Early Contractor Involvement in Design and Its Impact on Construction Schedule Performance

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Abstract: The importance of integrating construction knowledge into the design process has long been recognized by the construction industry. This paper studies early contractor involvement in design and its impact on construction schedule performance through a combined empirical case study and theoretical simulation analysis. Pipe and steel fabricators’ inputs at different design stages of industrial construction projects are identified. The case study shows that these inputs lead to improved drawing quality, material supply, information flow, and consequently improved construction schedule performance. This impact on construction schedule is illustrated using actual project data and simulation techniques. Simulation models were developed to demonstrate intuitively the impact at the construction operation level and they allow people to gain management insights through simulation experiments. Better understanding of the early contractor involvement process and its benefit can improve buy-in and help industry practitioners to reach the full potential of this concept.


CE Database subject headings: Partnerships; Design; Constructability; Contractors; Simulation; Scheduling.

Introduction

The ever growing size and complexity of construction projects necessitates the transition from “master builders” to specialized design professionals and construction trades. This specialization has made possible the delivery of many of the most complex facilities and structures. The traditional contracting practice, design bid build, further prompts the separation of the design and the construction processes. However, this separation also hinders design and construction knowledge integration and diminishes the opportunity for contractors to influence design decisions. During the design process, a designer works closely with a client and produces designs that are driven primarily by such factors as aesthetics, functionality, budget, as well as engineering considerations. Contractors are selected through competitive bidding at the end of the design process, thus, they have little input to design. Although construction knowledge and experience is recognized as an important design input, its impact on design is limited by the designer’s lack of construction experience and partial understanding of construction requirements (Arditi et al. 2002). Failure of design professionals to consider how a contractor will implement the design can result in scheduling problems, delays, and disputes during the construction process, and, hence, harm the overall project performance (Arditi et al. 2002). Therefore, how to effectively incorporate construction knowledge into the design process is an important subject for performance improvement (CII 1986; Pocock et al. 2006).

This paper studies contractor involvement in both early design and construction as one of the strategies to instill construction knowledge into design. The research aims at identifying contractor’s inputs during early design stages and illustrating the impact on construction schedule performance through an industrial case study and a simulation study. The goal of this combined empirical case study and theoretical modeling approach is to gain intuitive understanding of what a contractor can bring to the design table and how this early involvement effort influences construction schedule performance.

The paper is organized as follows. The next section discusses the early contractor involvement concept in relation to other value management concepts. The research scope and limitations are defined along with a review of available literature. Contractor’s inputs during design are then described based on a case study. This is followed by a simulation study on the impact of early contractor involvement on construction schedule performance.

Construction Knowledge in Design

Construction Knowledge and Value Management

In the pursuit of project efficiency, a variety of innovative management concepts are being introduced and applied to capital facility projects. These management concepts and techniques are categorized and formally defined by industry organizations and researchers, such as Construction Industry Institute’s 14 best practices (CII 2006), 44 value management practices (VMPs) (CII 2003), and independent project analysis’s (IPA) value improving practices (McCuish and Kaufman 2002). A common underlying theme of many of these value management concepts, such as
constructability and value engineering, is leveraging construction knowledge and experience to improve performance of engineering and construction projects.

CII defines constructability as the optimum use of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives (CII 1986). The basic principle of constructability is the involvement of experienced construction personnel in various project stages to ensure that construction factors are considered for decision making. Active involvement of construction knowledge in the conceptual planning phase is a basic principle of constructability suggested by CII (1986). Previous survey studies also showed that constructability has gained acceptance throughout the construction industry and it is increasingly applied in early project stages (Arditi et al. 2002; Pocock et al. 2006). Significant gains in project cost, schedule, and safety performance that resulted from constructability programs have been reported by many studies (CII 1986; Jergeas and Put 2001). Constructability is brought to design in a variety of ways, ranging from simple checklists, constructability review, design review, to placing construction experts in the design team.

As another example of value management concepts, value engineering (VE) identifies essential functions and develops methods to achieve these functions with the lowest life cycle cost. To achieve this goal, knowledge from a multidisciplinary team, including construction expertise, is required to perform the function analysis, identify high cost areas, and formulate alternatives. VE benefits include decreased costs, increased profits, and improved quality (Pulaski and Horman 2005). VE is carried out primarily as a design audit procedure at the schematic design stage with the assistance of an external team.

