Estimating the impact factor of undiscovered design errors on construction quality

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Abstract

Construction projects are complex as they include many activities which influence and interact with each other at different stages. The impact of design phase undiscovered rework on construction phase quality has been hypothesized as influential in project dynamics by many. However few empirical studies have measured this impact. In this paper we develop a simple system dynamics model, estimate it using data from 18 construction projects, and validate the model on a validation set of 15 projects. The model provides good fit for the calibration set and strong predictive power on the validation set. It also allows us to estimate the impact of undiscovered design changes on construction phase quality, which appears to be notable.

Keywords: Design Change Orders, Construction Performance, Project Supply Chain, System Dynamics, Project Management

Introduction

Two features distinguish construction projects from many routine work processes. First, construction projects are typically unique in terms of the final products and the parties who are involved in the project. They are also often unique in terms of the physical and socio-economic environment they are embedded in. These factors increase the variability from project to project and increases the complexity of the project management and control in construction. Second, construction projects are complex in terms of the number of the activities and parties that are involved in the project and their interactions. Typically over 1000 activities are involved in a medium size construction project, which can increase the unpredictability of project schedule and planning. Uncertainty propagates in a project as each activity is influenced by/influences other upstream and downstream activities, i.e. predecessors and successors. Overall, uniqueness, complexity, and uncertainty lead to significant cost and schedule over-runs across many projects. Understanding the mechanisms that explain these variations from plans and proposing methods to reduce variation and minimize costs remains a major goal for construction management research.

Change in construction projects

Changes, i.e. deviations from plan, are inevitable in most construction projects (Ibbs and Allen 1995; Hanna et al. (2002); Revay 2003). Change can be positive or negative. The positive change benefits the project to save cost, time, or even improve the quality or scope of work. However, the negative change deteriorates the project outcomes. The changes in the construction projects are typically documented in the form of the change orders. The change orders are the official documents attached to the original contract as modifications. They are issued to correct or modify the original contract. The change orders can be categorized by their features such as: reason, responsibility, legal aspects, and costs (Sun et al. (2008); Keane et al. (2010)). The reasons for change orders often fall in one of the four categories: design error, design omission, different site condition and scope change.

Many see changes as the main source of uncertainties in project prediction and have studied factors that influence changes (Arain et al. 2004, Sears and Sears 1994; O'Brien 1998; Ibbs and Allen 1995; Chappell and Willis 1996; Sanvido et al. 1997; Gray and Hughes 2001; Wang 2000;Fisk 1997;Dell'Isola 1982; Geok 2002; Thomas and Napolitan 1995; Arain 2002; Chan et al. 1997; Hsieh et al. 2004; Wu et al. 2004; Arain et al. 2005; Hanna (1999,2002,2004); Bower 2002). A wide range of hypotheses have been proposed and tested to identify the factors and measure their impacts on the project deviation. Hinze et al. (1992) stated that the cost overruns tend to increase with the project size. Thurgood et al. (1990) found that rehabilitation and reconstruction projects are more likely to increase the cost overruns in comparison with the maintenance projects. Riley et al. (2005) examined the effects of the delivery methods on the frequency and magnitude of change orders in mechanical construction. Gkritza and Labi (2008) showed that the project duration increases the chance of cost overrun. Kaming et al. (1997) found the design changes are one of the most important causes of time overruns in 31 high-rise projects studied in Indonesia. Moslehi et al. (2005) studied the impact of change orders on the labor productivity by using 117 construction projects in Canada and US. Acharya et al. (2006) identified the change orders as the third factor in construction conflicts in Korea. Assaf and Al-Hejji (2006) studied 76 projects in Saudi Arabia and found the change order as the most common cause of delay identified by all parties: owner, consultant and contractor

There is also a rich literature in system dynamics that covers project modeling in general and construction projects in particular (Lyneis and Ford 2007). This literature captures the change in projects through the rework cycle formulation (Sterman 2000) and builds on that the different feedback effects that endogenously change productivity and quality of work by project staff and thus regulate the rate of changes made through the project life cycle.

If we consider the two key phases of design and construction common to most projects, the impact of the design errors on the changes in construction is one of the important issues related to factors that derive project changes. Several researchers have hypothesized that undiscovered changes in the design phase increases the latent changes in the construction phase; Hauck (1983), Martin and Macleod (2004); Ransom (2008) and Sun and Meng (2009). This hypothesis is in line with previous modeling work in the system dynamics literature (Ford and Sterman 1998) but has received limited empirical tests due to the complexity of measuring undiscovered changes in design. In this study we propose to tackle this problem using data from multiple construction projects and leveraging the system dynamics modeling framework.

