LEAN DESIGN MANAGEMENT IN AN INFRASTRUCTURE DESIGN-BUILD PROJECT: A CASE STUDY

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ABSTRACT

This paper describes a current-state practice observed for proposal development of a $500M Design-Build-Operate-and-Maintain (DBOM) infrastructure project in the public sector. The observed team's 4-month-long design and estimating process revealed problems inherent in their current approach. With the team being a three-party joint venture, integration and collaboration among designers and engineers was difficult and infrequent, creating waste and rework.

Based on this retrospective case study, this paper presents recommendations regarding improvements potentially achievable through implementation of lean concepts. Application of lean design practices could have fostered better team collaboration by integrating the design and estimating processes, and presumably achieved a more competitive proposal. Lean concepts discussed in this paper include Choosing by Advantages (CBA), set-based design, cross functional teaming, co-location, and Target Value Design (TVD).

By presenting a specific example of an infrastructure Design-Build (DB) project, this case study contributes to testing the hypothesis that lean design management can be beneficially applied to projects that do not immediately result in design or constructed facilities, but instead end with the presentation of a competitive proposal.

KEYWORDS

Lean design management, Design-build (DB), Design-build-operate-and-maintain (DBOM), Choosing by advantages (CBA), Set-based design, Cross functional team, Target value design (TVD), Public sector, Infrastructure project

INTRODUCTION

The first part of this paper describes a current-state practice observed for proposal development of a $500M Design-Build-Operate-and-Maintain (DBOM) infrastructure project in the public sector. This project is to provide transportation in a target urban area, where the existing public transportation system does not fully meet public demand. A public transportation agency (the Agency) therefore committed to delivering an Automated Guideway Transit (AGT) system with higher capacity than the existing roadway system. With federal economic stimulus funding, the project is also intended to create local job opportunities for the next five years.

The Agency's Request for Proposal (RFP) described the project as twofold:

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Design and construction/installation (DB) of a 3.2 mile-long AGT system

Operation and maintenance (O&M) of the system for 20 years

The proposal development schedule for this Design-Build-Operate-and-Maintain (DBOM) project was very tight (4 months). Four bidders submitted qualification packages and all were deemed qualified to respond to the RFP, given their experience and reputation. Among those four was a three-party joint venture (the JV), that was established in May 2009 based on an exclusive agreement between a designer (the Designer), a train supplier (the AGT Supplier), and an O&M contractor. [4]

Including a series of federal and local funds, the Agency's affordability goal was set and announced at the time of the RFP, and specified as follows:

Construction affordability target – $435M

Operations affordability target – $8.8M per annum

Total affordability target – $480M

At the time of submittal, the JV's proposal development efforts yielded a cost estimate of $517M, exceeding the total affordability target. Given that the Financial Parcel accounted for 50% of the total evaluation, and given that the low bidder's cost estimate was $440M, it came as no surprise that the JV did not win this project.

The JV's proposal development process revealed problems inherent in conventional design and estimating practice, which reflected a point-based approach (Ward et al. 1995). Integration and collaboration among designers and engineers was difficult and infrequent, inevitably creating a significant amount of waste and rework.

As a retrospective case study, this paper describes observations and recommends improvements potentially achievable when applying lean concepts. This study contributes to testing the hypothesis that lean design management can be beneficially applied to projects that do not immediately result in design or constructed facilities, but instead end with the presentation of a competitive proposal.

We next present our observations of the JV's current state of practice.

OBSERVATION OF CURRENT PRACTICE

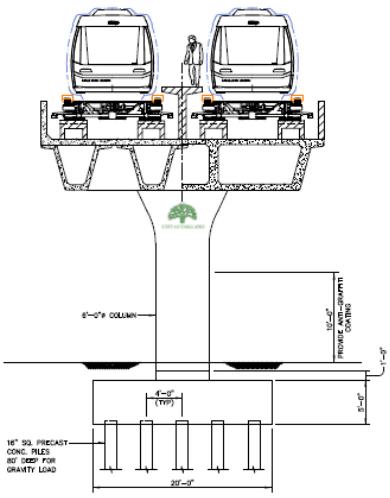
For the sake of discussion, we present the structural design process of the elevated guideway (in particular the superstructure design, among many design issues) as a case study in this paper because the JV spent significantly more energy designing the elevated guideway than any other aspect of the structure. The JV's value engineering efforts included considering multiple design alternatives in the design development process. However, the design decision making process based on a point-based approach was found questionable and rather problematic especially from a lean perspective. The JV's process for evaluating design alternatives will be discussed to illustrate what the problems were.