Besides constructability and value engineering, construction knowledge and experience can also be found as an important element in many other concepts, such as lean construction, partnering, risk management, and design review. These concepts overlap in terms of utilizing construction knowledge, although they may be different in terms of scope, goals, and the timing of implementation. A common issue related to utilizing construction knowledge is about who provides such knowledge and expertise. The traditional sense of master builder is clearly not an option due to the trend of specialization. Viable resources of construction knowledge can be largely grouped in four categories, which are in-house expertise of designers and owners, construction management consultants, general or specialty contractors, and formalized knowledge management systems. First, designers and owners can assign their own personnel with construction background to the design team. Many organizations help new engineers to acquire construction experience by rotating them between the field and the office through a multiyear program (Ford et al. 2002). However, the benefit may be limited by their partial understanding of construction requirements and diverging goals between design and construction professionals (Arditi et al. 2002). Second, construction management consultants may be retained to provide construction knowledge to design and offer opinions independent of designers and contractors. The third approach engages contractors early in the design process to provide both generic constructability knowledge and contractor-specific information. Finally, knowledge systems show future potential to automatically incorporate formal and explicit construction knowledge to design in a computerized environment (Fisher and Tatum 1997; Soibelman et al. 2003). This paper studies the third approach of introducing construction knowledge, early contractor involvement in design.

**Early Contractor Involvement in Design**

Early contractor involvement in design is defined here as a relationship between a contractor and an owner or a designer that engages the contractor from the early design stage and allows the contractor to contribute its construction knowledge and experience to design. This approach emphasizes both direct and early involvement of contractors themselves in the design process in order to deliver the best value to a project. Direct contractor involvement fosters better cooperation between the contractor and other project participants throughout the design and construction process (Jergeas and Put 2001). To obtain maximum benefits, construction knowledge must also be introduced to the early planning and design stages (Mendelsohn 1997).

Early contractor involvement presents several distinct advantages over other sources of construction knowledge. First, when compared to designers and owners, contractors have a higher level of construction expertise because of their specialized training, in-depth knowledge of construction materials, methods, and local practice. Beyond the generic constructability guidance, contractors are in the best position to provide project and contractor specific information on the availability and limitations of resources in terms of cost, performance, access, and site conditions to support design. Second, contractors are ultimately responsible for the actual construction operations. Contractors’ inputs to design have a direct impact on their own construction performance. The interaction between a contractor and a designer throughout the design process will also further improve their collaboration during construction. Third, by engaging a contractor up front, the contractor can make inputs, on a continuous basis, during early design stage, which has the best opportunity to influence project cost. This arrangement also gives contractors adequate time for a better quality of construction planning. In comparison, many constructability and value engineering programs tend to be applied periodically during detail design stages. This limits their effectiveness for improving value and reducing wasteful redesign cycles (Pulaski and Horman 2005). Finally, contractors can collect lessons learned and track costs and benefits of their early involvement at a more meaningful level of details. This knowledge development and performance measurement effort closes the loop for continuous improvement and will allow the contractor to provide even greater value to all project participants.

Benefits from early contractor involvement to owners include but are not limited to improved schedule, cost, safety, and quality performance (Gil et al. 2004; Jergeas and Put 2001; Uhlik and Lores 1998). Besides these improvements, contractors are also paid off with potentially more and steady construction workload (Gil 2001). Significant benefits for designers are developing better relationships with owners and contractors, being involved in fewer lawsuits, and building a good reputation (Arditi et al. 2002).

**Barriers of Early Contractor Involvement**

Early contractor involvement represents a radical change from the traditional business practice. Admittedly, there are many challenges in involving contractors in early design stages. O’Connor and Miller (1994) identified common barriers that prevent effective use of construction knowledge in constructability programs. Among these more common barriers, early contractor involvement in particular faces challenges in the areas of contracting practice, teamwork, and culture change. As will be discussed in the following section, alternative project delivery methods and
partnering, which are increasingly applied to the construction industry, can alleviate some of these barriers. The resistance to culture change remains the biggest barrier for implementing early contractor involvement. Much of the resistance problem is due to a lack of understanding of the concept and its benefits. A better understanding of the early contractor involvement process and a clear demonstration of its impact on project success will improve the motivation for actions. Limited research has been conducted to clarify the benefits of this strategy and demystify the concept for wider acceptance.

