., change object family types) or a change in process (i.e., change methods of installation), they may swap a current product with another product in the model's product library and select an alternative of installation to see changes in final cost. If process and cost modifications are desired, team members could access the database to make adjustments. For example, team members may adjust crew composition, activity durations, transportation distance, etc., according to conditions of the current project. Since process- and cost data are linked to the product model, the team will be instantly provided with related changes in both product cost and process cost. The linking of data between the product model and the process cost model yields an integrated product/process/cost model that can provide quick cost feedback to designers.

8.1.2.1 When Should PBCM be Used in the TVD Process?

By design and as revealed in Chapters 4 and 7, the PBCM is best applied during the Design Development phase in the IPD environment. Further research is needed to investigate the use of the PBCM in Conceptual Design and Construction Document phases.

During the Conceptual Design phase, the project team focuses on exploring alternatives on form, function, scale, and space planning of the designed facility. The team begins to discuss process alternatives such as preliminary construction sequence or opportunity for prefabrication. This phase may involve the owner, the architect, the engineer, the GC, and some key construction trade partners, such as structural steel, structural concrete, and MEP. As building components and systems as well as their installation alternatives are not yet well defined in this phase, and with a limited involvement of trade partners, the PBCM may have limited application in this phase of design.

During the Design Development phase, the IPD team recruits many but not all of trade partners for the project, expanding the project team already in place in the Conceptual Design phase. The IPD team refines the design concept and the building literally begins to take shape. Decisions made during this phase often have a major impact on Target Costs and target values (AIA 2007). Such decisions may include dimensions for building components or systems, choice of materials, construction sequence, prefabrication, material quantities, material handling, site logistics, and installation method. As building components and systems as well as their installation alternatives get defined and trade partners are on board in this phase, the PBCM is effective during this phase of design.

During the Construction Document phase, the project team refines the drawings from Design Development into construction documents. This phase consists of preparation of drawings and specifications that establish the requirements for construction of the project. By this time, most key decisions on product and process have been made and the project team focuses on detailing to prepare for construction. Decisions made in this phase may not have as high a cost and value impact as decisions made during the Design Development phase. As building components and systems as well as their installation processes get to be better defined, the PBCM may be used in this phase to model process cost. However, the level of process detail required to evaluate alternatives of process design in this phase may result in increasing the size of the process- and cost database. A large database may become difficult to manage and hence may prevent an effective application of PBCM. Further research is needed to investigate the applicability of PBCM during the Construction Document phase (refer to section 8.4).

8.1.2.2 Who Should be Involved in the PBCM Process?

As pointed out in Chapters 4 and 6, during the Design Development phase, an integrated team of designers, engineers, suppliers, and specialty contractors could examine construction processes in a virtual environment to achieve a common understanding of coordination, logistics, and installation processes. Based on that, they share their experience and ideas to investigate alternative ways of doing the work or to suggest changes to design to improve constructability. As revealed in Chapter 5, the participation of specialty contractors and suppliers during design may help to make process inefficiencies and wastes explicit to the project team so that these can be minimized or eliminated.

In addition, collaboration tools such as process mapping, model-based process simulation, and CBA helped the cross-functional team generate ideas, communicate design and construction knowledge, evaluate advantages and costs of each alternative, and decide on a best alternative for integrating product- and process design. Owners can encourage the use of the PBCM on a project by hiring specialty contractors and suppliers during the design phase of the project. An IPD contract such as IFOA could incentivize collaboration of the cross-functional team for a successful implementation of the PBCM.

8.1.2.3 How Does the IPD Team Make Decisions When Considering Factors Other Than Cost?

As revealed in Chapter 6, the team can use CBA to evaluate alternatives considering both cost and value. CBA helps the IPD team establish target values through specifications of ‘must’ and ‘want’ criteria, and provides a sound method for evaluating alternatives according to those criteria. During the evaluation process, the team explicitly identifies differences between alternatives and recognizes the importance of those differences. CBA helps the team to trade off both cost and non-cost factors and aligns the team’s design decisions with target values.

As shown in Chapter 6, by working collaboratively, using CBA, and by having nearly immediate process cost feedback, the team was able to come up with a new alternative that brings the most value to the project at a cost equal to that of what initially appeared to be the lowest cost option.

8.1.3 How Should Process Cost Data be Collected to Support PBCM?

As pointed out in Chapters 4 and 6, process- and cost data should be collected according to activities as in the case for ABC. In order to support model-based cost estimating, the activity costs should be allocated to each product unit.

The window case study (Chapter 5) demonstrated the use of process mapping and direct observation to map existing process and collect process data for products or systems with standardized installation processes.

The VDW case study (Chapter 6) demonstrated the use of process mapping and 4D simulation in a cross-functional team coordination setting. The 4D simulation triggered a discussion on detailed logistics and installation processes and constructability issues. As presented in this case study, design-team conversations pertained to multiple categories such as constructability, fabrication, transportation, site logistics, and installation. These conversations helped the team in forming a common understanding of logistics and installation processes, the constraints related to those processes, as well as hand-offs between trade partners. Process mapping made logistics and installation activities of the VDW system explicit to the cross-functional team, each trade partner understood the work of others as well any coordination effort required for producing successful hand-offs.

In order to validate process- and cost data, estimators should compare their estimates against actual costs when the work is completed and as a learning exercise. Actual cost feedback helps estimators verify the reliability of process- and cost data used, review their data adjustment decisions, and adjust the cost model. Feedback of actual costs should be consistently used to review and adjust the process- and cost data for estimating future projects. Further research is needed to study the mechanism of adjusting PBCM based on feedback from the actual cost data (refer to section 8.4).

8.1.4 How Should PBCM Integrate Process Cost Data in a Building Information Model?

Chapter 7 illustrated the data linking mechanism using LeanEst, software used to create object properties that can contain cost data. It could attach cost data from an external, editable database to an object family in a product model. The software also produced a link between the created object properties and values in a cost database so that these values were displayed as properties of an object family.

LeanEst automates the process of creating and attaching multiple shared parameters to an Autodesk Revit object family and links those parameters to cost data in an external database. The LeanEst Add-In creates a menu in Revit's External Tools. This menu includes three functions: (1) AddSharedParameters that pulls in a pre-defined set of shared parameters to a new Autodesk Revit project, (2) AddParamsToFamily that adds shared parameters to a selected family type, and (3) LinkCostData that writes values from a Microsoft Access 2007 database to the created shared parameters. The advantages of linking cost directly to BIM objects and display cost information within the modeling software are to (1) facilitate model-based cost estimating, and (2) make cost information instantly available to the design team.

8.2 CONTRIBUTIONS TO KNOWLEDGE

This dissertation provided a theoretical understanding of the reasons why traditional cost modeling methods were insufficient to support TVD. This understanding formulated directions for developing the PBCM framework. My findings from the literature review (Chapter 3) and my observations of the current state of cost modeling during the Design Development phase in the TVD environment at CHH (Chapter 4) revealed (1) the lack of an effective cost modeling method to inform TVD during Design Development and (2) the lack of a framework to take advantage of BIM in estimating product- and process cost. This dissertation delivered a proof of concept for a PBCM framework and validated it through case studies and action research. PBCM has more advantages in supporting TVD than traditional cost estimating methods do (refer to section 8.1). In addition, findings from this dissertation suggested the development of LeanEst

(Chapter 7), software that works as an Add-In to an existing BIM tool, Autodesk Revit Architecture 2010. LeanEst automates the process of creating and attaching multiple shared parameters to a Revit object family and links those parameters to cost data in an external database. The advantage of LeanEst is in linking cost directly to BIM objects and displaying cost information within the modeling software. This linking mechanism provides designers with nearly immediate cost feedback on how total cost is affected by their changes in product design or changes in process design. Feedback from practitioners at CHH (refer to section 7.5) revealed that the PBCM used in connection with BIM can provide more useful data in comparing design solutions than traditional cost models do.

Table 8.1 summarizes contributions to knowledge from each case study according to the research objectives set out for this dissertation research. The bold headings represent initial research goals.

Table 8.1 Contributions to knowledge from case studies

Window	Viscous Damping Wall	LeanEst Revit Add-In
Develop a cost modeling method that supports TVD during Design Development		
Analyze the conventional practice of estimating using historical cost.	Evaluate the effectiveness of estimating in a cross-functional team.	Demonstrate a method of providing immediate product- and process cost feedback to designers during the Design Development phase.
Show a method of creating a baseline process by removing waste from the original process map. Suggest the use of this baseline process as benchmark for future project.	Evaluate the application of 4D simulations in directing the cross-functional team's discussion on process design addressing issues such as constructability, lead time, make ready work, work duration, crew composition, and types of equipment.	Provide an interface for adjusting process- and cost data through process maps.
	Demonstrate a method to collect process- and cost data according to process activity.	Demonstrate the technical feasibility of PBCM.
	Demonstrate a method to allocate process cost to product unit using ABC to support model-based estimating.	Collect practitioners' feedback on the PBCM software application.
Develop a method of collecting process- and cost data		
Develop a method to establish a process database for products or systems with standard process designs.	Develop a method to establish a process database for products or systems that require new process designs.	Specify a framework for establishing and using process- and cost database.

Window	Viscous Damping Wall	LeanEst Revit Add-In
Analyze conventional practices of designing, estimating, delivery, and installation of a window system to identify process inefficiencies and to discuss how they may affect cost estimates of future projects.	Explore the application of model-based process simulation to support design collaboration, process mapping, and cost estimating.	
Demonstrate the use of process mapping and DES to separate costs of process waste from the total process cost.	Explore the application of CBA to make decisions considering both cost and non-cost factors.	
	Verify the feasibility of collecting process- and cost data during design in an IPD environment.	Validate the process- and cost database with practitioners.
Establish a framework to integrate process cost data in BIM.		
Discuss how rapid product- and process cost feedback can affect design decisions.	Discuss the need for product- and process cost feedback to support design to target.	Develop a mechanism of linking product-, process-, and cost data to provide rapid cost feedback and support model-based cost estimating during Design Development.
	Illustrate the use of BIM in model-based cost estimating and discuss how model-based estimating facilitates TVD.	Demonstrate the application of LeanEst Revit Add-In to link a BIM object to process- and cost data.
	Identify the need for linking cost directly to BIM objects and display cost information within modeling software.	Develop a method to link each activity in a process map to its data record in a process- and cost database using the ODBC and make these data accessible from the BIM model using the URL.

8.3 CROSS CASE-STUDY CONCLUSIONS

The best project environment in which to apply PBCM is in projects that use the IPD approach, where key players from upstream to downstream of the project, such as owners, architects, engineers, the GCs, specialty contractors, suppliers, and permitting agencies, are members of the design team. This PBCM can be used in more traditional project delivery systems with integrated approaches such as DB, Construction Manager at Risks and Multi-Prime with DB where the contracts allow early involvement of constructors in the design process. Since such early involvement is limited when using DBB as the project delivery model, a PBCM has few opportunities for effective application in DBB.

In a conventional DBB contract, the subcontractors and the suppliers are selected only after finishing the Design Development phase and Construction Document phase. Thus the designer of the project cannot benefit in the course of design from cost advice from downstream players. Any process coordination or request for trade input could only be done after bidding when subcontractors and suppliers are on board; at which time design typically becomes too costly to change. A transactional type of contractual relationship such as DBB prevents early coordination and thus prevents designers from having timely cost feedback on their design decisions. In some cases, the owner in a DBB contract may allow early involvement of contractors during design. However, in order to avoid conflict of interest in bidding, especially in public sector projects, those contractors are often excluded from the owner's bidding list. Although those contractors may provide process and cost advice to designers and they may help in estimating product and process cost, their cost estimates may not be reliable since the contractors who are actually selected to perform the work may use different means and methods for construction.

An IFOA could incentivize a cross-functional team to collaborate for a successful implementation of PBCM. As in the case on CHH, The IFOA created the contractual and financial framework to facilitate effective collaboration between the owner, the GC, architects, engineers, specialty contractors, and supply chain members. The IFOA also allowed trade partners be paid according to actual cost incurred during construction. Profit was a negotiated lump-sum and to be paid per schedule. That eliminated estimators' tendency of adding 'fat' to their estimates during design to buffer for uncertainty and/or increase profit as is common in the traditional lump-sum contract. That also explained why, under an IFOA, the GC often trusts estimates provided trade partners, as is the case at CHH. As suggested from the case studies, any contingency or buffer that is considered necessary by the team should be set aside as a separate cost item, it should be monitored when the design progresses. When the project team has more detailed information, the contingency/buffer may become an actual cost item or may be eliminated.