SUPERSTRUCTURE DESIGN

Design of the superstructure started with an analysis of constraints. The first step was to define the AGT system configuration. Its uniqueness restricted the designer significantly with regards to design alternatives. The ground rule was first set by the AGT Supplier at the kick-off meeting in June 2009 for the guideway section in terms of the vertical and horizontal dimensions. The team preferred concrete structures from

[4] Due to confidentiality, the authors may not disclose the project name or company names.

the beginning because a concrete deck and flying surface (plinth) were required[5]. Figures 1 and 2 show the final design and layout of the guideway structure.



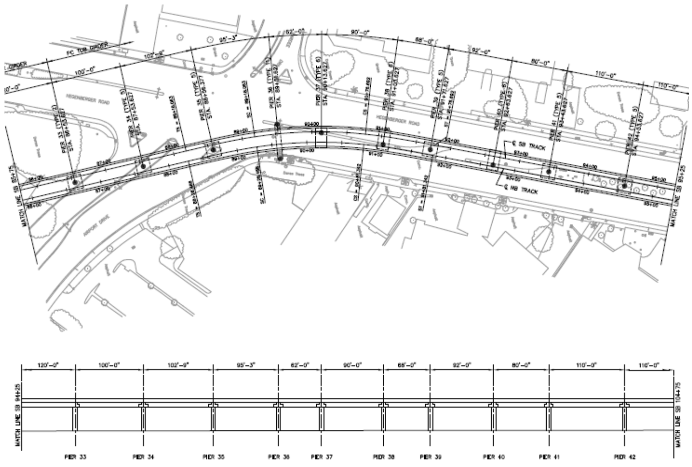


Figure 1: Elevated Guideway Section (The JV 2009)

Figure 2: Elevated Guideway Layout (The JV 2009)

The second step was to examine the RFP package from the Agency, which consisted of drawings and specifications. The package offered only a rough guideline with minimal detail for structural plans and sections. Accordingly, the team started developing its own designs from scratch. Important design constraints included:

- ‘No-column zones’ where no column shall be located due to street traffic
- Aesthetics requirements on the superstructure such as no open bottom allowed and monolithic figure preferred
- Traffic management requirement

GIRDER DESIGN

At first, the JV considered only cast-in-place (CIP) box girders, believing that CIP guarantees the lowest construction cost. Later, a JV partner suggested considering the use of precast girders on the heavily trafficked streets (50% of the project site). They interpreted the traffic management requirement in a way that made it almost impossible to construct the CIP superstructure due to the falsework needed during construction of the CIP girders. So, as an alternative, the JV considered I-girders, yet later found this infeasible because I-girders could not achieve the longer spans needed in the ‘no-column zones.’ Alternatively, the Designer then suggested Bulb-T girders (Figure 3), believing they are structurally superior to I-girders. Similar iterations continued to be observed throughout the proposal process, creating rework and wasting time.

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5 The AGT Supplier is a world-renowned ski lift manufacturer. One unique aspect of their AGT system is that it is rope-driven which guarantees a comfortable ride while producing a minimum level of noise. Another unique aspect is that the AGT trains glide on a concrete plinth with air cushions (no wheels) just like a hovercraft.

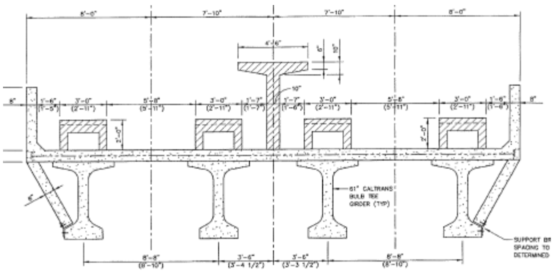


Figure 3: Bulb-T Girder (The JV 2009)

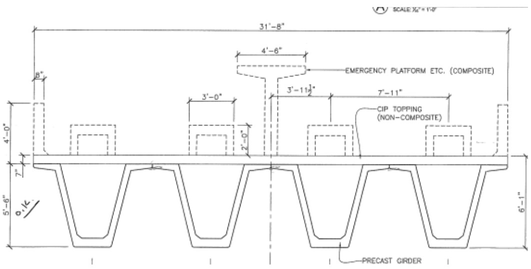


Figure 4: U-section (The JV 2009)

At the very last minute, a precast U-section (Figure 4) was introduced by a precast supplier and the JV selected it over Bulb-T girders due to the U-section's closed bottom and sides. The team believed these would better satisfy the owner's aesthetic requirements and eliminate the need for additional construction ($2M estimated) of the bottom needed with the Bulb-T design. However, the last-minute change caused the Designer to panic because they already had produced proposal drawings with the Bulb-T design. Figure 5 shows the timeline of the superstructure design development in terms of design alternatives considered.

