DECISION ANALYSIS USING VIRTUAL FIRST-RUN STUDY OF A VISCOUS DAMPING WALL SYSTEM

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ABSTRACT

Although Building Information Modeling (BIM) practices such as 3D modeling, 4D simulation, clash detection, model-based analysis, model-based scheduling and estimating have been widely utilized by the A/E/C industry, there is insufficient guidance on the application of BIM to assist the team in integrating product design and process design to meet target value in an Integrated Project Delivery (IPD) environment. This paper investigates the possibility of performing a virtual first-run study (VFRS) during a project's design phase. VFRS is a first-run study carried out in a virtual environment, where objects of study are created in a computer model in three dimensions, and those objects are linked to process and resource data to represent the process of construction.

The paper describes a case study of employing VFRS, process mapping, and Choosing By Advantages to choose a method for the installation of Viscous Damping Walls at the Cathedral Hill Hospital Project in San Francisco. The paper concludes by proposing an integrated framework for the efficient application of VFRS to support project teams on constructability review, construction planning, and operation design.

KEY WORDS

Virtual first-run study (vfrs), bim, work structuring, choosing by advantages.

INTRODUCTION

Researchers have analyzed the effectiveness of 4D models on different areas of design and construction. For example, 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 on planning construction operations. Akinci et al. (2002) studied the use of 4D models for planning work space and site logistics. However, with the integrated project delivery approach in a Lean Project Delivery System, the cross-functional project team needs a framework on how to structure coordination meetings that take full advantage of 4D simulation. The challenge is to incorporate innovative ideas generated from the meeting to both product design and

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process design in order to streamline fabrication, logistics, and construction/installation processes.

The objective of this study is to investigate the possibility of performing a first-run study in a virtual environment during a project's design phase. A researcher of the Project Production Systems Laboratory (P^2SL), who is the first author of this paper, worked for one year as a member of Virtual Design and Construction team at the Cathedral Hill Hospital Project (CHH) to help establish a framework for introducing 4D models to facilitate supply chain coordination meetings. This researcher became part of the project team, collecting data through observations, interviews, and document analysis while participating in the implementation of the experiment and helping make adjustments to the experimental process. This paper presents a VFRS framework established by the team and its application in a Viscous Damping Wall (VDW) case study. The installation of VDWs required coordination of multiple specialty contractors (trade partners), such as the Structural Engineer of Record (SEOR), VDW fabricator, shipping company, hoisting subcontractor, and steel structure supplier. The VDW presented a coordination challenge for logistics and field operations thus the Integrated Project Delivery (IPD) team at the CHH project wanted to further explore different methods for their installation. A detailed description of the implementation of VFRS to evaluate installation alternatives of VDW is provided to illustrate its effectiveness. As a result of this study, the structural cluster team has successfully coordinated companies across the VDW supply chain and incorporated their innovative ideas in the evaluation and selection of a VDW installation process.

BACKGROUND

CATHEDRAL HILL HOSPITAL (CHH) PROJECT

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

To support lean thinking, the CPMC team developed its own relational contract called Integrated Form of Agreement (IFOA) (Lichtig 2005). The IFOA created the contractual and financial framework to facilitate the effective collaboration between 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 project cost exceeds the EMP, the shared risk pool will be used to repay the owner. 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 shared risk pool account. With this arrangement, Sutter has removed all but a small quantified amount of risk from the project for IPD team members (IPDT 2007). This brings the freedom for team members to collaborate and focus their effort in maximizing overall values of the project instead of trying to optimize their own operations. During the design phase, team collaboration efforts were orchestrated through a Target Value Design process.

TARGET VALUE DESIGN (TVD)

Target Value Design (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 allowable budget. 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 project 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. TVD spans from project definition phase to design phase and it help steer 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 (Lostuvali et al. 2009).

To implement the TVD process, cross-functional teams (clusters) of designers and specialty contractors (trade partners) met on a weekly basis to coordinate the design of major building components and systems. Continuous value analysis and cost updates took place within the cross-functional teams for monitoring estimated costs against target costs. For components or systems which pose potential challenges to fabrication, logistics, or installation, such as the VDW system in this case study, the team needed to organize design and construction coordination meeting to address supply chain issues and identify an optimum integration of a product and process design alternatives that meet specified value targets.