The case studies presented in this dissertation highlight the benefit of using process-based tools (e.g., process map, CBA, ABC, and model-based process simulation) and technological tools (e.g., BIM applications, OBDC, and LeanEst) that help implement PBCM. Process mapping helps the team specify activities and their sequence and identify waste in the process. A baseline process can be created by removing waste from the current state process map. As suggested by the case studies, this process map could be used to collect process data in order to separate real process cost and cost of process waste. This classification will help estimators make a more accurate estimate on process cost and resource needs. CBA helps the team to trade off both cost and non-cost factors and aligns the team's design decisions with target values. BIM and process simulation help to visualize product and process to the design team. OBDC creates a bi-directional data connection between a process map and a cost database and keeps the two versions of the data synchronized. LeanEst helps to link a BIM object to cost and process data in order to provide rapid cost feedback to designers.

8.4 FUTURE RESEARCH

This dissertation delivered a proof of concept for PBCM. It illustrated the applicability of PBCM during Design Development in an IPD setting. Since action research seeks to find solutions that are "localized" for specific situations, the results of action research are not necessarily generalizable for broad application (Stringer 2007). Further case studies should be conducted on different types of products or systems to test and to further refine steps that should be included in the implementation of PBCM during Design Development. In addition, as discussed in section 8.1.2.1, further research is required to investigate the application of PBCM during Conceptual Design and Construction Document phases.

Based on this research, it seems that PBCM should be implemented to estimate costs for products or systems that have been sufficiently defined for process analysis. The low level of detail of a product design may prevent the cross-functional team from effectively discussing process design alternatives. In contrast, the high level of detail of a product design may cause waste and rework in the re-design process when the cross-functional team decides to change or eliminate the product design. Therefore, further research is required to determine the most preferred level of detail of a product design for PBCM to start.

The application of PBCM requires cross-organizational collaboration. Different participants in a project team may use different BIM applications and different cost database platforms. The interoperability of BIM applications and database platforms is important for designers, engineers, and specialty contractors to effectively exchange product, process, and cost information. Further research is needed to address the technical difficulties in integrating product models and cost data between various platforms for an effective application of PBCM.

As presented in this research, the PBCM uses the most likely activity durations and the most likely activity unit costs provided by trade partners to perform cost estimating, hence the result of the PBCM provides a point estimate. This approach does not fully address the fact that there is a range of possible outcomes; some outcomes are more probable than others. In contrast, a stochastic model would use random variables to look at what the expected conditions of the project might be. As a result, a distribution of outcomes is available which shows not only the most likely estimate but also what ranges are reasonable. Chapter 5 revealed that it was possible to collect stochastic input data for PBCM but it may be costly to do so on a large scale. Further research is needed to evaluate the merit as well as the challenge of extending PBCM with stochastic values.

As revealed in Chapter 6, in order to estimate the cost of the VDW system using PBCM, the IPD team at CHH took into account the cost impact of the interaction between individual components, i.e., between the VDWs, the T-shaped steels, and the girders. That helped the team to factor the possible work stoppage, work-space interference, productivity gains/losses, etc., into their estimates. In this aspect, a system-based estimating approach seems to be more rational than a component-based estimating approach (refer to section 1.3.1). Further research is needed to spell out the advantage as well as the accuracy of the system-based estimating approach in comparison to the component-based estimating approach.

A project team can validate a PBCM using feedback of actual costs to review and adjust the process- and cost data as well as to adjust PBCM for estimating costs of future projects. Further research is required to study the mechanism of adjusting PBCM based on feedback from the actual cost data.

As presented in Chapters 4 and 7, the proposed process cost database structure that contains an activity cost table and a unit cost table worked effectively in the VDW case study. However, that database structure should be evaluated in a larger scale application when it involves hundreds of product or more. Further research is required to optimize the process cost database structure for a large scale application of PBCM. In addition, as mentioned in section 8.1.2.1, the level of process detail required to evaluate alternatives of process design towards the end of the Design Development phase or during the Construction Document phase may result in increasing the size of the process- and cost database. Further research is needed to identify and address the issue of a large database that may affect the effective application of the PBCM.

As a proof of concept, LeanEst was developed to work specifically with the Autodesk Revit Architecture modeling software, a popular platform for product modeling during the Design Development phase. However, it is common for different members in an IPD team to use different modeling software that meets their specific needs of product design. Further research is required to advance LeanEst so that it could exchange process- and cost data with different product modeling software. In addition, LeanEst’s ability to link process- and cost data, including activities’ names, durations, and resources in a BIM model creates another interesting research opportunity to automate the model-based process simulation.

Research presented in this dissertation reviewed limitations of traditional cost modeling methods and explored how a PBCM may be established and applied to support TVD in a LPDS™. It demonstrated that PBCM was more effective in supporting TVD than traditional cost estimating methods were during Design Development. Based on case-study findings, I expect PBCM can be applied more broadly to support TVD. Future research is necessary to refine steps of PBCM and further advance tools to facilitate the implementation of PBCM.

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APPENDIX A. AVAILABLE TOOLS/SOLUTIONS FOR MODEL-BASED PROCESS SIMULATION

A.1 AUTODESK NAVISWORKS 2009

The Autodesk Navisworks 2009 product family comprises three 3D design review software products and one free viewer application. Among them, Navisworks Manage and Navisworks Simulation offer 4D scheduling capability. Navisworks is capable of opening and combining files in all the popular and critical file formats including Industry Foundation Classes (IFC). It offers file converters for design applications such as Revit and ArchiCAD. Navisworks reduces the size of a file significantly since Navisworks represents an object by its surfaces instead of being a solid object. Navisworks Timeliner can import schedules from Primavera P6, SureTrak, and Microsoft Project. The 4D construction simulation in Navisworks Timeliner works by linking the 3D model with a construction schedule. 3D objects can be selected and manually attached to tasks. Timeliner also allows automatic generation of tasks according to selection sets, layers, or object names.

All the individual tasks from the linked task schedule file can be imported, associated with a task type such as Construct, Demolish, or Temporary, and finally, assigned the model items that need to be associated with them. After all the items in the model have been assigned to tasks, the display settings for the simulation can be defined and the simulation can be played, showing the sequence in which the project will be built. Navisworks TimeLiner also allows the export of images and animations based on the results of the simulation. Once the model objects are linked to tasks in a schedule, TimeLiner can update the simulation if the model or schedule changes (Khemlani 2008a).

Navisworks allows object animation using its Animator tool. This feature gives Navisworks a big advantage over other 4D scheduling software. Using Animator, users can add animations to objects; users can also write scripts to control the animation. This makes simulations of site construction processes look more realistic. For example, users may animate the movement of trucks, materials, or cranes on a construction site.

However, Navisworks does not have object editing capabilities; it does not allow objects to be divided into parts (i.e., concrete slab) for phasing in scheduling; and it does not integrate with cost estimating applications. Table A.1 summarizes features and advantages of Navisworks in comparison to other model-based process simulation applications.

A.2 VICO 2008

Vico's suite consists of the following six components:

- Vico Constructor 2008, to create 3D models as the foundation for the other tools
- Vico Estimator 2008, for model-based estimating
- Vico Control 2008, for location-based scheduling
- Vico 5D Presenter 2008, to see the 3D model, the schedule, and the cost estimate in one view
- Vico Cost Manager 2008, to monitor and control changes to a project’s cost

- Vico Change Manager 2008, to track revisions for consistency across all representations

Vico Control is a solution for 4D scheduling. It differentiates itself from other 4D solutions by using a recipe to contain object data and by employing location-based scheduling.

As illustrated in Figure A.1, a recipe is mapped to a 3D object to create a linkage between the 3D model and the cost estimation and scheduling modules. The recipe contains methods (i.e., tasks) for which it is known what resources are required per unit work.

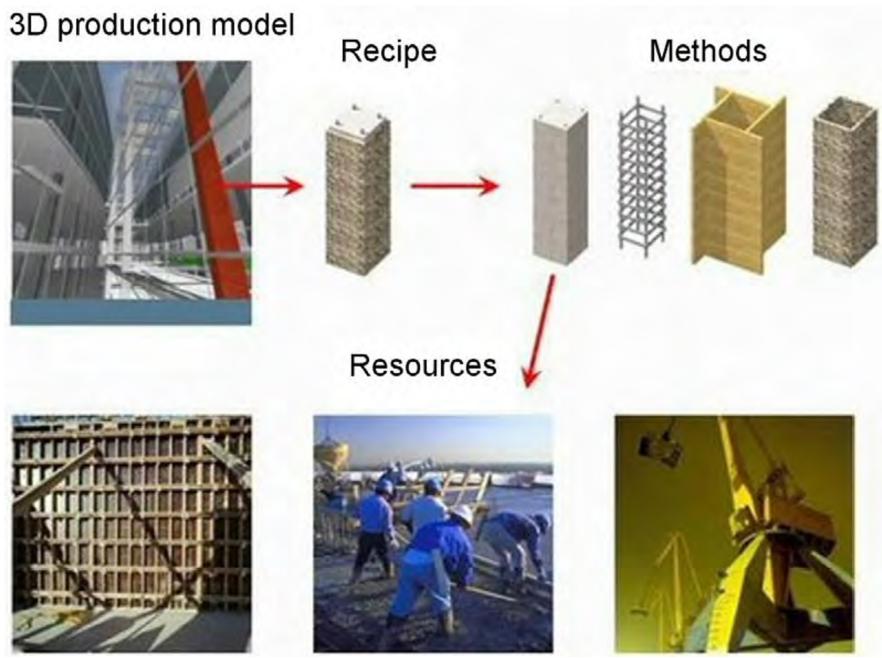

Figure A.1 Vico's recipe (courtesy of Vico)

Vico Control is characterized by location-based scheduling (Line of Balance) (Kankainen and Seppänen 2003). In a location-based schedule, locations are represented on the vertical axis and project time on the horizontal axis. The lines represent construction operations by crews as illustrated in figure A.1. Calculation of durations is based on (1) the amount of work calculated from the bill of quantities, (2) resources, and (3) the estimated production rate.

Visualization advantages of location-based scheduling:

- When a location-based schedule shows several tasks that begin in the same location at the same time, this is a sign of congestion in that location.
- Empty spaces on a location-based schedule mean there is no work going on in these areas at the given time. These locations should be utilized to alleviate congestion or to accelerate the schedule.
- A task with broken lines indicates discontinuities of work-flow in which specialty contractors need to start and stop working multiple times. This cause extra mobilization and demobilizations or redirection of resource to work on other areas to keep them busy, resulting in out-of-sequence of work and potentially additional congestion.

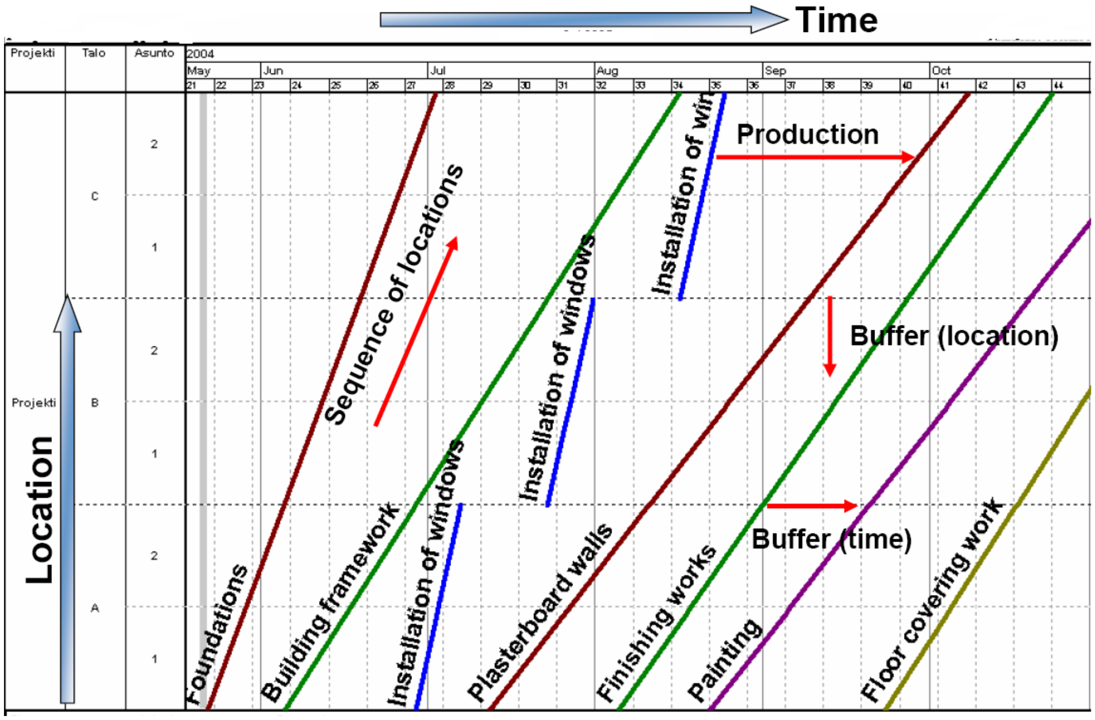

Figure A.2 Example of a location-based schedule (courtesy of Vico)

Some techniques to avoid conflicts and congestions in location-based scheduling:

- Besides breaking down the building floor by floor, separate each floor to smaller areas (zoning) to avoid stacking of trades and allow a better workflow through the project.
- Organize schedule by trades to allow better evaluation of crew continuity.
- Be able to adjust the number and size of crews to better suit the available work areas. This helps minimize multiple mobilizations and demobilizations.
- Link quantity to task to ensure reasonable schedule durations and allow effective plan percent complete tracking and schedule forecasting.