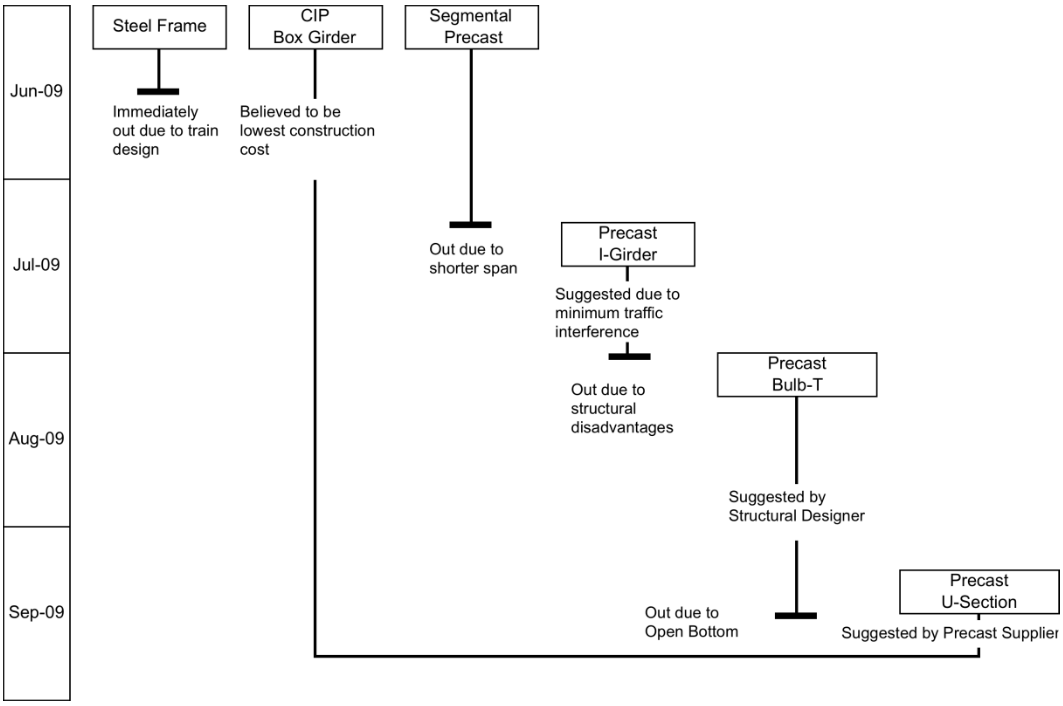


Figure 5: Timeline of Design Alternatives Considered in Current-state Practice

The observed, current-state design practice followed by the JV has several shortcomings, including:

- Negative (non-value-adding) design iteration, characteristic of point-based design (Ballard 2000)
- Last-minute changes
- Lack of a systematic approach to promote innovative thinking
- Poor communication
- Poor integration of design concepts

POTENTIAL FUTURE PRACTICE

The second part of this paper challenges the current-state practice. Having observed its inefficiency, we present how this practice might have been different when applying lean concepts including systematic design constraint analysis, Choosing by Advantages, set-based design, and cross functional teaming.

DESIGN CONSTRAINT ANALYSIS

During constraint analysis of the design requirements, two design spaces are identified where designers can have multiple design solutions (Figure 6).

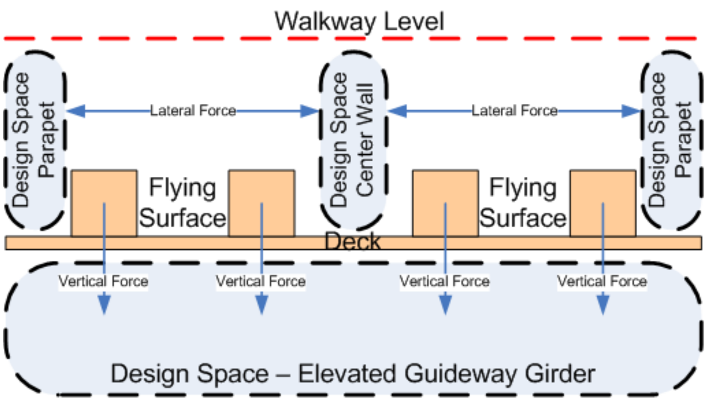


Figure 6: Design Spaces Verified with AGT System Requirements

Design Space 1 – Elevated guideway girder
  Most flexible area to carry the vertical force of AGT trains
  Design alternatives – CIP, steel, or precast
  Aesthetics issues – Open or closed bottom and side