Practitioners with the early contractor involvement practice have the knowledge and experience to share. This research uses a case study approach to observe how early contractor involvement is implemented and what services and inputs a contractor can provide during design. Furthermore, to enhance intuitive understanding of its benefit, the case study is extended with a simulation study to demonstrate the impact of early contractor involvement on project performance. Although performance can be measured by many criteria, this research is limited to measure the benefit in terms of construction schedule performance because of its importance to the overall project success. The following section reviews relevant research in the implementation of early contractor involvement, contractor’s inputs during design, and its schedule impact.

Related Research

Implementation Strategy

The traditional design-bid-build practice practically eliminates the opportunity of contractor involvement in early design stages. Alternative project delivery methods and the partnering concept have been utilized to overcome this contracting barrier. Uhlik and Lores (1998) conducted a survey to assess constructability practice among general contractors. It was found that design-build and construction management contracts facilitate the integration of a general contractor’s knowledge into design. Gil et al. (2004) studied early involvement of specialty contractors in the design process. The authors showed that early specialty contractor involvement can be achieved through design build with specialty contractors, contractor design-assist services, or nominated contractors. Jergeas and Put (2001) noted cases of getting contractors involved in design by forming long-term partnership among owners, engineers, contractors, and suppliers. Major partners are selected and involved from the beginning of the design process. A CII research (CII 1998) took one step further and developed a new project delivery method that reconfigured the traditional engineering, procurement, and construction (EPC) model into procurement, engineering, procurement, and construction (PEpC). By actually reaching full commercial and contractual agreement with key suppliers prior to design, PEpC can utilize supplier expertise in all project phases including design. The case study presented in this paper uses essentially a partnering strategy to integrate contractors into the design process.

Contractors’ Inputs during Design

The survey conducted by Uhlik and Lores (1998) shows that the top three activities performed by general contractors during the conceptual design phase are preparing schedule and budget, selecting major materials and construction methods, and suggesting structural systems. During the design phase, the top three activities are preparing schedule and budget, providing material and equipment information, and reviewing specifications. From a specialty contractor’s perspective, Gil et al. (2004) categorized the inputs in four areas, including ability to develop creative solutions, knowledge of construction space needs, knowledge of fabrication and construction capabilities, and knowledge of supplier lead time and reliability. Services and inputs of pipe and steel fabricators involved in industrial construction projects are presented in this paper.

Impact on Schedule Performance

It is important to clarify the benefit and impact of early contractor involvement on schedule performance. However, little has been done to measure the impact of this relatively new practice. Alternatively, simulation modeling has been used to study the schedule impact of early contractor involvement on a theoretical basis. The new PEpC system was modeled by reconfiguring a classic EPC process model in order to estimate the range of time savings (CII 1998). Gil et al. (2004) used a simulation model to evaluate the impact of early specialty contractor involvement to the design and construction process. The study was limited to analyze the impact of a single factor, design length of spools, on construction duration. In both studies, the simulation models are project-level generic models used for a theoretical comparison of different business strategies.

There are advantages and limitations of both empirical case study and theoretical simulation modeling. An in-depth case study can sharpen our understanding of the early contractor involvement process and its benefit in a real-life context. However, it falls short in illustrating the impact on construction operations and the ability to test alternative strategies to gain more management insights. In this paper, the limitations of case study are compensated by a simulation study. A simulation model was developed to accurately represent an actual case study. This base model was then reconfigured to represent hypothetical scenarios for performance comparisons. The following sections describe the case study and the simulation study.

Early Contractor Involvement in Industrial Construction Projects

Industrial construction projects, such as the construction of refineries and plants, are large, technically complicated, and logistically challenging, and they require a high level of coordination to ensure project success. This case study describes the early contractor involvement practice of an owner organization and its partners involved in industrial construction projects.

Value-Based Supplier Integration

The owner is a major energy company focusing on crude oil and natural gas production. Over the past several years, the owner has revolutionized its material and service acquisition process, moving from a traditional method of procurement to a value-based integrated supply chain management system. Early contractor involvement is the basis of this strategy in reforming the contractor’s role in design. The goal is to deliver continuous value improvement and cost reduction for both the owner and its suppliers. Supplier integration is a commitment-intensive process and the major barrier is the lack of mutual trust among project par-
participants with potentially conflicting goal and work philosophy. The owner adopted the partnering concept to overcome this barrier.