Synchronization and pacing are two main principles used to minimize the variations shown in Figure A.3 and to plan for a better work-flow. By synchronizing tasks, a planner aims to achieve a similar production rate for activities. A synchronized schedule is characterized by parallel lines that show a constant time buffer and space buffer between tasks. Pacing means that the activities are scheduled to continue from one location to another without interruptions (Jongeling and Olofsson 2007).

In general, high rise buildings such as the CHH project could benefit from location-based scheduling due to the repetitive nature of construction activities between floors. Especially when limited work space and trade interference are potential problems, location-based scheduling would be an appropriate solution for visualization and to optimize work space usage.

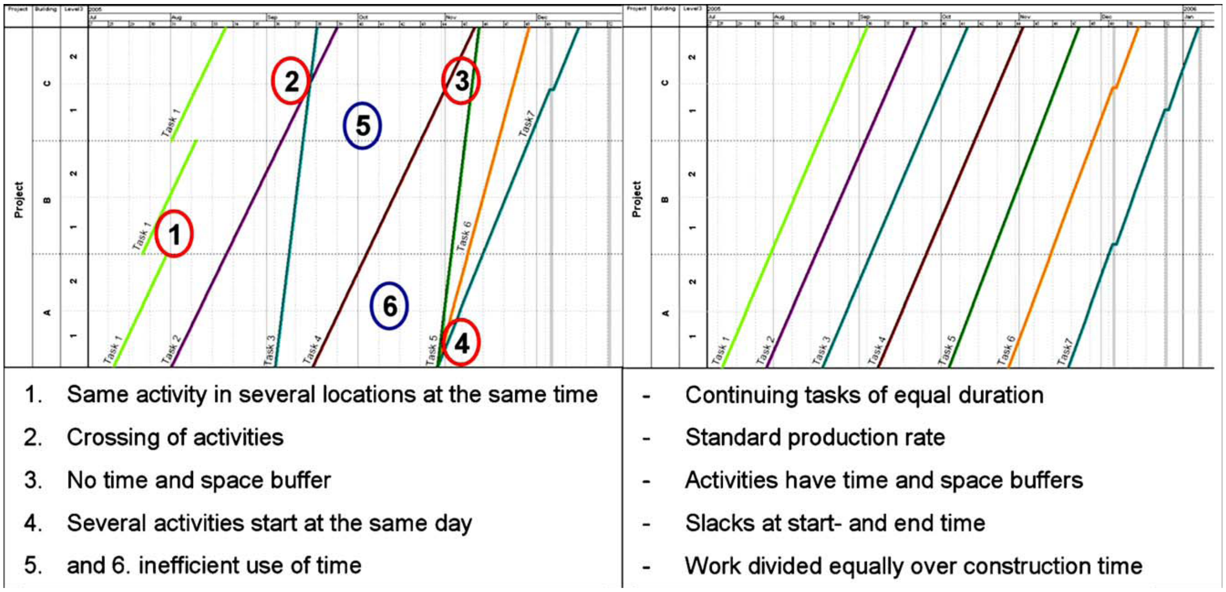

Figure A.3 (Left) Common scheduling variation types in a location-based schedule. (Right) Typical solutions to address variation in a location-based schedule (Jongeling and Olofsson 2007)

Table A.1 summarizes features and advantages of Vico Control in comparison to other model-based process simulation applications.

A.3 TEKLA STRUCTURES 15

Besides providing modeling and detailing capabilities, Tekla now provides tools for construction management which allow users to manage and track project status.

Tekla Structures support various neutral file formats such as IFC, SDNF, CIS/2, and DXF, and also provides an API (application programming interface) built using .NET standards for easy access to both 3D geometry and project data. A Tekla model can be exported as an IFC file and opened in other BIM applications. Tekla provides a light-weight web-model publishing capability to communicate model views to other project stakeholders. Models in IFC, DWG, and DGN formats can be imported as reference models in Tekla Structures. Tekla can check clashes between the Tekla model and reference models. Tekla proactively facilitates clash detection at the time of design to resolve conflicts and constructability issues. That is more efficient in contrast to doing clash detection reactively during the design coordination stages. Due to a data structure that keeps file sizes low, Tekla Structures is capable of working on large projects (Khemlani 2008b).

Tekla Construction Management is one programming module added to Tekla Structures since the version 14.1. With Tekla Structures 15, the Construction Management module can import other models such as architecture, MEP, and structural in IFC format as reference models to allow the team to work from one consolidated model for construction management. Tekla Construction Management does not provide object editing as it needs to preserve model integrity, but it allows users to separate models or slabs into zones for location-based scheduling. In addition, users can use Tekla's tools to view the properties of the objects in the models as well as attach additional attributes to them such as cost, phase, RFI number, and change order number.

The Construction Management module also allows scheduling data to be imported from Microsoft Office Project and Primavera P6. Individual tasks can be created within Tekla Structures using its Task Manager interface, which can be used to manage scheduled tasks and link tasks to their corresponding elements. The tasks can be used to create color-coded model views and 4D simulations of how the project is going according to its schedule. The Construction Management module also allows automated quantity take-off in formats such as text, Excel, HTML, and relational database (Khemlani 2008b). These files can be integrated with estimating applications such as Sage Timberline. Table A.1 summarizes features and advantages of Tekla CM in comparison to other model-based process simulation applications.

A.4 GOOGLE – SKETCHUP PRO 6.0

SketchUp Pro 6.0 has limited functions for 4D scheduling but it can be used as a support tool for modeling equipment and temporary works to serve 4D scheduling and animation in other BIM applications. SketchUp is a surface modeling tool provided by Google, it is simple and affordable. SketchUp is not an object modeler and it is often used as a sketching tool to demonstrate size, shape, location, and appearance of objects. Due to its simplicity, SketchUp can be used to quickly convey the essential information about a situation (mostly related to size, location, and appearance) into a 3D model. A SketchUp model can be imported and appended to other models using NavisWorks. Once in NavisWorks, it is possible to run a clash detection with the SketchUp model, or to use it in NavisWorks' Time Liner or Animator. At CHH, modelers found it very efficient to import construction equipment and site objects such as tower cranes, trucks, and formwork from Sketchup to Navisworks for 4D simulation.

Table A.1 Comparison of capabilities of selected 4D solutions

#	*Factors*	**Innovaya Visual Simulation**	**Synchro**	**Navisworks Timeliner**	**Vico control**	**Tekla CM**
1	*Model import*	Can import files in INV format only. INV composers are available for Revit and 3D CAD	Can import files in: - 3D CAD - DWF - Sketchup (.skp)	Can import files in: - Revit - 3D CAD - IFC - Sketchup and many others	Can import files in: - Revit - ArchiCAD - 3D CAD - IFC	Can import files in: - Tekla - IFC
2	*Schedule import*	- Microsoft Project	- Microsoft Project (.xml template) - Primavera	- Microsoft Project - Primavera 4-6 - Asta Power	- Microsoft Project - Primavera	- Microsoft Project - Primavera
3	*Ability to create schedule without importing*	Yes, tasks can be created using existing building section names or object names. Convenient.	Yes. Not very convenient.	Yes, tasks can be created using names of object, selection set, or layer. Very convenient.	Yes, tasks can be created using existing building section names or object names. Convenient.	Yes, tasks can be created using a Task Manager interface. Convenient.
4	*Updating/synchronizing ability when 3D model or schedule changes*	Yes, simulation can be updated by reimporting the updated 3D model in INV format	Yes, by reimporting the updated 3D model in dwf format	Yes, by reimporting the updated 3D model in nwd format. More convenient.	Yes, by reimporting the updated 3D model	Yes, by reimporting the updated 3D model
5	*Tutorial*	Simple, lack of detail	Fair, Somewhat difficult to follow	Very detailed, easy to follow	Very detailed, easy to follow	Very detailed, easy to follow
6	*Ease of use*	Very easy to use, but due to lack of function	Easy to use	Very easy to use	Easy to use	Easy to use
7	*Navigation*	Simple, basic navigation tools. Able to hide/display objects	Better navigation tools. Not able to hide/display objects	Much better navigation tools. Easy to look closely at any object	Much better navigation tools. Easy to look closely at any object	Much better navigation tools. Easy to look closely at any object
8	*Software has been used in large projects*	No information available	No information available	Yes, many projects	Yes, some projects	Has just been released
9	*Resource allocation ability*	Yes	Yes	No	Yes	Yes
10	*Display object cost and risk information*	No	Yes, display both cost and risk information	No	Yes, display both cost and risk information	Yes, display cost information
11	*Ability to link simulation and clash detection*	No	No	Yes	No	Yes
12	*Ability to devide model into zones*	No	No	No	Yes	Yes
13	*Ability to link to cost estimating/control software*	No	No	No	Yes, link to Vico Cost Manager	Yes, through Microsoft Excel

APPENDIX B. EZSTROBE© SIMULATION RESULTS

This Appendix shows simulation results of the current state model (Table B1) and the future state model (Table B2) of the window case study in Chapter 5.

Table B1 (1 of 7): Simulation results of the current state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
1	201.010	1206.060	51	203.043	1218.258	101	203.619	1221.714
2	201.017	1206.102	52	203.046	1218.276	102	203.621	1221.726
3	201.330	1207.980	53	203.050	1218.300	103	203.630	1221.780
4	201.338	1208.028	54	203.056	1218.336	104	203.640	1221.840
5	202.053	1212.318	55	203.060	1218.360	105	203.641	1221.846
6	202.062	1212.372	56	203.061	1218.366	106	203.643	1221.858
7	202.159	1212.954	57	203.076	1218.456	107	203.650	1221.900
8	202.169	1213.014	58	203.104	1218.624	108	203.650	1221.900
9	202.317	1213.902	59	203.111	1218.666	109	203.662	1221.972
10	202.328	1213.968	60	203.120	1218.720	110	203.662	1221.972
11	202.362	1214.172	61	203.128	1218.768	111	203.665	1221.990
12	202.374	1214.244	62	203.144	1218.864	112	203.666	1221.996
13	202.381	1214.286	63	203.162	1218.972	113	203.673	1222.038
14	202.394	1214.364	64	203.194	1219.164	114	203.679	1222.074
15	202.419	1214.514	65	203.208	1219.248	115	203.686	1222.116
16	202.425	1214.550	66	203.213	1219.278	116	203.686	1222.116
17	202.433	1214.598	67	203.219	1219.314	117	203.688	1222.128
18	202.440	1214.640	68	203.228	1219.368	118	203.691	1222.146
19	202.498	1214.988	69	203.237	1219.422	119	203.692	1222.152
20	202.514	1215.084	70	203.240	1219.440	120	203.696	1222.176
21	202.566	1215.396	71	203.244	1219.464	121	203.701	1222.206
22	202.583	1215.498	72	203.254	1219.524	122	203.710	1222.260
23	202.644	1215.864	73	203.256	1219.536	123	203.717	1222.302
24	202.657	1215.942	74	203.259	1219.554	124	203.720	1222.320
25	202.662	1215.972	75	203.262	1219.572	125	203.728	1222.368
26	202.676	1216.056	76	203.267	1219.602	126	203.730	1222.380
27	202.696	1216.176	77	203.269	1219.614	127	203.733	1222.398
28	202.716	1216.296	78	203.278	1219.668	128	203.742	1222.452
29	202.727	1216.362	79	203.281	1219.686	129	203.746	1222.476
30	202.733	1216.398	80	203.302	1219.812	130	203.748	1222.488
31	202.748	1216.488	81	203.310	1219.860	131	203.762	1222.572
32	202.755	1216.530	82	203.318	1219.908	132	203.841	1223.046
33	202.760	1216.560	83	203.327	1219.962	133	203.850	1223.100
34	202.783	1216.698	84	203.349	1220.094	134	203.853	1223.118
35	202.817	1216.902	85	203.359	1220.154	135	203.856	1223.136
36	202.841	1217.046	86	203.375	1220.250	136	203.863	1223.178
37	202.868	1217.208	87	203.386	1220.316	137	203.866	1223.196
38	202.891	1217.346	88	203.398	1220.388	138	203.870	1223.220
39	202.893	1217.358	89	203.410	1220.460	139	203.879	1223.274
40	202.898	1217.388	90	203.481	1220.886	140	203.881	1223.286
41	202.904	1217.424	91	203.494	1220.964	141	203.891	1223.346
42	202.912	1217.472	92	203.519	1221.114	142	203.898	1223.388
43	202.918	1217.508	93	203.533	1221.198	143	203.901	1223.406
44	202.927	1217.562	94	203.536	1221.216	144	203.903	1223.418
45	202.986	1217.916	95	203.551	1221.306	145	203.911	1223.466
46	202.989	1217.934	96	203.574	1221.444	146	203.911	1223.466
47	202.996	1217.976	97	203.581	1221.486	147	203.922	1223.532
48	203.000	1218.000	98	203.590	1221.540	148	203.925	1223.550
49	203.038	1218.228	99	203.598	1221.588	149	203.926	1223.556
50	203.043	1218.258	100	203.601	1221.606	150	203.934	1223.604