Viscous Damping Wall (VDW)

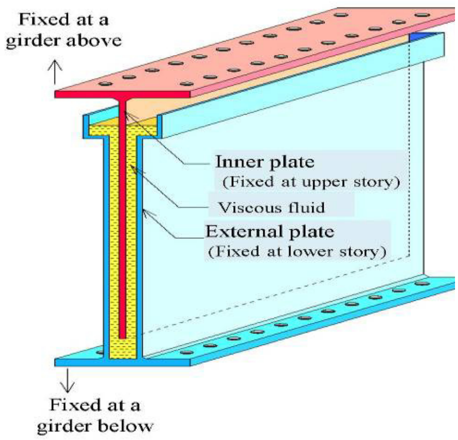

Figure 1: Viscous Damping Wall Composition (In Courtesy of Dynamic Isolation System, Inc.)

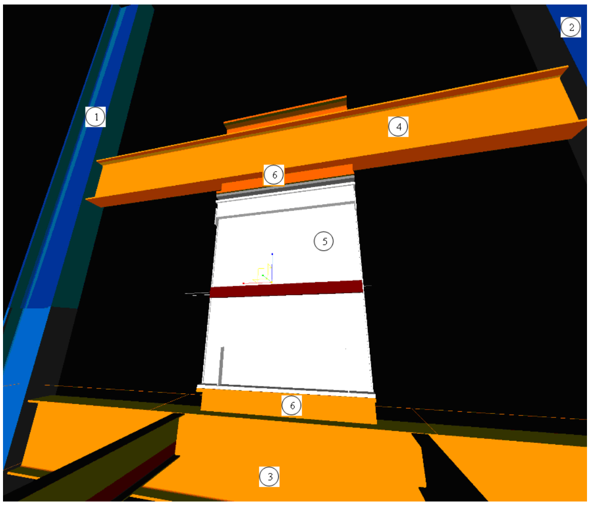

Figure 2: A 3D Rendering of A VDW on Structural Steel. Captions: (1) and (2) Columns; (3) Lower Girder; (4) Upper Girder; (5) VDW; (6) T Shaped Steel to Connect Girders and the VDW.

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

Figure 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. VDWs are used to reduce seismic accelerations and wind induced vibration. Although they have been widely used in Japan, to our knowledge CHH is the first project in the United States to use 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). VDWs are connected to the frame along the base and top of the damping wall unit, distributing the seismic forces more evenly to the structure through a longer connection. VDWs help 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. CHH will comprise 155 units of VDWs in the current structural design, standardized to three different sizes of 7'x 9', 7'x 10', and 7'x 12' to match with different floor to floor heights.

VIRTUAL FIRST-RUN STUDY (VFRS)

In a conventional project management characterized by decomposition (i.e., using WBS), designers often leave interface resolution, such as dealing with issues of scope gap and scope overlap, to the builders (Tsao et al. 2004). While the design of each part may appear to be reasonable and logical upon inspection, the design of the overall assembly may actually be far from optimal. The uncertainties and errors created during design may prove to be detrimental to performance during installation (Tommelein et al. 1999). Ballard (1999) and Ballard et al. (2001) introduced work structuring principles to integrate product design and process design. Work structuring 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).