The partnering concept of sharing business objectives, communicating with openness, and working together for common goals has been reported by CII to result in many noteworthy accomplishments (CII 1996). Partnering can be either a strategic alliance that focuses on long-term commitment or a project specific relationship that limits to a single project (CII 1996). This owner favors a long-term partnering relationship with suppliers to deliver the best value. This is achieved by establishing a strategic alliance with a small number of contractors, such as steel, pipe, and cable suppliers. The strategic alliance requires contractors to be involved from the beginning of a project and work with designers as a team. Contractors are chosen based primarily on cultural fit, open commitment for continuous improvement, performance on the owner’s past projects, as well as the willingness to take a new role in design. Of course, the supplier of choice strategy is not an exclusive arrangement and chosen suppliers may also be required to bid depending on particular project circumstances. Savings were observed in actual projects. For example, in steel construction, the partnership helped in reducing design changes and errors, standardizing design, and achieving fabricate-to-erection schedule. In another example, cables were cut to length and delivered on a daily basis to the construction site, which avoids significant material delays. The long-term relationship allows contractors to share the owner’s success and benefit from relatively constant workload and reduced learning curve.

Fabricator’s Inputs during Design

Pipe and steel are two types of bulk materials intensively used in industrial construction projects. Pipe spools and steel pieces are normally prefabricated in fabrication shops, assembled into larger modules, and then shipped to the construction site for installation. The percentage of shop fabrication in construction has been increasing because production is much better managed in a controlled shop environment than it is in the field. Timely delivery of pipe and steel is critical to the overall project success. Many wastes and inefficiencies during fabrication can be traced back to the lack of design and construction coordination during the design stage. To eliminate these wastes, services and inputs of pipe and steel fabricators during different design stages must be defined first.

Industrial facility design is an evolving process, which is comprised of multiple stages of development, review, and refinement. Fabricator’s services and inputs are different at different stages of design. In a typical industrial construction project, the design process involves design basis memorandum (DBM), engineering design specification (EDS), and detail design. During the DBM stage, project goals and objectives are restated based on the owner’s business decisions with a further level of refinement in determining the project feasibility and the design basis. Upon the completion, the EDS stage produces process and mechanic design and equipment specifications, which become the basis for the detail engineering design. Various engineering disciplines are involved in the detail design stage to fully define the scope of work and generate engineering drawings for contractors.

In the value-based integration environment, fabricators have the opportunity to get involved starting at one of these design stages. In this case study, two chosen suppliers of the owner, a pipe fabricator and a steel fabricator, as well as the owner were interviewed to identify fabricator’s inputs at different design stages. Early involvement strategy has been tested in several owners’ past projects. Table 1 summarizes the identified fabricator services and inputs at each design stage. These inputs distribute in three areas, including project management, design assistance, and construction planning. In the project management area, fabricators along with other chosen suppliers develop a realistic project budget and schedule. Greater accuracy in budgeting and planning helps the owner and the designer to better rationalize early design decisions. Fabricators can also provide design assistance by reviewing models, drawings, specifications, and assisting design optimization, modularization, and standardization. It helps to improve the contractor’s understanding of engineering information, and reduce design errors, omissions, and inconsistencies that contribute to various types of delays during construction. Finally, using their construction knowledge, fabricators can better plan shop operation, optimize material and construction method selection, and improve temporary structure design to further reduce construction delays.

Effect of Fabricator’s Design Inputs

With the above-mentioned fabricator inputs, improvement of drawing quality, material supply, and information flow were commonly observed by the fabricators and the owner in past projects. Effect of early fabricator involvement in these areas can be measured by the reduction of four common delay contributors, namely, drawing revision, material shortage, nonconformance report (NCR), and request for information (RFI). The delay contributors are described below:

• After issuance of design drawings for construction, drawings may be revised due to many reasons, such as design errors, omissions, or scope change. Drawing revision requires extra time for additions or deletions of work completed or underway.