Design Space 2 – Parapets, center wall, and walkway
  a. Minimum 8" (± 20 cm) thick walls to carry the lateral force of AGT trains
  Design alternatives – CIP or precast
  Walkway design alternatives – Side or center location

Design Space 1 has fewer constraints because any design can be applied as long as it supports the designed vertical force. Hence, design solutions for the design space include most concrete bridge designs available.

CHOOSING BY ADVANTAGES

In the process of exploring alternatives and selecting one, design team members will articulate judgments based on their interpretation of project requirements and preferences. In order to come up with a selection that best suits the project overall, yet recognizing that all decision-making is subjective, the design team must use a decision-making system that allows everyone a voice in the process and that encourages everyone to share their expertise. The system for decision-making called Choosing by Advantages (CBA) (Suhr 1999) suits this decision-making aspect in lean design management (e.g., Parrish and Tommelein 2009).

The CBA system emphasizes that decision-making must be anchored to the relevant facts and based on the importance of advantages of different alternatives being considered. CBA defines its own terminology, urging people who use the system to speak in the same language. The terms used are the following:

Alternative: possible decision or choice

Factor: container for criteria, attributes, advantages, importances, and other types of data

Criterion: decision rule or guideline established by the decision-maker. It can be indicated as a must criterion (mandatory) or a want criterion (desirable)

Attribute: a characteristic, quality, or consequence of one alternative

Advantage: beneficial difference between two and only two attributes

The CBA process starts by the team defining design alternatives (top row of Table 1), as well as factors and criteria for decision-making (left column of Table 1) that reflect values the team wants to instill in their design solutions. Each alternative shown meets the must criterion for the factor 'deck and flying surface construction' which requires that a design is acceptable only when it can 'support the AGT system;' Accordingly, the table shows only want criteria.

The next step is for the team to collect data in order to describe the attributes of each alternative, corresponding to the factors and criteria shown (filling out the other cells of Table 1). Repeating row by row, for each want criterion, the team then determines which alternative has the least preferred attribute, and underlines it. This attribute defines the baseline against which the team must gauge the advantage of each other alternative according to that want criterion. In the same row, the team then looks for the attribute that is most favorable relative to the baseline, and highlights (or grey-shades) that.

In order to define a scale to gauge importances of advantages (IoAs) for use in the entire table, the team looks at each row in the table and assesses the difference between the underlined attribute and the highlighted attribute according to what they value. Across all rows, the team then chooses which one of those is the so-called 'paramount' advantage. That advantage (circled) gets assigned 100 points on the importance of advantages (IoA) scale, relative to the underlined attributes which get assigned 0 points. Using that scale, the team then deliberates on the degree of importance of each other (i.e., not underlined and not grey-shaded) advantage relative to its baseline. To conclude, the team adds up the importance of advantages for each alternative (bottom row of Table 1). According to this system the alternative with the greatest total importance of advantages represents the best value solution.

"Many fewer shutdowns" was determined to outweigh the importance of the other advantages and was therefore selected as the paramount advantage. Accordingly, 100 IoAs were assigned to it and every other advantage was gauged relative to it. Table 1 shows that the U-section has the largest total value in importance of advantages and should therefore be carried forward in the proposal.