Research methodology

A system dynamics model is developed to represent the construction projects' behavior in terms of the cost over time. The data of the 33 actual construction projects were gathered to calibrate a two-phase system dynamics model of construction dynamics. The available project data include: the estimated duration (T_0), estimated cost (W_0), actual duration (T) and actual cost (W) of the design and construction activities along with the list of the design and construction change orders during the project. The cumulative amount of the design and construction change orders over time produce the design and construction cost deviation curves. The Figure 1 shows the design and construction cost overrun curves of an example project.

Eighteen projects are randomly selected out of the 33 to perform the model calibration and the data from the other 15 projects is used for validation purposes. Simulation calibration is used to estimate the impact of the design changes on the construction performance indices.

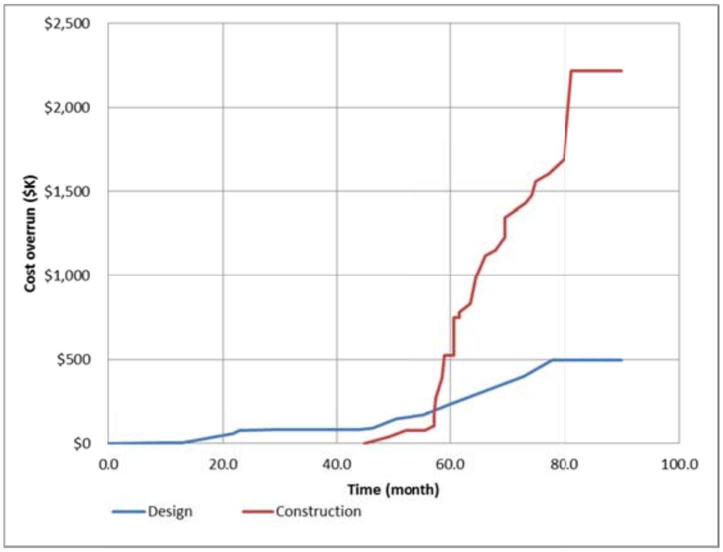


Figure 1: The cost deviation curves of the design and construction of an example project

Model Structure

The model builds on the basic rework cycle formulation of Richardson and Pugh (1981). It captures two phases of design and construction (See Figure 2). It also includes a feedback mechanism that relates the undiscovered reworks in design phase to the quality of construction phase. For each phase quality specifies the fraction of work that is done correctly, with 1-quality going to the undiscovered error stock, to be discovered with a delay. We use Equation 1to formulate the impact of undiscovered design errors on construction quality:

$$\textit{Construction Quality}=\textit{Normal Construction Quality}*(1+UC/W0)^{-\beta}$$

Equation 1: Impact of undiscovered design errors on construction quality

Here *Normal Construction Quality* is assumed to be a constant for each project. *UC* is the Undiscovered Rework in Design phase and *W0* is the total design phase work. Parameter β estimates the impact of undiscovered design errors on construction work quality. Design quality is assumed to be constant throughout the project timeline.

In the absence of data on the number of project staff, we use initial scope of each phase and divide that by the initial schedule to get a constant normalizing factor for firepower of the project (i.e. the parameter *Design>P* and *Construction>P* in Figure 2is calculated as this normalizing factor multiplied by a project specific variation in productivity). The model also includes formulations to measure changes in each phase, cumulative changes, final design and construction finish time based on a 99 percent threshold for completion, and design and construction overlap. *Design>ActualCompletionToStartConstuction* is the design percent completion as a threshold to start construction. The model is available online as a supplement to this paper.