Table 1. Fabricator Services and Inputs at Different Design Stages

<table>
<thead>
<tr>
<th>Design stage</th>
<th>Fabricator services and inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBM stage</td>
<td>Assist in design optimization</td>
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<tr>
<td></td>
<td>Develop integrated engineering procurement construction schedule</td>
</tr>
<tr>
<td></td>
<td>Assist in defining overall execution strategy</td>
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<tr>
<td></td>
<td>Budget fabrication and construction activities</td>
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<tr>
<td></td>
<td>Develop construction philosophy and work breakdown structure</td>
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<tr>
<td></td>
<td>Estimate fabrication shop capacity</td>
</tr>
<tr>
<td>EDS stage</td>
<td>Review specifications</td>
</tr>
<tr>
<td></td>
<td>Refine estimate, schedule, and work breakdown structure</td>
</tr>
<tr>
<td></td>
<td>Develop preliminary construction plans</td>
</tr>
<tr>
<td></td>
<td>Select materials and standardize module design</td>
</tr>
<tr>
<td></td>
<td>Incorporate fall arrest systems and scaffold reduction</td>
</tr>
<tr>
<td>Detail design stage</td>
<td>Assist in design development, e.g., assembly connection, critical lift and crane requirements, fireproofing, and coating requirements</td>
</tr>
<tr>
<td></td>
<td>Review models at various levels of completion</td>
</tr>
<tr>
<td></td>
<td>Refine estimate, schedule, and work breakdown structure</td>
</tr>
<tr>
<td></td>
<td>Review and formalize standards and details</td>
</tr>
<tr>
<td></td>
<td>Identify material shortage</td>
</tr>
<tr>
<td></td>
<td>Expedite material and equipment</td>
</tr>
</tbody>
</table>
• Certain equipment components and bulk materials, such as pipe and steel, may be supplied by owners because of their relative high cost. Inaccurate quantity take off or specifications can cause material shortage and work stoppage during construction.

• NCRs are prepared by an inspector when a defect or shortcoming in the quality of the work performed is discovered. In the context of this research, NCRs refer to the design nonconformities that are identified by a fabricator during construction.

• RFIs are issued by a fabricator to the designer when design details need clarification. Transaction and processing of NCRs and RFIs interrupt construction operations and cause delays.

Fig. 1 shows a conceptual system model of the engineering, procurement, and construction process and early fabricator involvement. It should be noted that bidding and contractor selection no longer exist in the strategic alliance mode. The design process is followed immediately by material procurement and construction. In the case study, the owner was responsible for procuring steel and pipe materials with the hope of lowering procurement cost. After obtaining design drawings and raw materials, the construction process can proceed. The construction process, which includes detailing, fabrication, and assembly, will be described later in this paper. In this figure, solid lines indicate the normal flow of information or material and dotted lines represent harmful flows of delay or rework related to the identified delay contributors.

Impact of Early Contractor Involvement on Construction Schedule

Although the owner and the contractors have perceived that early fabricator involvement had led to reduced overall construction duration based on their past experience, no detail data are available to demonstrate step by step how the time savings was actually achieved at the operation level. Measuring the overall benefit of the early contractor involvement strategy has been partially addressed by Jergeas and Put (2001). Instead, this paper proposes to demonstrate how the time saving is achieved at a detailed operation level using simulation techniques. Simulation is an ideal tool to model construction operations and capture operation phenomena, such as project complexity, resource constraints, combined effects of influencing factors, and out of sequence work due to various delays. This modeling capability can trace the influence at a detailed operation level, thus, it can provide a clear and intuitive understanding of the benefit of early contractor involvement. It also allows people to gain management insights by experimenting and comparing project performance under different scenarios.

Modeling Pipe and Steel Construction Process

To achieve the above-mentioned goals, the construction process, represented by the element “detailing, fabrication, and assembly” in Fig. 1, was studied in detail. The pipe and steel construction process starts with the preparation of fabrication and erection shop drawings by the fabricator’s own drafting departments or detailing subcontractors. When shop drawings and owner-supplied raw materials are ready, pipe and steel fabrication can proceed. Fabricated pipe and steel pieces are then assembled at the pipe fabricator’s yard into modules, which are later shipped to the construction site for final installation. Besides the normal flow of operations, rework cycles and delays due to the four identified delay contributors must also be captured in the simulation model.