Table 1: Choosing By Advantages for Girder Design

Superstructure on Busy Streets	Alternative 1 **CIP Box Girder**		Alternative 2 **Steel Beam**		Alternative 3 **I-Girder**		Alternative 4 **Bulb-T**		Alternative 5 **U Segmental**		Alternative 6 **U-Section**	
Factor: Speed of Construction Criterion: Faster is better	100% on-site operation		Prefabrication Much faster	60	Prefabrication Much faster	60	Prefabrication Much faster	60	Prefabrication but much on-site operation needed Faster	40	Prefabrication Much faster	60
Factor: Ease of Construction Criterion: More is better	100% on-site forming/pouring/stripping		On-Site Installation only Much Easier	30	On-Site Installation only Much Easier	30	On-Site Installation only Much Easier	30	More Installation needed with more pieces Easier	10	On-Site Installation only Much Easier	30
Factor: Falsework Requirement Criterion: Less is better	Due to falsework, involves traffic lane shutdowns		Installation will be done at night time Many fewer shutdowns	100	More night time shutdowns wth more pieces Fewer shutdowns	70	Installation will be done at night time Many fewer shutdowns	100	More night time shutdowns wth more pieces Fewer shutdowns	70	Installation will be done at night time Many fewer shutdowns	100
Factor: Aesthetics Criterion: Closed bottom is better	Closed bottom Much more closed	80	Many openings		Open bottom More closed	20	Open bottom More closed	20	Closed bottom Much more closed	80	Closed bottom Much more closed	80
Factor: Span Length Criterion: Longer is better as fewer columns will be needed	Span more than 120 feet (± 37 meter) Much longer span	80	Span more than 120 feet (± 37 meter) Much longer span	80	Max Span at ± 100 feet (± 30 meter) Longer span	30	Max Span at ± 125 feet (± 38 meter) Much longer span	80	Max Span at ± 80 feet (± 24 meter)		Max Span at ± 125 feet (± 38 meter) Much longer span	80
Factor: Maintenance Criterion: Less is better	Little maintenance Much less maintenance	50	Periodic steel coating		Little maintenance Much less maintenance	50	Little maintenance Much less maintenance	50	Little maintenance Much less maintenance	50	Little maintenance Much less maintenance	50
		210		270		260		340		250		400

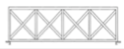
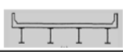
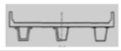
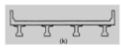
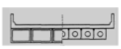
SET-BASED DESIGN

A design team's exploration of alternatives takes place over time. Set-based design (SBD) is a lean design management strategy to promote delaying design decisions in order to allow time for a team to explore and evaluate as many feasible design solutions as possible. Ward et al. (1995) argued that the traditional approach to design is point-based design in which a single, presumably best (at least from one design specialist's perspective) design solution is selected among many alternatives earlier than necessary, and proven infeasible later (especially when feedback from other design specialists is considered), which results in repeating the process over and over again. Although SBD may begin with the same design problem definition phase as in a current-state practice, it suggests that designers carry forward a set of design solutions and gradually narrow down the set in conversation with other designers by eliminating overall inferior solutions over time in order to converge on a solution (Liker et al. 1996). This narrowing may be done using CBA at different stages of detail in design development.

To illustrate a SBD approach (without using a CBA table) based on the analysis of all potential design solutions for the DBOM project, Design Space 1 starts with nine design alternatives (two steel, six precast, and one CIP). Two of them are eliminated early: a space frame is not suitable for deck construction, and a CIP box girder requires 100% falsework construction in the middle of the heavily trafficked streets, creating a serious conflict with the Agency's traffic control requirements. Subsequently, an assessment of span length eliminates the I-girder and segmental precast design due to their inability to support longer spans.

The set gets narrowed further when the team considers the speed of construction, ease of construction, maintenance, and the 'closed bottom' aesthetic preference. Table 2 illustrates how design alternatives might have been considered and eliminated over time, converging to the best value design, here the U-section.

Table 2: Set Narrowing Process (Figures in column 3 adapted from Barker and Puckett 2006)

Design Alternatives			Deck and FS	Falsework Requirement	Span Length	Speed of Construction	Ease of Construction	Maintenance	Closed Bottom
Steel	Space Frame		Not suitable for concrete						
	Steel Beam							Expensive periodic coating	
Precast	U-Section								
	Bulb-T Girder								Additional $$ for bottom
	T-Section						Hard to build		
	Closed Box					Slow construction			
	I-Girder				Does not support long span				
	U Segmental				Does not support long span				
CIP	Box Girder			100% falsework					

CROSS FUNCTIONAL TEAMING

When design team members are highly specialized and geographically dispersed, cross functional teaming and co-location are particularly appropriate lean practices. In the Lean Production System (Liker 2004), Toyota brings core suppliers into the process early and treats them as part of the team. Toyota establishes a cross functional team (CFT) where suppliers assist in set-based design and learn about requirements and potential problems so that they can contribute better and earlier in the process than would otherwise be the case (Liker 2004).

Similarly, among lean construction practitioners, cross functional teaming represents a series of efforts to involve downstream players (e.g., subcontractors or suppliers) in upstream decision making. Gil (2001) identified early design can benefit from subcontractors' knowledge thanks to "(1) their ability to develop creative solutions; (2) their knowledge of space considerations for construction processes; and (3) their knowledge of fabrication and construction capabilities." These benefits help integrate product design with process design to enhance constructability, which can result in cost and time savings.