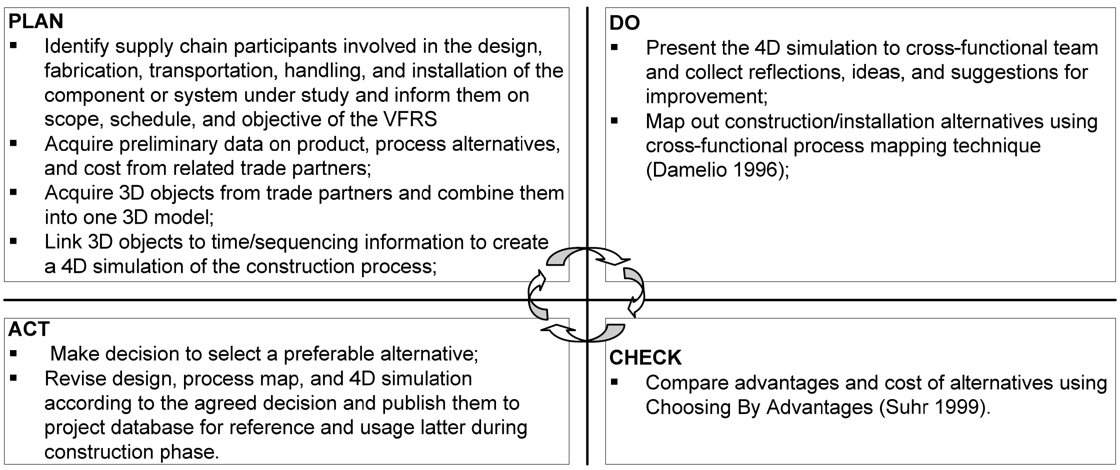

Figure 3: Virtual First Run Study WORK FLOW

Ballard and Howell (1997) recommended the adaptation and use of Plan - Do - Check - Act (PDCA) cycle to study first runs of major operations during 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". This paper investigates the possibility of performing virtual first-run study (VFRS) early on during design phase. VFRS is defined as a first-run study carried out in a virtual environment, where objects of study are virtually created in three dimensions and those objects are linked to scheduling information to represent the sequence of construction. While first-run study helps with process design during construction phase, VFRS is intended to help integrate product and process design during design phase. Figure 3 illustrates the VFRS work flow experimented in this case study.

IDENTIFYING PARTICIPANTS

Participants of the VFRS included representatives of companies involved in the design, fabrication, and installation of VDWs: Degenkolb Engineers (Structural Engineering), Dynamic Isolation Systems (DIS), Inc. (Design and fabrication of VDWs), Herrick Steel, Inc.: (Fabrication and installation of structural steel), Charles Pankow Builders, Ltd. (Concrete works), and HerreroBoldt (General Contractor).

VDW INSTALLATION ALTERNATIVES

The following descriptions of VDW installation alternatives refer to Figure 2. At the factory, the inner plate and the external plate of a VDW are temporarily attached so that the height of the VDW unit is shorter than the distance between the surfaces of the T shaped steel (6). The VDW is then filled with viscous fluid and transported to a storage area. By researching the installation of VDWs in construction projects in Japan, structural cluster figured out three alternatives as summarised in Table 1.

Table 1: VDW Installation Alternatives

Alternative 1 Pre-bolting	**Alternative 2** Inserting	**Alternative 3** Sequential Installation
- 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 lower girder (3)	- Erect columns (1) and (2) - Erect upper girder (4) - Lift and insert VDW unit to the gap between lower and upper girders - Bolt VDW to lower girder (3) - Detach inner plate and external plate - Bolt inner plate to upper girder (4)	- Erect columns (1) and (2) - Lift and bolt the VDW (5) unit on lower girder (3) - Erect upper girder (4) - Detach inner plate and external plate - Bolt inner plate to upper girder (4)

Alternative 1- Pre-bolting: After the lower girder (3) is in place, VDWs are shipped to the jobsite. An upper girder (4) is slowly set down on the top surface of a VDW (5) and these are bolted together. The upper girder and VDW unit are lifted up with a crane and attached to the building structure. Since the inner plate and external plate of the VDW are temporary combined with a clearance designed to be smaller than the actual clearance needed to reach the surface of the lower girder, a gap of about 1 ½" remains between the bottom of a VDW and the surface of the lower girder. This leaves enough clearance to install the upper girder. It is necessary to de-attach the inner plate and the external plate; the external plate lowers slowly under the resistance of viscous fluid, which enable a precise installation of the external plate.

Alternative 2- Inserting: After columns (1) and (2), lower girder (3), and upper girder (4) are in place, the VDW will be inserted to the gap between lower and upper girders and bolted to the lower girder (3). The inner and the external plates of VDW unit are detached so that the inner plate could be lifted up gradually while it is bolted to 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 lower girder. Then the upper girder (4) will be erected. The inner and external plates of the VDW are detached so that the inner plate can be lifted up gradually while it is bolting to the upper girder (4).