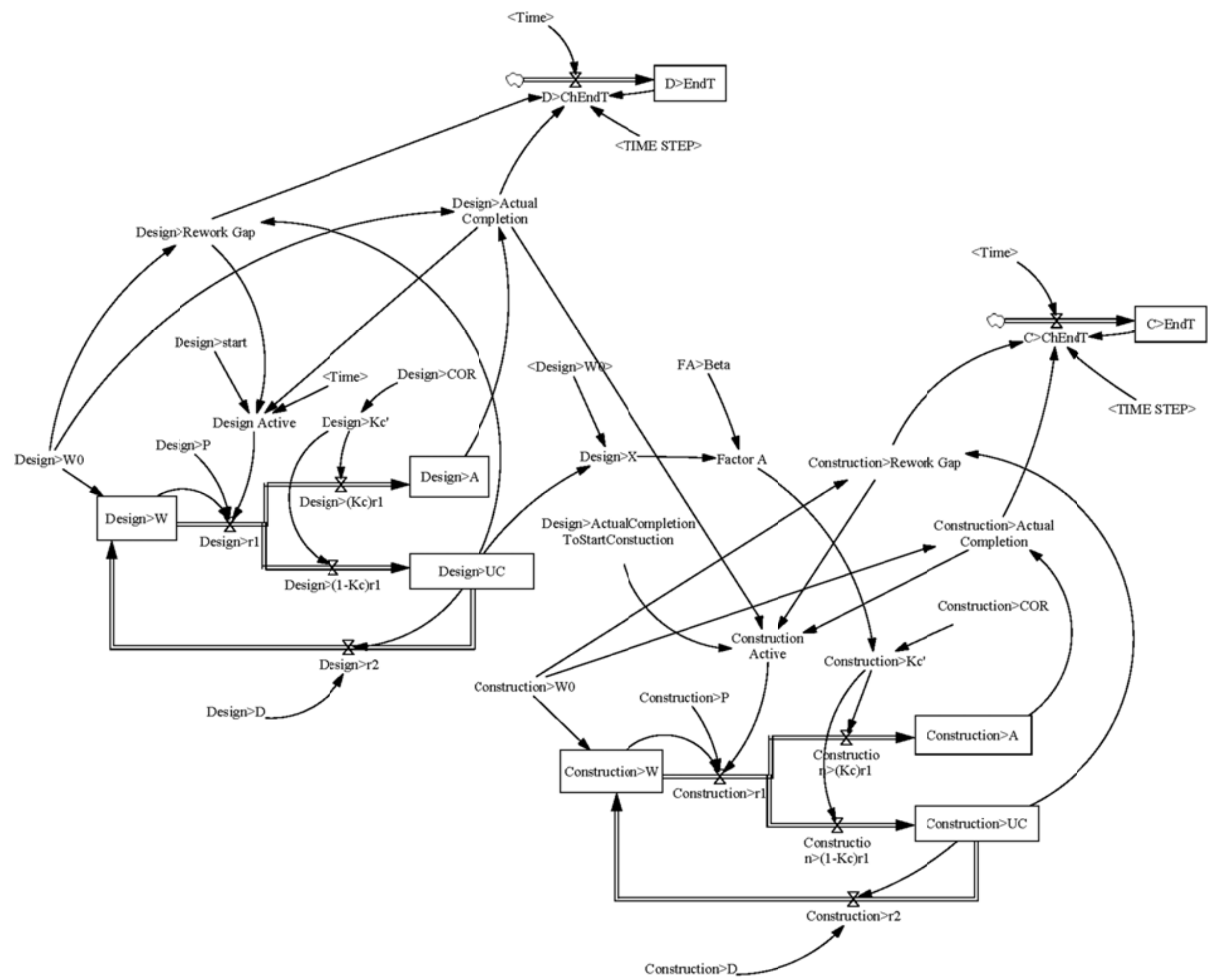


Figure 2: The proposed system dynamics model

Model Estimation

Mathematically, the calibration process is an optimization problem to minimize the distance between the model outcome and the actual data by searching for the best fitting model parameters in the feasible parameter space. The objective (payoff) function is usually defined as a weighted sum of some function of errors (difference between model and data) across different data series and time. Typical error functions are squared error, absolute error, percentage error squared, and absolute percentage error. In this research, we use a calibration payoff function including three terms: (1) sum of squared percentage error for final time (SSEP[T]) in each phase, (2) sum of squared percentage error of final cost overrun (SSEP[CO]) for each stage, and (3) sum of the squared percentage error of the cost overrun behavior over time (SSEP[COB]) for each phase. Figure 3 shows those terms. Note that while T and CO error components are only calculated at the end of project, COB component is integrated over time.