Figure 7 depicts a swim-lane diagram of a CFT which the JV could have used to minimize the observed negative iterations in the process by means of:

The JV teaming up with a precast supplier earlier

A series of design workshops (and potentially co-location of JV participants and suppliers) to facilitate design integrations and rapid estimating for evaluating constructability and cost effectiveness of design alternatives

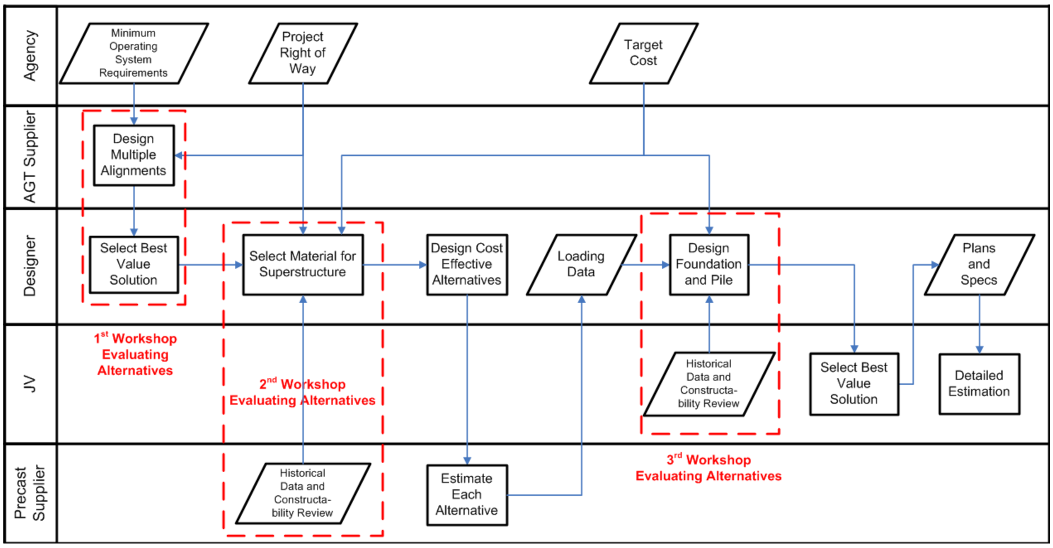


Figure 7: Swim-lane Diagram of Suggested Elevated Guideway Structure Design Process

TARGET VALUE DESIGN

Last but not least in the application of lean practices is Target Value Design (TVD). TVD is a management method to keep design and cost aligned while delivering customer value by doing “design-to-cost.” TVD is a critical and complementary piece of the case study as presented here as it pertains to the cost aspects of the proposal development process. In the infrastructure RFP process, target costs can be defined with suggested prices of bidders and the bidding process establishes a business feasibility test of the proposed infrastructure. Thus, cost reductions with design innovations are essential for maintaining project profitability. Space limitations prevented us from expanding on the potential application of TVD on this DBOM project but we will expand on this aspect in subsequent papers. Readers interested in discussing this topic further are welcome to contact the authors.

CONCLUSION

Designing a $500M infrastructure project is a daunting task. The process becomes even more challenging if multiple parties are involved, when those parties are based in different locations, and when the bid must be submitted in a short period of time.

The DBOM project described in this paper was an ambitious project, planned and executed by the Agency, to provide a 3.2-mile-long Automated Guideway Transit in an urban area. With a series of federal funds, the RFP was issued in June 2009 and pre-qualified bidders were requested to submit their DBOM proposals 4 months later.

A three-party JV managed to propose an AGT system meeting all the requirements with a suggested total price of $517M. However, as part of the team, the author observed that the 4-month-long design and estimating process was rather problematic, leading to the total price that exceeded the Agency’s total affordability target of $480M.

Design-Build is becoming the delivery system of choice of public agencies delivering large infrastructure projects. To minimize waste and maximize efficiency in the application of this delivery process, this paper proposes a set of lean practices that can guide public infrastructure developers in their design and estimating work for proposal development. We suggested that current proposal development practice can benefit from systematic, lean approaches, such as those presented in this paper, in order to more predictively achieve successful performance in the design and estimation of a megaproject. While acknowledging the limitation of the retrospective approach, our hypothesis is that application of lean design management could have improved the design and estimating process of the project and enhanced the chance to be a low bidder.

ACKNOWLEDGMENTS

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