Table B1 (2 of 7): Simulation results of the current state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
151	203.946	1223.676	201	204.133	1224.798	251	204.386	1226.316
152	203.950	1223.700	202	204.148	1224.888	252	204.391	1226.346
153	203.951	1223.706	203	204.160	1224.960	253	204.392	1226.352
154	203.954	1223.724	204	204.167	1225.002	254	204.395	1226.370
155	203.957	1223.742	205	204.176	1225.056	255	204.397	1226.382
156	203.958	1223.748	206	204.180	1225.080	256	204.400	1226.400
157	203.958	1223.748	207	204.184	1225.104	257	204.407	1226.442
158	203.962	1223.772	208	204.190	1225.140	258	204.412	1226.472
159	203.966	1223.796	209	204.198	1225.188	259	204.414	1226.484
160	203.968	1223.808	210	204.199	1225.194	260	204.416	1226.496
161	203.970	1223.820	211	204.214	1225.284	261	204.417	1226.502
162	203.970	1223.820	212	204.229	1225.374	262	204.420	1226.520
163	203.971	1223.826	213	204.246	1225.476	263	204.421	1226.526
164	203.977	1223.862	214	204.249	1225.494	264	204.425	1226.550
165	203.981	1223.886	215	204.257	1225.542	265	204.429	1226.574
166	203.982	1223.892	216	204.258	1225.548	266	204.432	1226.592
167	203.990	1223.940	217	204.262	1225.572	267	204.435	1226.610
168	204.005	1224.030	218	204.266	1225.596	268	204.440	1226.640
169	204.008	1224.048	219	204.267	1225.602	269	204.445	1226.670
170	204.009	1224.054	220	204.276	1225.656	270	204.450	1226.700
171	204.019	1224.114	221	204.278	1225.668	271	204.458	1226.748
172	204.020	1224.120	222	204.283	1225.698	272	204.467	1226.802
173	204.023	1224.138	223	204.283	1225.698	273	204.472	1226.832
174	204.025	1224.150	224	204.288	1225.728	274	204.476	1226.856
175	204.026	1224.156	225	204.288	1225.728	275	204.482	1226.892
176	204.032	1224.192	226	204.292	1225.752	276	204.487	1226.922
177	204.036	1224.216	227	204.303	1225.818	277	204.488	1226.928
178	204.037	1224.222	228	204.306	1225.836	278	204.498	1226.988
179	204.044	1224.264	229	204.307	1225.842	279	204.500	1227.000
180	204.051	1224.306	230	204.310	1225.860	280	204.503	1227.018
181	204.056	1224.336	231	204.312	1225.872	281	204.506	1227.036
182	204.064	1224.384	232	204.312	1225.872	282	204.507	1227.042
183	204.065	1224.390	233	204.315	1225.890	283	204.516	1227.096
184	204.079	1224.474	234	204.317	1225.902	284	204.520	1227.120
185	204.083	1224.498	235	204.321	1225.926	285	204.522	1227.132
186	204.083	1224.498	236	204.331	1225.986	286	204.529	1227.174
187	204.085	1224.510	237	204.336	1226.016	287	204.538	1227.228
188	204.087	1224.522	238	204.340	1226.040	288	204.544	1227.264
189	204.096	1224.576	239	204.341	1226.046	289	204.545	1227.270
190	204.099	1224.594	240	204.347	1226.082	290	204.545	1227.270
191	204.101	1224.606	241	204.349	1226.094	291	204.547	1227.282
192	204.102	1224.612	242	204.351	1226.106	292	204.554	1227.324
193	204.103	1224.618	243	204.351	1226.106	293	204.554	1227.324
194	204.107	1224.642	244	204.352	1226.112	294	204.555	1227.330
195	204.107	1224.642	245	204.362	1226.172	295	204.562	1227.372
196	204.108	1224.648	246	204.365	1226.190	296	204.562	1227.372
197	204.110	1224.660	247	204.366	1226.196	297	204.564	1227.384
198	204.110	1224.660	248	204.370	1226.220	298	204.567	1227.402
199	204.120	1224.720	249	204.374	1226.244	299	204.569	1227.414
200	204.122	1224.732	250	204.374	1226.244	300	204.573	1227.438

Table B1 (3 of 7): Simulation results of the current state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
301	204.575	1227.450	351	204.799	1228.794	401	205.023	1230.138
302	204.160	1224.960	352	204.800	1228.800	402	205.028	1230.168
303	204.167	1225.002	353	204.805	1228.830	403	205.042	1230.252
304	204.176	1225.056	354	204.807	1228.842	404	205.043	1230.258
305	204.180	1225.080	355	204.807	1228.842	405	205.045	1230.270
306	204.184	1225.104	356	204.816	1228.896	406	205.046	1230.276
307	204.190	1225.140	357	204.821	1228.926	407	205.048	1230.288
308	204.198	1225.188	358	204.827	1228.962	408	205.062	1230.372
309	204.199	1225.194	359	204.829	1228.974	409	205.063	1230.378
310	204.214	1225.284	360	204.831	1228.986	410	205.077	1230.462
311	204.229	1225.374	361	204.839	1229.034	411	205.081	1230.486
312	204.246	1225.476	362	204.845	1229.070	412	205.087	1230.522
313	204.249	1225.494	363	204.846	1229.076	413	205.105	1230.630
314	204.257	1225.542	364	204.850	1229.100	414	205.111	1230.666
315	204.258	1225.548	365	204.855	1229.130	415	205.112	1230.672
316	204.262	1225.572	366	204.856	1229.136	416	205.113	1230.678
317	204.266	1225.596	367	204.856	1229.136	417	205.128	1230.768
318	204.267	1225.602	368	204.857	1229.142	418	205.136	1230.816
319	204.276	1225.656	369	204.857	1229.142	419	205.148	1230.888
320	204.278	1225.668	370	204.866	1229.196	420	205.154	1230.924
321	204.283	1225.698	371	204.867	1229.202	421	205.156	1230.936
322	204.283	1225.698	372	204.873	1229.238	422	205.171	1231.026
323	204.288	1225.728	373	204.880	1229.280	423	205.171	1231.026
324	204.288	1225.728	374	204.881	1229.286	424	205.178	1231.068
325	204.292	1225.752	375	204.891	1229.346	425	205.180	1231.080
326	204.303	1225.818	376	204.894	1229.364	426	205.187	1231.122
327	204.306	1225.836	377	204.899	1229.394	427	205.188	1231.128
328	204.307	1225.842	378	204.908	1229.448	428	205.195	1231.170
329	204.310	1225.860	379	204.922	1229.532	429	205.196	1231.176
330	204.312	1225.872	380	204.930	1229.580	430	205.205	1231.230
331	204.312	1225.872	381	204.931	1229.586	431	205.208	1231.248
332	204.315	1225.890	382	204.932	1229.592	432	205.210	1231.260
333	204.317	1225.902	383	204.935	1229.610	433	205.227	1231.362
334	204.321	1225.926	384	204.940	1229.640	434	205.228	1231.368
335	204.331	1225.986	385	204.958	1229.748	435	205.228	1231.368
336	204.336	1226.016	386	204.968	1229.808	436	205.236	1231.416
337	204.340	1226.040	387	204.980	1229.880	437	205.238	1231.428
338	204.341	1226.046	388	204.985	1229.910	438	205.238	1231.428
339	204.347	1226.082	389	204.986	1229.916	439	205.243	1231.458
340	204.349	1226.094	390	204.989	1229.934	440	205.244	1231.464
341	204.351	1226.106	391	204.995	1229.970	441	205.244	1231.464
342	204.351	1226.106	392	204.996	1229.976	442	205.261	1231.566
343	204.352	1226.112	393	205.001	1230.006	443	205.266	1231.596
344	204.362	1226.172	394	205.004	1230.024	444	205.268	1231.608
345	204.365	1226.190	395	205.005	1230.030	445	205.277	1231.662
346	204.366	1226.196	396	205.006	1230.036	446	205.287	1231.722
347	204.370	1226.220	397	205.011	1230.066	447	205.291	1231.746
348	204.374	1226.244	398	205.011	1230.066	448	205.291	1231.746
349	204.374	1226.244	399	205.012	1230.072	449	205.295	1231.770
350	204.386	1226.316	400	205.014	1230.084	450	205.302	1231.812

Table B1 (4 of 7): Simulation results of the current state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
451	205.307	1231.842	501	205.427	1232.562	551	205.520	1231.872
452	205.312	1231.872	502	205.429	1232.574	552	205.522	1231.878
453	205.313	1231.878	503	205.429	1232.574	553	205.526	1231.896
454	205.316	1231.896	504	205.431	1232.586	554	205.526	1231.908
455	205.318	1231.908	505	205.434	1232.604	555	205.527	1231.938
456	205.323	1231.938	506	205.435	1232.610	556	205.530	1231.950
457	205.325	1231.950	507	205.436	1232.616	557	205.533	1231.956
458	205.326	1231.956	508	205.439	1232.634	558	205.534	1232.004
459	205.334	1232.004	509	205.439	1232.634	559	205.536	1232.004
460	205.334	1232.004	510	205.440	1232.640	560	205.538	1232.028
461	205.338	1232.028	511	205.440	1232.640	561	205.540	1232.064
462	205.344	1232.064	512	205.441	1232.646	562	205.549	1232.064
463	205.344	1232.064	513	205.446	1232.676	563	205.564	1232.064
464	205.344	1232.064	514	205.447	1232.682	564	205.564	1232.076
465	205.346	1232.076	515	205.448	1232.688	565	205.567	1232.112
466	205.352	1232.112	516	205.449	1232.694	566	205.576	1232.130
467	205.355	1232.130	517	205.450	1232.700	567	205.576	1232.136
468	205.356	1232.136	518	205.450	1232.700	568	205.577	1232.142
469	205.357	1232.142	519	205.454	1232.724	569	205.578	1232.148
470	205.358	1232.148	520	205.454	1232.724	570	205.579	1232.154
471	205.359	1232.154	521	205.455	1232.730	571	205.581	1232.178
472	205.363	1232.178	522	205.457	1232.742	572	205.582	1232.184
473	205.364	1232.184	523	205.457	1232.742	573	205.586	1232.196
474	205.366	1232.196	524	205.459	1232.754	574	205.589	1232.232
475	205.372	1232.232	525	205.464	1232.784	575	205.591	1232.244
476	205.374	1232.244	526	205.465	1232.790	576	205.591	1232.262
477	205.377	1232.262	527	205.467	1232.802	577	205.595	1232.262
478	205.377	1232.262	528	205.468	1232.808	578	205.595	1232.280
479	205.380	1232.280	529	205.470	1232.820	579	205.595	1232.286
480	205.381	1232.286	530	205.471	1232.826	580	205.598	1232.292
481	205.382	1232.292	531	205.472	1232.832	581	205.600	1232.334
482	205.389	1232.334	532	205.475	1232.850	582	205.605	1232.358
483	205.393	1232.358	533	205.475	1232.850	583	205.605	1232.376
484	205.396	1232.376	534	205.479	1232.874	584	205.605	1232.382
485	205.397	1232.382	535	205.483	1232.898	585	205.609	1232.400
486	205.400	1232.400	536	205.486	1232.916	586	205.612	1232.412
487	205.402	1232.412	537	205.487	1232.922	587	205.617	1232.412
488	205.402	1232.412	538	205.491	1232.946	588	205.621	1232.418
489	205.403	1232.418	539	205.492	1232.952	589	205.624	1232.424
490	205.404	1232.424	540	205.492	1232.952	590	205.629	1232.436
491	205.406	1232.436	541	205.493	1232.958	591	205.630	1232.436
492	205.406	1232.436	542	205.494	1232.964	592	205.631	1232.454
493	205.409	1232.454	543	205.496	1232.976	593	205.634	1232.466
494	205.411	1232.466	544	205.497	1232.982	594	205.642	1232.496
495	205.416	1232.496	545	205.497	1232.982	595	205.649	1232.496
496	205.416	1232.496	546	205.505	1233.030	596	205.658	1232.502
497	205.417	1232.502	547	205.507	1233.042	597	205.668	1232.526
498	205.421	1232.526	548	205.513	1233.078	598	205.678	1232.544
499	205.424	1232.544	549	205.515	1233.090	599	205.680	1232.550
500	205.425	1232.550	550	205.517	1233.102	600	205.684	1232.562