A construction simulation package, Simphony, was used to model the construction process mainly due to its open structure for developing customized simulation applications (Hajjar and Abou-Rizk, 2002). A special-purpose simulation tool was developed for modeling the pipe and steel construction process in Simphony. It features a number of graphical modeling elements, which represent pipe and steel pieces, detailing, fabrication, and module assembly operations (Song 2005). The features of the developed tool are briefly described as follows:

• Modules are the final products of the pipe and steel construction process. Each module contains several deck layers and each deck layer is comprised of a number of pipe spools and steel pieces. A pipe spool or a steel piece is the smallest production unit and, thus, modeled as an individual entity. An entity may also represent a sheet of drawing, an assembled deck layer, or a module depending on the context. Each entity carries information about its piece identifier, deck layer identifier, and module identifier. Modeling product at the most detailed level of the breakdown structure is necessary because construction operations and schedule delays are normally associated with each individual piece or drawing. This modeling strategy makes it possible to keep track of the processing of each individual entity during the construction process.

• Drawings, pipe spools, steel pieces, and modules are produced according to a predefined erection schedule. Each entity receives a priority number accordingly. An entity that has a higher priority number and satisfies all start constraints will be processed first. This “fabricate-to-erection” schedule practice is considered a standard practice regardless of fabricator early involvement. However, this prearranged sequence of production may be interrupted due to various causes of rework and delay.

• Modules are constructed by assembling individual deck layers sequentially from the ground level to Level 1, Level 2, etc. Deck assembly can start only after all pipe spools, steel pieces, and equipment components, if any, of a deck layer arrive at the module yard and the deck immediately below the current deck layer has been completed. Structural steel is erected first and followed by pipe spool and equipment component installation.

• The simulation tool is capable of modeling the entire process from drawing detailing, shop fabrication, to module assembly. Design activities are excluded from the study. Resource constraints, such as the number of draftspersons, shop work stations, and assembly crews, are modeled explicitly.

• Activities related to delay contributors, including drawing revision, material shortage, NCRs, and RFIs, are modeled explicitly. These activities cause immediate delay as described in the definitions of these delay contributors in the previous section. They may also result in a ripple effect on subsequent
activities. For example, when a pipe spool is delayed, the assembly of the corresponding deck layer and module will also be delayed.

- The simulation tool keeps track of all entities and activities for model validation purposes. Total project duration and man hours are reported as indexes for performance comparison. The optional data visualization function can help users to better understand the real-world system and model behavior.

To develop a credible simulation model, it was decided to model an actual project so that the historical project data can be used for model validation. A refinery expansion project which the fabricators recently completed was selected. This project represents the case with no early fabricator involvement. A simulation model of this project will serve as the baseline for a sensitivity study to demonstrate how early construction involvement can improve construction schedule performance.

The baseline simulation model is developed in a hierarchical manner. Lower level child elements present detail activities and processing logic of their parent element. Fig. 2 shows the child elements of the “detailing, fabrication, and assembly” element shown in Fig. 1. In this child model, steel and pipe detailing, shop fabrication, and module assembly activities are repetitive. These child elements can be further detailed. Due to the paper space limitation, only the child elements of the “spool detailing” element are illustrated here, as shown in Fig. 3. The model is self-explanatory. It uses two probability branches to represent the probability of drawing revision and RFIs.

Project managers and superintendents involved in the sample project were involved in the model development process and they provided assistance in data collection and model review. For the baseline model, data were collected from the project’s historical records and interviews with project managers and superintendents involved. Processing time of shop fabrication and module assembly and the frequency of delay contributors were collected from the project records. Processing time of drawing detailing and the severity of delay contributors were not available from the project records and project personnel’s estimates based on their project experience were used in the model. Processing time is modeled as triangular distributions using the minimum, maximum, and most likely values. Admittedly, the model is at its best an abstraction of the real-world system. To balance the model complexity and its accuracy, more than 20 simplifying assumptions were introduced during the model development process. These assumptions fall into three areas, including detailing, shop fabrication, and module assembly, and they are related to processing time, sequence, quantity of resources, and modeling of delays and reworks. Two sample assumptions from each area are illustrated below:

- Detailing: shop drawings for pipe spools or steel pieces are produced one by one but released to fabrication shops in batches of a fixed predefined size; the number of draftspersons assigned is determined by the equivalent number of draftspersons who work full time on a job.