Table 2: VFRS Discussion Outcomes

Category	Issues/questions	Suggestions/solutions
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 patent and diameter on a mock up
	T shaped steel with 10" in depth may not give enough room 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.
Site logistics	Two trucks may cause traffic congestion on the street. Possible delay if VDW truck fail to come in time	VDW to be transported to Herrick shop and Herrick will transport columns, girders and VDW together on one truck to the site
	Multiple lifts of VDW in windy condition	Ship VDWs in a rack and lift the whole rack to installation area.
	Site constraints	No storage area
Transportation	How many VDWs per truck?	Three for 7'x12', Four for 7'x9' and 7'x10'
	Must VDW be kept strictly vertical at all time?	May swing up to 40 degree in a short time, keep vertical during transportation
	Duration of transportation from manufacturing facility to site	From four to five hours
Fabrication	Procuring of key materials	Viscous fluid imported from Japan and steel from US steel mill
	Material lead time	DIS needs two months since procuring materials to start production
	Production rate	Three VDW units per week
	Storage capacity at fabricator	Up to 155 VDW units
	Shipping schedule	Three units/week. Max 10 units/week.
Installation	Rate of installation	Three units/day for alternative 1
		Up to ten units/day for alternative 3
	Installation schedule	Alternative 1: Need close coordination with structure erection sequence. Alternative 3: Less coordination needed.
	Equipment for site installation	Tower crane, bolt tightening tools
	Labor	A crew of six worker
	Impacts of different sizes of VDW on installation	No significant impact

ACQUIRE 3D OBJECTS AND SIMULATE VDW INSTALLATION ALTERNATIVES

Degenkolb used Autodesk Revit Structure 2009 to model the structural steel in 3D, including the VDWs. A modeller then converted this Revit model to Navisworks Manage 2009 file format. 3D models of a tower crane and trucks were appended to allow the simulation of transportation and site equipment operations. The modeller performed 4D sequencing using 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. 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.

PRESENT the 4D SIMULATIONS to Cross-Functional Team

4D simulations of installation alternatives were presented to the team. Table 2 summarizes key issues and questions raised by the team and solutions suggested. These fall in five categories: constructability, fabrication, transportation, site logistics, and installation. As the result of the discussion, the team came up with another alternative (alternative 4) which was similar to alternative 1 but instead of shipping VDW directly from the fabrication shop (DIS) to the site, VDW will be transported to structural steel fabrication shop (Herrick) and then loaded on the same truck with adjacent columns and girders to be transported to construction site.

PROCESS MAPPING

Process Mapping is 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). One benefit of process mapping is that it shows coordination processes across organizations. A cross-functional process mapping technique (Damelio 1996) was used to map major steps of design, fabrication, transportation, and site installation of VDWs (Figure 4).