Table B1 (5 of 7): Simulation results of the current state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
601	205.691	1234.146	651	205.857	1235.142	701	206.016	1236.096
602	205.696	1234.176	652	205.865	1235.190	702	206.017	1236.102
603	205.701	1234.206	653	205.870	1235.220	703	206.032	1236.192
604	205.714	1234.284	654	205.871	1235.226	704	206.036	1236.216
605	205.716	1234.296	655	205.874	1235.244	705	206.037	1236.222
606	205.717	1234.302	656	205.875	1235.250	706	206.044	1236.264
607	205.718	1234.308	657	205.875	1235.250	707	206.047	1236.282
608	205.731	1234.386	658	205.876	1235.256	708	206.052	1236.312
609	205.731	1234.386	659	205.876	1235.256	709	206.052	1236.312
610	205.731	1234.386	660	205.877	1235.262	710	206.054	1236.324
611	205.734	1234.404	661	205.877	1235.262	711	206.055	1236.330
612	205.742	1234.452	662	205.886	1235.316	712	206.060	1236.360
613	205.746	1234.476	663	205.898	1235.388	713	206.061	1236.366
614	205.748	1234.488	664	205.898	1235.388	714	206.062	1236.372
615	205.748	1234.488	665	205.899	1235.394	715	206.065	1236.390
616	205.750	1234.500	666	205.902	1235.412	716	206.071	1236.426
617	205.754	1234.524	667	205.905	1235.430	717	206.072	1236.432
618	205.760	1234.560	668	205.906	1235.436	718	206.079	1236.474
619	205.765	1234.590	669	205.909	1235.454	719	206.080	1236.480
620	205.768	1234.608	670	205.912	1235.472	720	206.084	1236.504
621	205.771	1234.626	671	205.914	1235.484	721	206.091	1236.546
622	205.776	1234.656	672	205.918	1235.508	722	206.093	1236.558
623	205.776	1234.656	673	205.921	1235.526	723	206.093	1236.558
624	205.779	1234.674	674	205.931	1235.586	724	206.093	1236.558
625	205.780	1234.680	675	205.939	1235.634	725	206.095	1236.570
626	205.799	1234.794	676	205.942	1235.652	726	206.102	1236.612
627	205.803	1234.818	677	205.943	1235.658	727	206.107	1236.642
628	205.805	1234.830	678	205.947	1235.682	728	206.110	1236.660
629	205.809	1234.854	679	205.950	1235.700	729	206.111	1236.666
630	205.809	1234.854	680	205.951	1235.706	730	206.113	1236.678
631	205.810	1234.860	681	205.955	1235.730	731	206.113	1236.678
632	205.811	1234.866	682	205.955	1235.730	732	206.116	1236.696
633	205.813	1234.878	683	205.955	1235.730	733	206.121	1236.726
634	205.813	1234.878	684	205.961	1235.766	734	206.133	1236.798
635	205.813	1234.878	685	205.964	1235.784	735	206.134	1236.804
636	205.816	1234.896	686	205.966	1235.796	736	206.136	1236.816
637	205.817	1234.902	687	205.967	1235.802	737	206.138	1236.828
638	205.819	1234.914	688	205.967	1235.802	738	206.138	1236.828
639	205.821	1234.926	689	205.971	1235.826	739	206.154	1236.924
640	205.824	1234.944	690	205.981	1235.886	740	206.159	1236.954
641	205.825	1234.950	691	205.984	1235.904	741	206.162	1236.972
642	205.826	1234.956	692	205.985	1235.910	742	206.177	1237.062
643	205.836	1235.016	693	205.986	1235.916	743	206.179	1237.074
644	205.837	1235.022	694	205.987	1235.922	744	206.184	1237.104
645	205.850	1235.100	695	205.994	1235.964	745	206.191	1237.146
646	205.852	1235.112	696	205.994	1235.964	746	206.196	1237.176
647	205.854	1235.124	697	206.004	1236.024	747	206.200	1237.200
648	205.854	1235.124	698	206.008	1236.048	748	206.202	1237.212
649	205.856	1235.136	699	206.008	1236.048	749	206.202	1237.212
650	205.857	1235.142	700	206.011	1236.066	750	206.202	1237.212

Table B1 (6 of 7): Simulation results of the current state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
751	206.205	1237.230	801	206.292	1237.752	851	206.389	1238.334
752	206.206	1237.236	802	206.293	1237.758	852	206.391	1238.346
753	206.209	1237.254	803	206.293	1237.758	853	206.393	1238.358
754	206.210	1237.260	804	206.294	1237.764	854	206.397	1238.382
755	206.210	1237.260	805	206.297	1237.782	855	206.398	1238.388
756	206.214	1237.284	806	206.301	1237.806	856	206.400	1238.400
757	206.215	1237.290	807	206.304	1237.824	857	206.402	1238.412
758	206.219	1237.314	808	206.304	1237.824	858	206.432	1238.592
759	206.222	1237.332	809	206.305	1237.830	859	206.434	1238.604
760	206.223	1237.338	810	206.306	1237.836	860	206.439	1238.634
761	206.225	1237.350	811	206.307	1237.842	861	206.442	1238.652
762	206.225	1237.350	812	206.309	1237.854	862	206.457	1238.742
763	206.225	1237.350	813	206.309	1237.854	863	206.457	1238.742
764	206.227	1237.362	814	206.309	1237.854	864	206.463	1238.778
765	206.233	1237.398	815	206.314	1237.884	865	206.466	1238.796
766	206.234	1237.404	816	206.314	1237.884	866	206.467	1238.802
767	206.235	1237.410	817	206.314	1237.884	867	206.474	1238.844
768	206.236	1237.416	818	206.314	1237.884	868	206.478	1238.868
769	206.238	1237.428	819	206.318	1237.908	869	206.479	1238.874
770	206.240	1237.440	820	206.321	1237.926	870	206.482	1238.892
771	206.240	1237.440	821	206.321	1237.926	871	206.490	1238.940
772	206.244	1237.464	822	206.323	1237.938	872	206.492	1238.952
773	206.244	1237.464	823	206.325	1237.950	873	206.496	1238.976
774	206.247	1237.482	824	206.332	1237.992	874	206.496	1238.976
775	206.252	1237.512	825	206.336	1238.016	875	206.497	1238.982
776	206.252	1237.512	826	206.337	1238.022	876	206.497	1238.982
777	206.262	1237.572	827	206.338	1238.028	877	206.511	1239.066
778	206.264	1237.584	828	206.342	1238.052	878	206.513	1239.078
779	206.265	1237.590	829	206.346	1238.076	879	206.514	1239.084
780	206.265	1237.590	830	206.348	1238.088	880	206.514	1239.084
781	206.265	1237.590	831	206.352	1238.112	881	206.514	1239.084
782	206.266	1237.596	832	206.356	1238.136	882	206.520	1239.120
783	206.273	1237.638	833	206.356	1238.136	883	206.522	1239.132
784	206.274	1237.644	834	206.356	1238.136	884	206.525	1239.150
785	206.274	1237.644	835	206.356	1238.136	885	206.532	1239.192
786	206.275	1237.650	836	206.357	1238.142	886	206.533	1239.198
787	206.277	1237.662	837	206.359	1238.154	887	206.533	1239.198
788	206.279	1237.674	838	206.360	1238.160	888	206.538	1239.228
789	206.280	1237.680	839	206.364	1238.184	889	206.540	1239.240
790	206.281	1237.686	840	206.369	1238.214	890	206.543	1239.258
791	206.282	1237.692	841	206.370	1238.220	891	206.544	1239.264
792	206.283	1237.698	842	206.371	1238.226	892	206.547	1239.282
793	206.283	1237.698	843	206.372	1238.232	893	206.556	1239.336
794	206.283	1237.698	844	206.372	1238.232	894	206.562	1239.372
795	206.283	1237.698	845	206.375	1238.250	895	206.569	1239.414
796	206.285	1237.710	846	206.375	1238.250	896	206.613	1239.678
797	206.286	1237.716	847	206.376	1238.256	897	206.616	1239.696
798	206.286	1237.716	848	206.377	1238.262	898	206.616	1239.696
799	206.289	1237.734	849	206.379	1238.274	899	206.619	1239.714
800	206.292	1237.752	850	206.380	1238.280	900	206.619	1239.714

Table B1 (7 of 7): Simulation results of the current state model

#	Duration (hour)	Man-hours
901	206.623	1239.738
902	206.624	1239.744
903	206.628	1239.768
904	206.635	1239.810
905	206.645	1239.870
906	206.655	1239.930
907	206.667	1240.002
908	206.677	1240.062
909	206.683	1240.098
910	206.686	1240.116
911	206.686	1240.116
912	206.699	1240.194
913	206.708	1240.248
914	206.710	1240.260
915	206.717	1240.302
916	206.721	1240.326
917	206.744	1240.464
918	206.765	1240.590
919	206.772	1240.632
920	206.782	1240.692
921	206.790	1240.740
922	206.804	1240.824
923	206.805	1240.830
924	206.808	1240.848
925	206.811	1240.866
926	206.813	1240.878
927	206.815	1240.890
928	206.815	1240.890
929	206.819	1240.914
930	206.823	1240.938
931	206.828	1240.968
932	206.832	1240.992
933	206.841	1241.046
934	206.391	1238.346
935	206.393	1238.358
936	206.397	1238.382
937	206.398	1238.388
938	206.400	1238.400
939	206.402	1238.412
940	206.432	1238.592
941	206.434	1238.604
942	206.439	1238.634
943	206.442	1238.652
944	206.457	1238.742
945	206.457	1238.742
946	206.463	1238.778
947	206.466	1238.796
948	206.467	1238.802
949	206.474	1238.844
950	206.478	1238.868
951	206.479	1238.874
952	206.482	1238.892
953	206.490	1238.940
954	206.492	1238.952
955	206.496	1238.976
956	206.496	1238.976
957	206.497	1238.982
958	206.497	1238.982
959	206.511	1239.066
960	206.513	1239.078
961	206.514	1239.084
962	206.514	1239.084
963	206.514	1239.084
964	206.520	1239.120
965	206.522	1239.132
966	206.525	1239.150
967	207.227	1243.362
968	207.251	1243.506
969	207.264	1243.584
970	207.282	1243.692
971	207.286	1243.716
972	207.288	1243.728
973	207.303	1243.818
974	207.371	1244.226
975	207.385	1244.310
976	207.387	1244.322
977	207.393	1244.358
978	207.398	1244.388
979	207.402	1244.412
980	207.402	1244.412
981	207.411	1244.466
982	207.417	1244.502
983	207.422	1244.532
984	207.430	1244.580
985	207.449	1244.694
986	207.451	1244.706
987	207.471	1244.826
988	207.492	1244.952
989	207.502	1245.012
990	207.515	1245.090
991	207.526	1245.156
992	207.598	1245.588
993	207.623	1245.738
994	207.667	1246.002
995	207.674	1246.044
996	207.700	1246.200
997	207.708	1246.248
998	207.929	1247.574
999	207.938	1247.628
1000	208.440	1250.640