- Fabrication: material shortage is always identified before the start of spool fabrication and material delay will only occur before fabrication; drawing revision during fabrication, if any, is assumed to occur only after fabrication is completed and rework items are always processed first.

- Module assembly: the number of concurrent module assembly activities is only limited by the number of available assembly crews, not by the size of the module yard; when a RFI is issued, the assembly activity will stop and the crew will be relocated to other modules waiting for assembly, if any.

These assumptions were presented during a structured model walk through with project managers and superintendents. All assumptions were reviewed and agreed upon. The validity of the simulation model is further examined later in this paper using actual project data.

### Quantifying Delay Contributors

As discussed previously, fabricator’s inputs during design lead to reduced drawing revision, material shortage, NCRs, and RFIs. Specifically, the impact of delay contributors on schedule performance can be quantitatively measured by their severity and frequency. The severity measures the consequence and magnitude of delay caused by a delay contributor, e.g., a RFI causes a delay of 5 days on average for feedback. The frequency measures how frequent a delay contributor occurs. To measure the schedule impact, both the severity and frequency of a delay contributor must be captured in the simulation model. Such data for the baseline simulation model were collected from the project records and project personnel. Table 2 shows the frequency of delay contributors during different construction stages based on data collected from the pipe fabricator. It represents the case in which there is no early contractor involvement. For example, the frequency of RFIs

### Table 2. Frequency of Delay—Without Early Contractor Involvement

<table>
<thead>
<tr>
<th>Process</th>
<th>Drawing revision</th>
<th>Material shortage</th>
<th>NCRs</th>
<th>RFIs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing detailing</td>
<td>15% of drawings</td>
<td>None</td>
<td>None</td>
<td>2% of drawings</td>
</tr>
<tr>
<td>Spool fabrication</td>
<td>10% of drawings</td>
<td>20% of spools</td>
<td>None</td>
<td>1% of spools</td>
</tr>
<tr>
<td>Module assembly</td>
<td>10% of drawings</td>
<td>60% of equipment modules</td>
<td>20% of modules</td>
<td>61% of modules</td>
</tr>
</tbody>
</table>
during module assembly is calculated as the ratio of the number of RFIs to the total number of modules of the project, which is 61% as shown in Column 5 and Row 4.

The severity of a delay contributor is defined as either the average of delay in working days or a percentage of the original processing time. Table 3 shows the severity of delay due to the four delay contributors at different pipe construction stages. For example, according to Column 2 and Row 3 of the table, drawing revision during the spool fabrication stage will result in the drawing being sent back to the detailing office for revision, which requires 30% of its original detailing time to fix. It was estimated to cost another 20% of its original fabrication duration for correction in the fabrication shop. Similar data as those presented in Tables 2 and 3 were also collected from the steel fabricator.

Since the sample project only represents a baseline case without early contractor involvement, the frequency and severity of delay contributors for scenarios with early fabricator involvement may differ and, thus, must also be measured in a similar fashion. This is discussed in the section of sensitivity study. The following section describes the validation of the baseline simulation model using actual project data.

**Model Validation**

The objective of model validation is to determine how closely the simulation model represents the actual system. The most definitive validation test is to compare the model output to the known output from the actual system (Law and Kelton 2000). The developed simulation model is based on the sample project, thus, it can be validated using actual project data. Actual project schedule, pipe, steel, and module data were collected from the fabricators’ historical project databases. Total man hours charged to fabrication and module assembly are also available. The developed simulation model was configured to represent this sample project. Simulation experiments were conducted to predict the total man hours of each construction stage. A comparison shows that fabrication and assembly man hours produced by the simulation model are all within plus and minus 5% range of the actual project values. The drawing detailing was dropped from the comparison due to the lack of actual data. It was concluded that the developed model represents closely the actual project for the purpose of schedule performance demonstration and relative sensitivity study.

**Sensitivity Study**

The purpose of the sensitivity study is to understand the impact of early contractor involvement on overall construction schedule performance and the effect of the timing of early contractor involvement. Depending on the contract agreement, fabricators may be involved in a project in the following four scenarios:

Scenario 1: fabricator involvement starting at the fabrication and assembly stage.

Scenario 2: fabricator involvement starting at the detail design stage.

Scenario 3: fabricator involvement starting at the EDS stage.