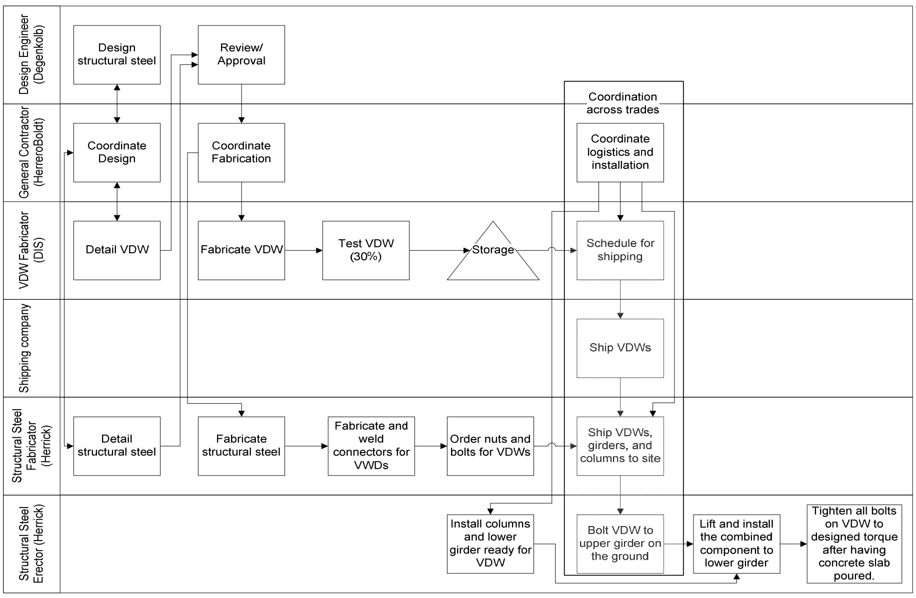

Figure 4: Process Map of Installation Alternative 4

LEGEND Underline Least Preferred Attribute Yellow cell = most important Advantage in Factor	Alternative 1 Pre-bolting VDW shipped directly to site		Alternative 2 Inserting		Alternative 3 Sequencial installation		Alternative 4 Pre-bolting VDW shipped to Herrick shop	
Installation Cost	$ 356,500		$ 463,450		$ 320,850		$ 356,500	
Storage cost	$ -		$ 25,000		$ 20,000		$ -	
Transportation cost	$ 108,500		$ 93,500		$ 93,500		$ 130,200	
TOTAL	$ 465,000		$ 581,950		$ 434,350		$ 486,700	
Factor: **Interference** *Criteria:* 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** *Criteria:* 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.** *Criteria:* 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 level		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** *Criteria:* 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 contaning three to four VDWs and place it on structural steel		Could lift a rack contaning 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** *Criteria:* Minimize temporary space usage for VDW handling and movement. Less is better. *Attribute:*	No temporary space needed		Need to temporary place VDWs on structural steel		Need to temporary 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** *Criteria:* Assure safety for workers. More is better. *Attribute:*	VDW and upper girder bolted on ground.		All connection performed on structural steel		All connection 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** *Criteria:* Ease for worker's operations and equipment operations during installation. More is better *Attribute:*	The resistance of viscous fluid allow external plate of the VDW lowering down slowly, which enable a precise installation of the external plate on 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 tight up upper bolts in a certain sequence for the inner plate to raise up		The resistance of viscous fluid allow external plate of the VDW lowering down slowly, which enable a precise installation of the external plate on 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 5: Choosing By Advantages Decision Making (In Courtesy of CHH IPD Team)

CHOOSING BY ADVANTAGES (CBA)

The IPD team at CHH project has been using the Choosing By Advantages Decision-making System (Suhr 1999) as the method for making 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 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. The priority of a criterion can be written 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, movement, temporary storage, and waiting for material, equipment, and labour were determined as factors containing 'want' criteria. By the time of submitting this paper, the CBA table has not been completed because data continues to be gathered and it is not the last responsible moment for this decision. The preliminary CBA results are presented in Figure 5. 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 would be eliminated since it does not pass the must criterion on 'ease of installation' factor. Alternative 1 would be rejected since it is about $30,000 more expensive but has 67 units of importance less than alternative 3. Although alternative 4 costs about $52,000 more than alternative 3, it ranked highest, in terms of 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.

RECOMMENDED WORK FLOW FOR VFRS

A VFRS work flow as illustrated in Figure 3 is recommended for future supply chain coordination meetings at CHH project. Right from the design development phase, an integrated team of designers, engineers and specialty contractors could perform a VFRS of construction processes to understand the impact of design decisions on coordination, logistics, and construction/installation processes. Specialty contractors examine operations in virtual environments and bring their experience and ideas to investigate alternative ways of doing the work or to suggest changes to design to improve constructability. In a VFRS, a 4D simulation helps cross-functional team generate ideas, communicate design and construction knowledge, evaluate advantages and costs of each alternative, and decide on a best alternative for work structuring.

CONCLUSIONS

The present paper introduces a VFRS framework that helps generate an integrated product, process, and resource model to support design coordination, construction planning and operation design. The main components of the VFRS framework include 4D simulation, integrated team coordination meeting, process mapping, and CBA. While FRS helps with process design during construction phase, VFRS help integrate product and process design during design phase. Effectiveness of the VFRS framework was illustrated by a VDW case study of at CHH project. By visualizing construction processes to a project team, VFRS facilitates the coordination between specialists, assists look-ahead planning, and yields reliable estimates of manpower and process-related cost. Further research needs to aim at developing guidelines for populating resource and cost data generated by VFRS to 3D objects to facilitate construction planning and control.

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