Mean of man-hours = 1231.432 man-hours
Standard deviation = 7.326 man-hours

Table B2 (1 of 7): Simulation results of the future state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
1	76.209	457.256	51	77.118	462.709	101	77.256	463.533
2	76.551	459.305	52	77.118	462.709	102	77.256	463.533
3	76.551	459.305	53	77.123	462.737	103	77.256	463.537
4	76.713	460.278	54	77.123	462.737	104	77.257	463.540
5	76.713	460.278	55	77.133	462.798	105	77.257	463.544
6	76.740	460.438	56	77.133	462.798	106	77.259	463.551
7	76.740	460.438	57	77.143	462.859	107	77.259	463.551
8	76.838	461.025	58	77.143	462.859	108	77.262	463.569
9	76.838	461.025	59	77.149	462.892	109	77.262	463.569
10	76.891	461.347	60	77.149	462.892	110	77.264	463.582
11	76.941	461.645	61	77.155	462.932	111	77.264	463.582
12	76.965	461.789	62	77.155	462.932	112	77.270	463.618
13	76.970	461.821	63	77.159	462.956	113	77.270	463.618
14	76.973	461.836	64	77.159	462.956	114	77.276	463.658
15	76.977	461.861	65	77.161	462.967	115	77.276	463.658
16	76.981	461.888	66	77.161	462.967	116	77.279	463.676
17	76.987	461.921	67	77.180	463.081	117	77.279	463.676
18	76.987	461.921	68	77.180	463.081	118	77.279	463.676
19	76.990	461.941	69	77.187	463.123	119	77.282	463.689
20	76.990	461.941	70	77.187	463.123	120	77.282	463.689
21	76.991	461.948	71	77.212	463.274	121	77.283	463.699
22	76.991	461.948	72	77.212	463.274	122	77.283	463.699
23	77.000	462.002	73	77.213	463.280	123	77.288	463.727
24	77.000	462.002	74	77.213	463.280	124	77.288	463.727
25	77.001	462.008	75	77.216	463.294	125	77.289	463.735
26	77.006	462.037	76	77.216	463.294	126	77.289	463.735
27	77.006	462.037	77	77.216	463.295	127	77.294	463.766
28	77.010	462.061	78	77.216	463.295	128	77.294	463.766
29	77.013	462.079	79	77.219	463.316	129	77.298	463.790
30	77.013	462.079	80	77.219	463.316	130	77.307	463.840
31	77.019	462.113	81	77.220	463.317	131	77.307	463.840
32	77.019	462.113	82	77.220	463.321	132	77.308	463.849
33	77.036	462.216	83	77.220	463.321	133	77.310	463.859
34	77.036	462.216	84	77.221	463.328	134	77.310	463.859
35	77.051	462.307	85	77.221	463.328	135	77.313	463.880
36	77.051	462.307	86	77.223	463.335	136	77.313	463.880
37	77.069	462.413	87	77.223	463.335	137	77.314	463.886
38	77.078	462.466	88	77.223	463.339	138	77.314	463.886
39	77.078	462.466	89	77.223	463.339	139	77.315	463.887
40	77.086	462.514	90	77.229	463.375	140	77.315	463.887
41	77.086	462.514	91	77.229	463.375	141	77.315	463.891
42	77.086	462.517	92	77.242	463.454	142	77.315	463.891
43	77.086	462.517	93	77.242	463.454	143	77.316	463.894
44	77.086	462.518	94	77.244	463.462	144	77.316	463.894
45	77.086	462.518	95	77.245	463.470	145	77.317	463.900
46	77.094	462.563	96	77.245	463.470	146	77.317	463.900
47	77.094	462.563	97	77.253	463.517	147	77.317	463.903
48	77.103	462.620	98	77.253	463.517	148	77.317	463.903
49	77.103	462.620	99	77.254	463.523	149	77.320	463.922
50	77.118	462.709	100	77.254	463.523	150	77.322	463.932

Table B2 (2 of 7): Simulation results of the future state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
151	77.323	463.939	201	77.361	464.165	251	77.399	464.396
152	77.323	463.940	202	77.362	464.171	252	77.400	464.399
153	77.324	463.941	203	77.362	464.171	253	77.400	464.402
154	77.324	463.945	204	77.362	464.174	254	77.401	464.403
155	77.325	463.951	205	77.363	464.180	255	77.402	464.414
156	77.325	463.951	206	77.363	464.180	256	77.405	464.428
157	77.326	463.957	207	77.367	464.204	257	77.405	464.429
158	77.327	463.960	208	77.367	464.204	258	77.405	464.431
159	77.328	463.966	209	77.369	464.212	259	77.408	464.445
160	77.328	463.967	210	77.369	464.212	260	77.408	464.450
161	77.328	463.967	211	77.369	464.212	261	77.408	464.450
162	77.329	463.973	212	77.369	464.212	262	77.411	464.464
163	77.333	463.995	213	77.369	464.213	263	77.413	464.480
164	77.333	463.995	214	77.369	464.213	264	77.414	464.481
165	77.333	463.999	215	77.369	464.216	265	77.414	464.481
166	77.333	463.999	216	77.369	464.216	266	77.414	464.485
167	77.334	464.002	217	77.372	464.231	267	77.415	464.487
168	77.334	464.002	218	77.372	464.231	268	77.415	464.487
169	77.335	464.011	219	77.372	464.233	269	77.415	464.488
170	77.336	464.013	220	77.372	464.233	270	77.415	464.490
171	77.336	464.016	221	77.374	464.244	271	77.416	464.494
172	77.336	464.016	222	77.374	464.244	272	77.416	464.494
173	77.337	464.021	223	77.375	464.252	273	77.416	464.495
174	77.337	464.021	224	77.375	464.252	274	77.417	464.500
175	77.338	464.030	225	77.377	464.264	275	77.418	464.506
176	77.339	464.036	226	77.377	464.264	276	77.418	464.507
177	77.339	464.036	227	77.379	464.271	277	77.419	464.512
178	77.339	464.036	228	77.379	464.271	278	77.420	464.518
179	77.340	464.042	229	77.381	464.285	279	77.420	464.520
180	77.344	464.063	230	77.381	464.285	280	77.420	464.520
181	77.344	464.064	231	77.382	464.291	281	77.421	464.523
182	77.345	464.069	232	77.382	464.291	282	77.421	464.523
183	77.345	464.071	233	77.382	464.292	283	77.423	464.537
184	77.345	464.071	234	77.384	464.301	284	77.423	464.537
185	77.347	464.080	235	77.386	464.317	285	77.423	464.539
186	77.347	464.080	236	77.387	464.320	286	77.424	464.541
187	77.347	464.083	237	77.389	464.333	287	77.425	464.548
188	77.347	464.083	238	77.390	464.342	288	77.425	464.548
189	77.347	464.084	239	77.393	464.359	289	77.425	464.548
190	77.347	464.084	240	77.393	464.360	290	77.425	464.548
191	77.349	464.093	241	77.394	464.365	291	77.426	464.554
192	77.356	464.137	242	77.395	464.371	292	77.426	464.555
193	77.356	464.137	243	77.396	464.373	293	77.426	464.555
194	77.357	464.143	244	77.396	464.374	294	77.426	464.555
195	77.359	464.151	245	77.398	464.389	295	77.427	464.564
196	77.360	464.162	246	77.398	464.390	296	77.428	464.565
197	77.360	464.162	247	77.398	464.390	297	77.428	464.565
198	77.361	464.164	248	77.399	464.391	298	77.428	464.567
199	77.361	464.164	249	77.399	464.395	299	77.428	464.567
200	77.361	464.165	250	77.399	464.396	300	77.428	464.570

Table B2 (3 of 7): Simulation results of the future state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
301	77.431	464.583	351	77.483	464.899	401	77.510	465.062
302	77.362	464.171	352	77.484	464.902	402	77.511	465.064
303	77.362	464.174	353	77.484	464.902	403	77.511	465.064
304	77.363	464.180	354	77.487	464.921	404	77.511	465.065
305	77.363	464.180	355	77.487	464.921	405	77.514	465.084
306	77.367	464.204	356	77.487	464.923	406	77.514	465.084
307	77.367	464.204	357	77.487	464.923	407	77.517	465.099
308	77.369	464.212	358	77.491	464.945	408	77.517	465.099
309	77.369	464.212	359	77.491	464.945	409	77.517	465.100
310	77.369	464.212	360	77.492	464.951	410	77.517	465.100
311	77.369	464.212	361	77.492	464.951	411	77.517	465.104
312	77.369	464.213	362	77.494	464.962	412	77.517	465.104
313	77.369	464.213	363	77.494	464.962	413	77.518	465.106
314	77.369	464.216	364	77.494	464.966	414	77.518	465.106
315	77.369	464.216	365	77.494	464.966	415	77.519	465.115
316	77.372	464.231	366	77.495	464.971	416	77.519	465.115
317	77.372	464.231	367	77.495	464.971	417	77.520	465.120
318	77.372	464.233	368	77.497	464.982	418	77.520	465.120
319	77.372	464.233	369	77.497	464.982	419	77.522	465.130
320	77.374	464.244	370	77.497	464.984	420	77.522	465.130
321	77.374	464.244	371	77.497	464.984	421	77.522	465.133
322	77.375	464.252	372	77.499	464.993	422	77.522	465.133
323	77.375	464.252	373	77.499	464.995	423	77.522	465.133
324	77.377	464.264	374	77.499	464.995	424	77.522	465.133
325	77.377	464.264	375	77.501	465.005	425	77.524	465.142
326	77.379	464.271	376	77.501	465.006	426	77.524	465.142
327	77.379	464.271	377	77.501	465.006	427	77.524	465.145
328	77.381	464.285	378	77.501	465.006	428	77.524	465.145
329	77.381	464.285	379	77.501	465.008	429	77.529	465.172
330	77.382	464.291	380	77.501	465.008	430	77.529	465.172
331	77.382	464.291	381	77.502	465.010	431	77.533	465.200
332	77.382	464.292	382	77.502	465.010	432	77.533	465.200
333	77.384	464.301	383	77.502	465.014	433	77.535	465.208
334	77.386	464.317	384	77.507	465.040	434	77.535	465.208
335	77.387	464.320	385	77.507	465.040	435	77.541	465.247
336	77.389	464.333	386	77.507	465.040	436	77.544	465.265
337	77.390	464.342	387	77.507	465.040	437	77.544	465.265
338	77.393	464.359	388	77.507	465.040	438	77.545	465.268
339	77.393	464.360	389	77.507	465.041	439	77.545	465.268
340	77.394	464.365	390	77.508	465.047	440	77.545	465.269
341	77.395	464.371	391	77.508	465.047	441	77.546	465.274
342	77.396	464.373	392	77.508	465.049	442	77.546	465.274
343	77.396	464.374	393	77.508	465.049	443	77.549	465.294
344	77.398	464.389	394	77.509	465.053	444	77.549	465.295
345	77.398	464.390	395	77.509	465.053	445	77.549	465.295
346	77.398	464.390	396	77.509	465.053	446	77.552	465.309
347	77.399	464.391	397	77.509	465.053	447	77.553	465.318
348	77.399	464.395	398	77.509	465.054	448	77.553	465.318
349	77.399	464.396	399	77.509	465.054	449	77.553	465.320
350	77.399	464.396	400	77.510	465.062	450	77.554	465.325