Scenario 4: fabricator involvement starting at the DBM stage.

The degree of fabricator involvement is different among these four scenarios. This difference can be measured by the varying amounts of reduction in terms of the frequency of drawing revision, material shortage, NCRs, and RFIs. Similar to Table 2, which represents Scenario 1, the frequency data must also be collected for the other three scenarios. However, because a real
The project can only represent one scenario exclusively, the other three scenarios are always hypothetical. Therefore, the frequency data of Scenarios 2, 3, and 4 do not exist in the sample project. The only option is using subjective estimates. Since both fabricators have been worked as chosen suppliers of the owner on similar projects before, their experience allows them to give realistic estimates. These estimates are considered adequate for a relative comparison of different scenarios. Table 4 shows an example of estimates on the frequency of delay contributors for Scenario 4, which corresponds to the case in which the fabricators have full involvement starting at the DBM stage. When compared to Scenario 1, Scenario 4 substantially reduces the frequency of delay contributors. Due to the space limit, data collected for Scenarios 2 and 3 are not presented here. It can be observed that the involvement strategies, from Scenarios 1 to 4, lead to reduced frequency of delay contributors in an increasing magnitude. However, due to the existence of other technical and management factors, the frequency cannot be reduced to zero.

Although these scenarios are different, construction activities and precedence logic do not change and, hence, are assumed to be the same. The baseline simulation model for Scenario 1 has been developed and validated as mentioned above. Its parameters related to the frequency of delay were modified to represent the other three scenarios for the sensitivity study. Simulation experiments were conducted and the results were compared to show the impact on schedule performance. This comparison is shown in Fig. 4. When compared to the base case scenario, Scenarios 2, 3, and 4 lead to a savings from 1.4 to 5.5% on total man hours and a larger savings from 3.4 to 12% on overall project duration. The magnitude of the estimated total project duration savings is consistent with the actual observed values. The comparison also confirms the observation that the earlier the fabricator is involved, the better he or she can contribute to reduce wastes and improve performance. To enhance this understanding, the construction operation was visualized, as demonstrated in Fig. 5. It shows entity routing, rework cycles, and cumulative delays of each delay contributor.

This simulation study was presented to the fabricators and the owner. The baseline simulation model was considered very credible by the participants because it accurately represents the project in which they were personally involved. This confidence has proven to be very helpful for the participants to understand other hypothetical scenarios in the sensitivity study. The presentation concluded that the system model and the simulated scenarios clearly show the early contractor involvement process and its impact on construction schedule performance. It was also agreed that the simulation study represents only an average case and it cannot guarantee the result of a particular project, which is influenced by a handful of other technical and management factors. The sensitivity study is intended for gaining management insights instead of for estimating purposes.

**Conclusions**

The importance of integrating construction knowledge into the design process has long been recognized by the construction industry. This paper studies early contractor involvement in design as a design and construction integration strategy. This strategy is defined in relation to other value management concepts that also capitalize on the use of construction knowledge during the design process. Contractors’ inputs at different design stages are identified through a case study of a pipe and steel construction project. Commonly observed benefits of early fabricator involvement include improved drawing quality, material supply, and information flow. The empirical case study is combined with a theoretical simulation study. The study shows that early contractor involve-
ment leads to reduced project duration and total man hours. This research improves the understanding on what contractors can bring to the design table and how this early involvement effort can influence construction schedule performance.

This research is limited to measuring only the impact on construction schedule performance, while other benefits such as cost and safety are not measured. It is also not a complete cost-benefit analysis, although anecdotal evidence and relevant research show that the benefit of partnering far outweighs the cost of partnering itself (CII 1996). To accurately measure the effectiveness and maturity of this practice, enterprise as well as project level tracking of costs, benefits, and lessons learned must be performed. Benchmarks must be established to help owners and contractors to measure their performance and improve their practice.

Like many other management concepts, the early contractor involvement strategy will excel only in an appropriate context and it is not a quick fix to problems. This strategy in particular faces challenges in the areas of contracting practice, teamwork, and more profound, culture change. Alternative project delivery methods and the partnering concept are reforming the relationships among project participants and creating a favorable environment for implementing early contractor involvement. It is hoped that a better understanding of the concept and its benefit can further improve buy-in and help industry practitioners to reach the full potential of the early contractor involvement strategy.

References