Table B2 (4 of 7): Simulation results of the future state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
451	77.554	465.325	501	77.575	465.450	551	77.608	465.329
452	77.555	465.329	502	77.575	465.450	552	77.608	465.329
453	77.555	465.329	503	77.575	465.452	553	77.609	465.334
454	77.556	465.334	504	77.575	465.452	554	77.609	465.334
455	77.556	465.334	505	77.576	465.454	555	77.610	465.339
456	77.557	465.339	506	77.576	465.454	556	77.610	465.343
457	77.557	465.343	507	77.577	465.460	557	77.610	465.343
458	77.557	465.343	508	77.577	465.460	558	77.610	465.346
459	77.558	465.346	509	77.578	465.468	559	77.611	465.348
460	77.558	465.348	510	77.578	465.468	560	77.612	465.348
461	77.558	465.348	511	77.579	465.472	561	77.613	465.353
462	77.559	465.353	512	77.579	465.472	562	77.613	465.353
463	77.559	465.353	513	77.580	465.482	563	77.614	465.354
464	77.559	465.354	514	77.580	465.482	564	77.614	465.354
465	77.559	465.354	515	77.583	465.500	565	77.615	465.361
466	77.560	465.361	516	77.583	465.500	566	77.615	465.361
467	77.560	465.361	517	77.583	465.500	567	77.616	465.363
468	77.561	465.363	518	77.583	465.500	568	77.616	465.363
469	77.561	465.363	519	77.583	465.500	569	77.617	465.368
470	77.561	465.368	520	77.583	465.500	570	77.617	465.368
471	77.561	465.368	521	77.584	465.502	571	77.617	465.368
472	77.561	465.368	522	77.584	465.502	572	77.618	465.368
473	77.561	465.368	523	77.587	465.522	573	77.618	465.370
474	77.562	465.370	524	77.587	465.522	574	77.619	465.370
475	77.562	465.370	525	77.589	465.532	575	77.619	465.370
476	77.562	465.370	526	77.589	465.532	576	77.620	465.376
477	77.563	465.376	527	77.591	465.547	577	77.621	465.376
478	77.563	465.376	528	77.591	465.547	578	77.621	465.377
479	77.563	465.377	529	77.594	465.563	579	77.624	465.377
480	77.563	465.377	530	77.594	465.563	580	77.624	465.378
481	77.563	465.378	531	77.596	465.573	581	77.625	465.378
482	77.563	465.378	532	77.596	465.573	582	77.628	465.379
483	77.563	465.379	533	77.599	465.595	583	77.628	465.379
484	77.563	465.379	534	77.599	465.595	584	77.628	465.382
485	77.564	465.382	535	77.600	465.599	585	77.628	465.382
486	77.564	465.382	536	77.600	465.599	586	77.628	465.392
487	77.565	465.392	537	77.602	465.613	587	77.628	465.392
488	77.565	465.392	538	77.602	465.613	588	77.631	465.394
489	77.566	465.394	539	77.605	465.630	589	77.631	465.394
490	77.566	465.394	540	77.605	465.630	590	77.634	465.396
491	77.566	465.396	541	77.606	465.633	591	77.634	465.396
492	77.566	465.396	542	77.606	465.633	592	77.635	465.402
493	77.567	465.402	543	77.606	465.634	593	77.637	465.409
494	77.568	465.409	544	77.606	465.634	594	77.638	465.409
495	77.568	465.409	545	77.606	465.638	595	77.641	465.419
496	77.570	465.419	546	77.606	465.638	596	77.642	465.419
497	77.570	465.419	547	77.607	465.644	597	77.645	465.419
498	77.570	465.419	548	77.608	465.645	598	77.645	465.449
499	77.575	465.449	549	77.608	465.645	599	77.646	465.449
500	77.575	465.449	550	77.608	465.647	600	77.647	465.450

Table B2 (5 of 7): Simulation results of the future state model

#	Duration (hour)	Man-hours
601	77.648	465.889
602	77.648	465.889
603	77.649	465.892
604	77.649	465.895
605	77.650	465.898
606	77.650	465.900
607	77.651	465.904
608	77.651	465.908
609	77.652	465.914
610	77.653	465.919
611	77.653	465.920
612	77.655	465.928
613	77.655	465.932
614	77.656	465.937
615	77.656	465.937
616	77.656	465.938
617	77.656	465.938
618	77.657	465.940
619	77.657	465.940
620	77.659	465.953
621	77.659	465.953
622	77.665	465.988
623	77.665	465.988
624	77.668	466.009
625	77.668	466.009
626	77.672	466.030
627	77.672	466.030
628	77.672	466.031
629	77.672	466.031
630	77.674	466.044
631	77.674	466.044
632	77.675	466.049
633	77.675	466.049
634	77.675	466.052
635	77.675	466.052
636	77.676	466.055
637	77.678	466.069
638	77.678	466.069
639	77.680	466.078
640	77.681	466.084
641	77.681	466.085
642	77.681	466.088
643	77.682	466.094
644	77.683	466.096
645	77.683	466.099
646	77.683	466.100
647	77.684	466.103
648	77.684	466.103
649	77.686	466.113
650	77.686	466.113

#	Duration (hour)	Man-hours
651	77.686	466.115
652	77.686	466.117
653	77.686	466.117
654	77.687	466.121
655	77.687	466.121
656	77.687	466.121
657	77.688	466.128
658	77.688	466.130
659	77.688	466.130
660	77.689	466.136
661	77.689	466.136
662	77.691	466.143
663	77.691	466.143
664	77.691	466.143
665	77.691	466.144
666	77.692	466.153
667	77.692	466.153
668	77.693	466.155
669	77.693	466.157
670	77.693	466.157
671	77.694	466.163
672	77.694	466.165
673	77.697	466.179
674	77.697	466.181
675	77.699	466.193
676	77.699	466.193
677	77.701	466.205
678	77.701	466.206
679	77.701	466.206
680	77.705	466.227
681	77.705	466.227
682	77.705	466.230
683	77.705	466.232
684	77.706	466.234
685	77.706	466.234
686	77.708	466.250
687	77.709	466.255
688	77.710	466.262
689	77.711	466.265
690	77.713	466.276
691	77.714	466.282
692	77.716	466.294
693	77.716	466.295
694	77.717	466.301
695	77.717	466.302
696	77.718	466.308
697	77.718	466.310
698	77.718	466.310
699	77.721	466.323
700	77.721	466.324

#	Duration (hour)	Man-hours
701	77.723	466.335
702	77.725	466.348
703	77.727	466.361
704	77.728	466.369
705	77.728	466.370
706	77.728	466.370
707	77.729	466.371
708	77.732	466.391
709	77.732	466.391
710	77.733	466.400
711	77.733	466.400
712	77.738	466.425
713	77.738	466.425
714	77.739	466.436
715	77.739	466.436
716	77.743	466.458
717	77.743	466.458
718	77.744	466.462
719	77.744	466.462
720	77.744	466.464
721	77.744	466.464
722	77.747	466.484
723	77.747	466.484
724	77.748	466.486
725	77.748	466.486
726	77.748	466.490
727	77.748	466.490
728	77.748	466.490
729	77.748	466.490
730	77.750	466.502
731	77.750	466.502
732	77.751	466.507
733	77.751	466.507
734	77.753	466.520
735	77.753	466.520
736	77.755	466.528
737	77.755	466.528
738	77.758	466.545
739	77.758	466.545
740	77.758	466.547
741	77.758	466.547
742	77.763	466.580
743	77.763	466.580
744	77.765	466.588
745	77.765	466.590
746	77.765	466.592
747	77.769	466.615
748	77.770	466.622
749	77.774	466.642
750	77.776	466.654

Table B2 (6 of 7): Simulation results of the future state model

#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours	#	Duration (hour)	Man-hours
751	77.777	466.662	801	77.845	467.071	851	77.879	467.271
752	77.778	466.670	802	77.847	467.081	852	77.879	467.273
753	77.788	466.729	803	77.847	467.081	853	77.879	467.276
754	77.789	466.731	804	77.848	467.085	854	77.880	467.278
755	77.795	466.768	805	77.848	467.086	855	77.880	467.282
756	77.795	466.768	806	77.849	467.093	856	77.884	467.303
757	77.799	466.794	807	77.850	467.099	857	77.884	467.305
758	77.799	466.794	808	77.851	467.106	858	77.885	467.311
759	77.802	466.812	809	77.852	467.113	859	77.887	467.320
760	77.802	466.812	810	77.853	467.120	860	77.887	467.323
761	77.806	466.834	811	77.854	467.122	861	77.887	467.324
762	77.806	466.834	812	77.854	467.124	862	77.889	467.331
763	77.807	466.841	813	77.857	467.140	863	77.889	467.336
764	77.807	466.841	814	77.857	467.140	864	77.890	467.339
765	77.809	466.856	815	77.857	467.140	865	77.892	467.354
766	77.809	466.856	816	77.857	467.141	866	77.894	467.362
767	77.812	466.874	817	77.857	467.143	867	77.894	467.364
768	77.812	466.874	818	77.857	467.144	868	77.895	467.368
769	77.814	466.882	819	77.858	467.146	869	77.897	467.380
770	77.814	466.882	820	77.858	467.149	870	77.897	467.380
771	77.816	466.898	821	77.858	467.150	871	77.897	467.383
772	77.816	466.898	822	77.859	467.151	872	77.899	467.391
773	77.817	466.899	823	77.859	467.153	873	77.899	467.392
774	77.817	466.899	824	77.859	467.155	874	77.899	467.396
775	77.818	466.909	825	77.860	467.158	875	77.900	467.401
776	77.818	466.909	826	77.861	467.165	876	77.903	467.420
777	77.819	466.912	827	77.862	467.173	877	77.904	467.423
778	77.819	466.912	828	77.862	467.173	878	77.906	467.436
779	77.820	466.921	829	77.862	467.174	879	77.907	467.440
780	77.820	466.921	830	77.864	467.183	880	77.907	467.444
781	77.821	466.925	831	77.864	467.185	881	77.909	467.452
782	77.824	466.943	832	77.864	467.185	882	77.909	467.453
783	77.824	466.945	833	77.865	467.190	883	77.909	467.456
784	77.827	466.959	834	77.865	467.191	884	77.910	467.459
785	77.829	466.973	835	77.867	467.200	885	77.910	467.459
786	77.831	466.985	836	77.867	467.204	886	77.910	467.460
787	77.831	466.986	837	77.868	467.205	887	77.911	467.467
788	77.832	466.994	838	77.868	467.209	888	77.912	467.474
789	77.837	467.020	839	77.869	467.213	889	77.916	467.493
790	77.837	467.021	840	77.869	467.215	890	77.916	467.493
791	77.841	467.045	841	77.870	467.219	891	77.916	467.497
792	77.842	467.054	842	77.872	467.233	892	77.919	467.512
793	77.843	467.060	843	77.872	467.234	893	77.919	467.516
794	77.843	467.060	844	77.874	467.242	894	77.920	467.522
795	77.844	467.062	845	77.874	467.243	895	77.921	467.523
796	77.844	467.063	846	77.874	467.244	896	77.924	467.545
797	77.844	467.064	847	77.875	467.251	897	77.925	467.547
798	77.844	467.065	848	77.877	467.260	898	77.925	467.548
799	77.845	467.070	849	77.877	467.263	899	77.926	467.553
800	77.845	467.070	850	77.878	467.270	900	77.926	467.553

Table B2 (7 of 7): Simulation results of the future state model

#	Duration (hour)	Man-hours
901	77.927	467.563
902	77.928	467.566
903	77.929	467.573
904	77.930	467.579
905	77.931	467.587
906	77.931	467.587
907	77.934	467.606
908	77.935	467.607
909	77.935	467.607
910	77.936	467.613
911	77.936	467.615
912	77.936	467.617
913	77.938	467.626
914	77.938	467.628
915	77.939	467.633
916	77.939	467.633
917	77.939	467.636
918	77.942	467.653
919	77.942	467.653
920	77.943	467.655
921	77.945	467.668
922	77.946	467.676
923	77.946	467.676
924	77.946	467.676
925	77.946	467.678
926	77.947	467.680
927	77.947	467.681
928	77.948	467.686
929	77.949	467.692
930	77.950	467.699
931	77.951	467.707
932	77.951	467.708
933	77.953	467.715

#	Duration (hour)	Man-hours
934	77.879	467.273
935	77.879	467.276
936	77.880	467.278
937	77.880	467.282
938	77.884	467.303
939	77.884	467.305
940	77.885	467.311
941	77.887	467.320
942	77.887	467.323
943	77.887	467.324
944	77.889	467.331
945	77.889	467.336
946	77.890	467.339
947	77.892	467.354
948	77.894	467.362
949	77.894	467.364
950	77.895	467.368
951	77.897	467.380
952	77.897	467.380
953	77.897	467.383
954	77.899	467.391
955	77.899	467.392
956	77.899	467.396
957	77.900	467.401
958	77.903	467.420
959	77.904	467.423
960	77.906	467.436
961	77.907	467.440
962	77.907	467.444
963	77.909	467.452
964	77.909	467.453
965	77.909	467.456
966	77.910	467.459

#	Duration (hour)	Man-hours
967	78.015	468.088
968	78.018	468.109
969	78.022	468.134
970	78.023	468.138
971	78.023	468.140
972	78.030	468.177
973	78.031	468.183
974	78.031	468.184
975	78.036	468.213
976	78.039	468.236
977	78.040	468.239
978	78.046	468.275
979	78.056	468.337
980	78.061	468.368
981	78.064	468.381
982	78.072	468.430
983	78.073	468.436
984	78.075	468.449
985	78.093	468.557
986	78.095	468.567
987	78.098	468.586
988	78.101	468.605
989	78.118	468.706
990	78.136	468.814
991	78.151	468.905
992	78.180	469.079
993	78.183	469.098
994	78.189	469.133
995	78.209	469.253
996	78.232	469.390
997	78.261	469.565
998	78.329	469.973
999	78.349	470.096
1000	78.438	470.630

Mean of man-hours = 465.478 man-hours
Standard deviation = 1.640 man-hours

APPENDIX C. ALLOCATING PROCESS COST TO PRODUCT

Table C.1 Calculation of cost/unit (cost allocated to one VDW unit) for alternative 1

Alternative 1 - Pre-bolting	Quantity	Cost driver	Unit Rate	Cost	Cost/unit
Material					
VDW size 7' x 9'	76	unit	$30,600	$2,325,600	$30,600
VDW size 7' x 12'	79	unit	$40,500	$3,199,500	$40,500
Inventory cost at DIS					
Minimum inventory, no charge	0	sf/year	$26.00	$0	$0.00
Material handling at DIS	155	unit	$22.50	$3,488	$22.50
Transportation					
Transport VDW from DIS to site	52	trip	$2,100	$109,200	$704.52
Installation					
Bolt VDW to upper girder on the ground	0.5	hour/unit	$900	$450	$450
Lift and install the combined component to lower girder	1	hour/unit	$900	$900	$900
Tighten all bolts on VDW to designed torque after having concrete slab poured.	1	hour/unit	$900	$900	$900

Unit rate provided by the VDW fabricator

Unit rate provided by the structural steel contractor

Table C.2 Calculation of cost/unit (cost allocated to one VDW unit) for alternative 2

Alternative 2 - Inserting	Quantity	Cost driver	Unit Rate	Cost	Cost/unit
Material					
VDW size 7' x 9'	76	unit	$30,600	$2,325,600	$30,600
VDW size 7' x 12'	79	unit	$40,500	$3,199,500	$40,500
Inventory cost at DIS					
Occupy 1000 sf for a year	1,000	sf/year	$26.00	$26,000	$167.74
Material handling at DIS	155	unit	$22.50	$3,488	$22.50
Transportation					
Transport VDW from DIS to site	45	trip	$2,100	$94,500	$609.68
Installation					
Lift VDW from ground and place it on floor on a roller after having concrete slab poured	0.33	hour/unit	$900	$297	$297
Insert and bolt VDW unit to the gap between lower and upper girders	2	hour/unit	$900	$1,800	$1,800
Tighten all bolts on VDW to designed torque.	1	hour/unit	$900	$900	$900

Unit rate provided by the VDW fabricator

Unit rate provided by the structural steel contractor

Table C.3 Calculation of cost/unit (cost allocated to one VDW unit) for alternative 3

Alternative 3 - Sequencing	Quantity	Cost driver	Unit Rate	Cost	Cost/unit
Material					
VDW size 7' x 9'	76	unit	$30,600	$2,325,600	$30,600
VDW size 7' x 12'	79	unit	$40,500	$3,199,500	$40,500
Inventory cost at DIS					
Occupy 700 sf for a year	700	sf/year	$26.00	$18,200	$117.42
Material handling at DIS	155	unit	$22.50	$3,488	$22.50
Transportation					
Transport VDW from DIS to site	45	trip	$2,100	$94,500	$609.68
Installation					
Lift VDW from ground and place on lower girder	0.33	hour/unit	$900	$297	$297
Bolt VDW unit to lower and upper girders	1	hour/unit	$900	$900	$900
Tighten all bolts on VDW to designed torque after having concrete slab poured.	1	hour/unit	$900	$900	$900

Unit rate provided by the VDW fabricator

Unit rate provided by the structural steel contractor

Table C.4 Calculation of cost/unit (cost allocated to one VDW unit) for alternative 4

Alternative 4 - Pre-bolting with kitting	Quantity	Cost driver	Unit Rate	Cost	Cost/unit
Material					
VDW size 7' x 9'	76	unit	$30,600	$2,325,600	$30,600
VDW size 7' x 12'	79	unit	$40,500	$3,199,500	$40,500
Inventory cost at DIS					
Minimum inventory, no charge	0	sf/year	$26.00	$0	$0.00
Material handling at DIS	155	unit	$22.50	$3,488	$22.50
Transportation					
Transport	52	trip	$1,900	$98,800	$637.42
Material handling at Herrick's shop	155	unit	$22.50	$3,488	$22.50
Transport from Herrick to the site	155	trip	$188	$29,063	$187.50
Installation					
Bolt VDW to upper girder on the ground	0.5	hour/unit	$900	$450	$450
Lift and install the combined component to lower girder	1	hour/unit	$900	$900	$900
Tighten all bolts on VDW to designed torque after having concrete slab poured.	1	hour/unit	$900	$900	$900

Unit rate provided by the VDW fabricator   Unit rate provided by the structural steel contractor

APPENDIX D. AUTODESK REVIT ARCHITECTURE 2010 TERMINOLOGY (Autodesk 2009a, Autodesk 2009b)

In Revit Architecture, a project is the single database of information for a design, it is also regarded as the building information model. The project file contains various types of information for a building design, from geometry to construction data. This information includes components used to design the model, views of the project, and drawings of the design. By using a single project file, Revit Architecture allows the user to alter the design and have changes reflected in all associated areas such as plan views, elevation views, section views, and schedules.

Revit Architecture classifies elements by categories, families, types, and instances.

Category: A category is "a group of elements that you use to model or document a building design. For example, categories of model elements include walls and beams" (Autodesk 2009a). Categories of annotation elements include tags and text notes.

Family: Families are "classes of elements in a category" (Autodesk 2009a). A family groups elements with a common set of parameters (properties), identical use, and similar graphical representation. Different elements in a family may have different values for some or all properties, but the set of properties (their names and meaning) is the same. For example, six-panel colonial doors could be considered one family, although the doors that compose the family come in different sizes and materials. Structural members (such as W shapes) are another family.

Type: Each family can have different types. A type can be a specific size of a family, such as a 30" x 80" door or a 32" x 84" door. A type can also be a style, such as 'default aligned' or 'default angular' style for dimensions. A family can have several types. For example, a table may be available in several sizes. Each size table is a different type within the same family.

Instance: Instances are the actual items (individual elements) that are placed in the project and have specific locations in the building (model instances) or on a drawing sheet (annotation instances). Each instance belongs to a family and, within that family, a particular type.

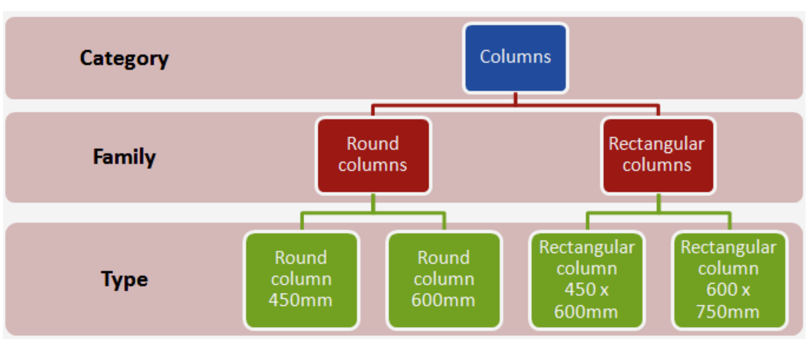

Figure D.1 Element classification structure in Revit Architecture (Autodesk 2009a)

For example, the Furniture category includes families and family types that the user can use to create different pieces of furniture, like desks, chairs, and cabinets. Although these families serve different purposes and are composed of different materials, they have a related use. Each type in the family has a related graphical representation and an identical set of parameters, called the family type parameters.

When a user creates an element in a project with a specific family and family type, that user creates an instance of the element. Each element instance has a set of properties, in which the user can change some element parameters independently of the family type parameters. These changes apply only to the instance of the element, the single element in the project. If the user makes any changes to the family type parameters, the changes apply to all element instances that the user created with that type.

Parameters (aka. element properties) are "settings that control the appearance or behavior of elements in a project. Element properties are the combination of instance properties and type properties" (Autodesk 2009b). In a Revit project, parameters define the relationships between elements of the building model. These relationships are created automatically by Revit Architecture by users during design. As the user works in drawing and schedule views, Revit Architecture collects information about the building model. The Revit parametric change engine automatically coordinates changes in all model views, drawing sheets, schedules, sections, and plans.

Shared parameters are "parameters that a user can add to families or projects and then share with other families and projects" (Autodesk 2009b). They allow users to add specific data that is not already predefined in the family file or the project template. Shared parameters are stored in a file independent of any family file or Revit Architecture project; this allows users to access the file from different families or projects.

A schedule is a "tabular display of information, extracted from the properties of the elements in a project" (Autodesk 2009a). A schedule can list every instance of a family type, or it can collapse multiple instances onto a single row, based on the schedule's grouping criteria. Revit Architecture allows users to create different types of schedules, including quantities, material take-offs, view lists, and drawing lists.

Autodesk includes a wide range of system families in Revit Architecture and provides tools for users to create their own loadable and in-place families. Taking this opportunity, many fabricators and suppliers in the construction industry have modeled their product lines in Revit and made them available to designers. Seek.autodesk.com is a popular website where fabricators and suppliers post their product models and product specifications. Since many different file formats can be posted to introduce the product model, this platform can also be used for sharing product installation instructions as well as process- and cost data.

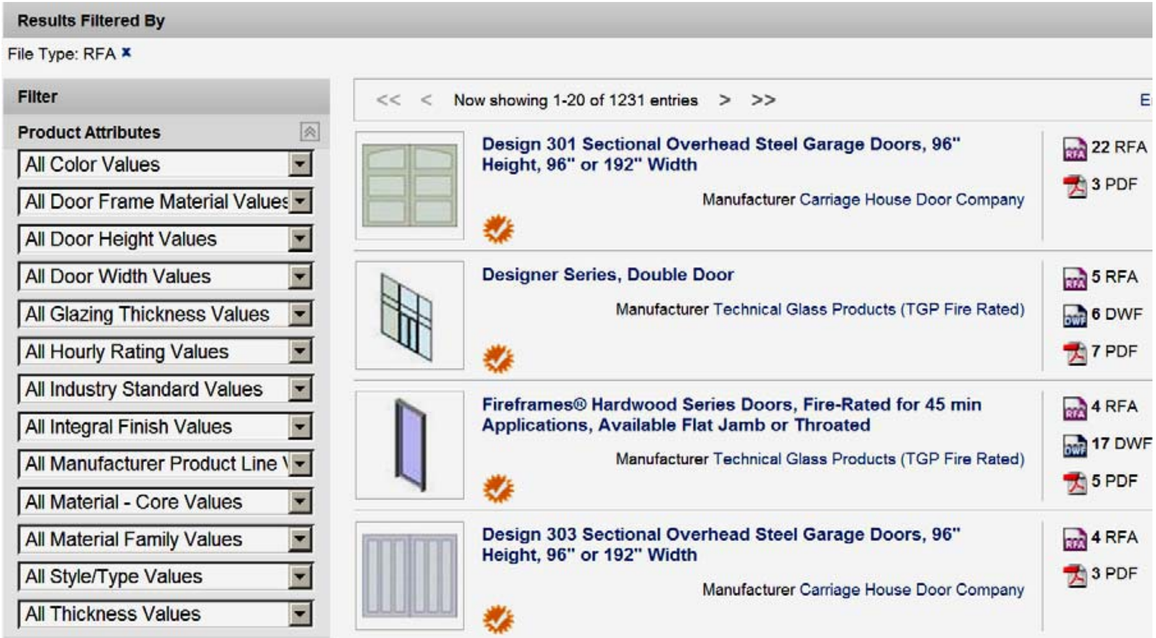

Figure D.2 Product models posted on seek.autodesk.com by fabricators (visited on January 10, 2010)