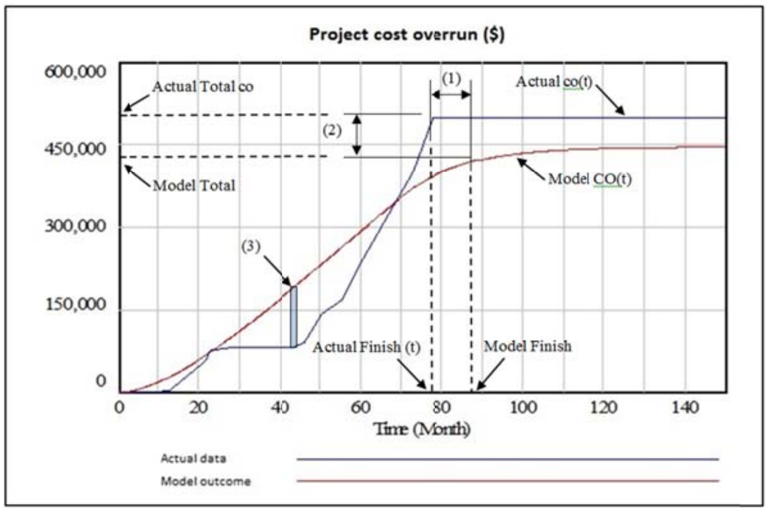


Figure 3: Calibration payoff function terms

The model parameters fall into two categories: 1) the project-specific parameters, and 2) parameters common across different projects. The project-specific parameters consist of the design and construction production rate (P), quality (COR) and time to detect undiscovered changes (D). The parameter (β) that regulates the impact of undiscovered design changes on construction quality is the only common parameter that we estimate in the developed model. The calibration is performed by simultaneously estimating the project-specific parameters (7 parameters) and a common parameter across all 18 calibration projects (total of 127 parameters) to minimize the sum of errors across all the projects. Figure 4 demonstrates the cost overrun curves for four sample calibrated projects against their actual cost overrun curves.

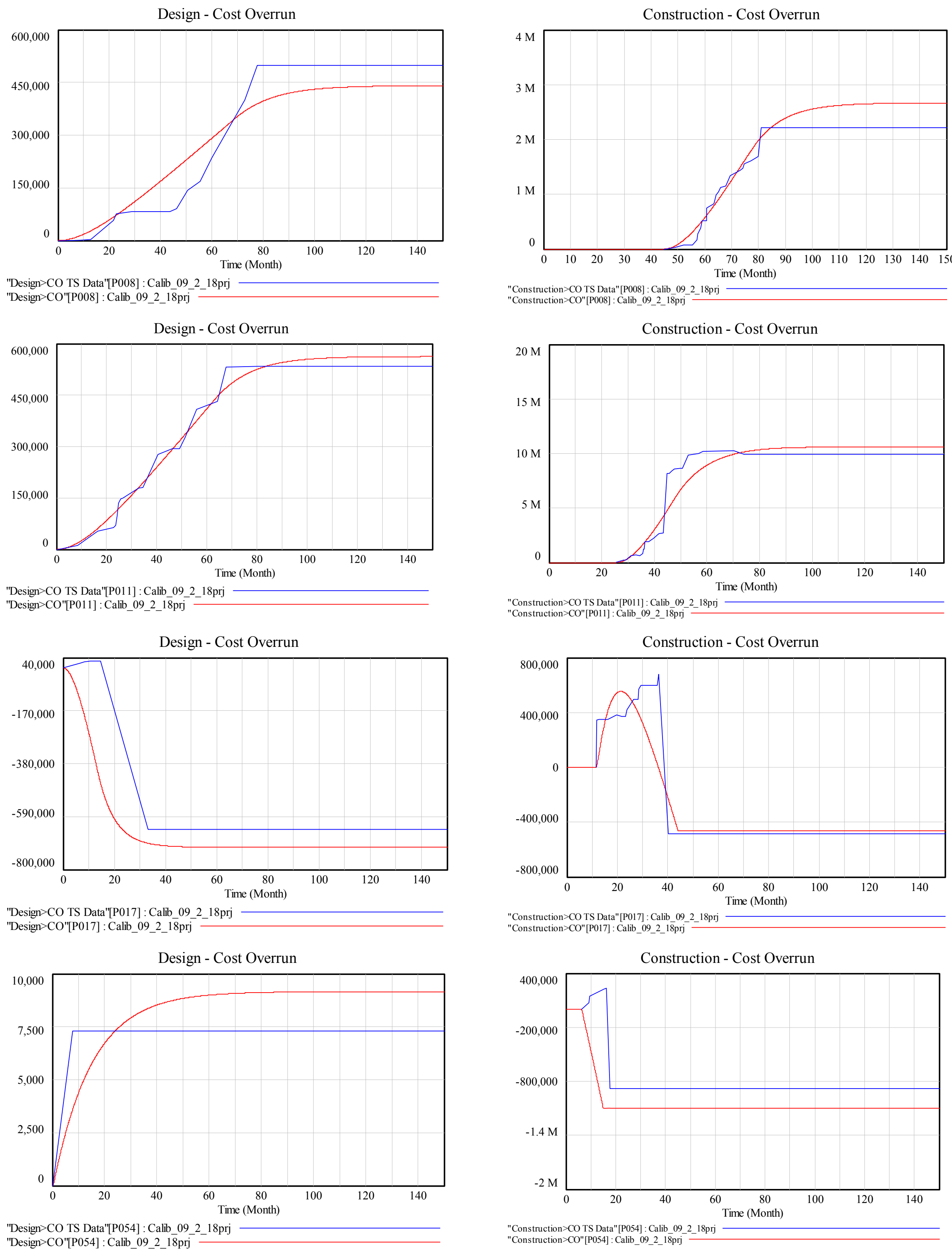
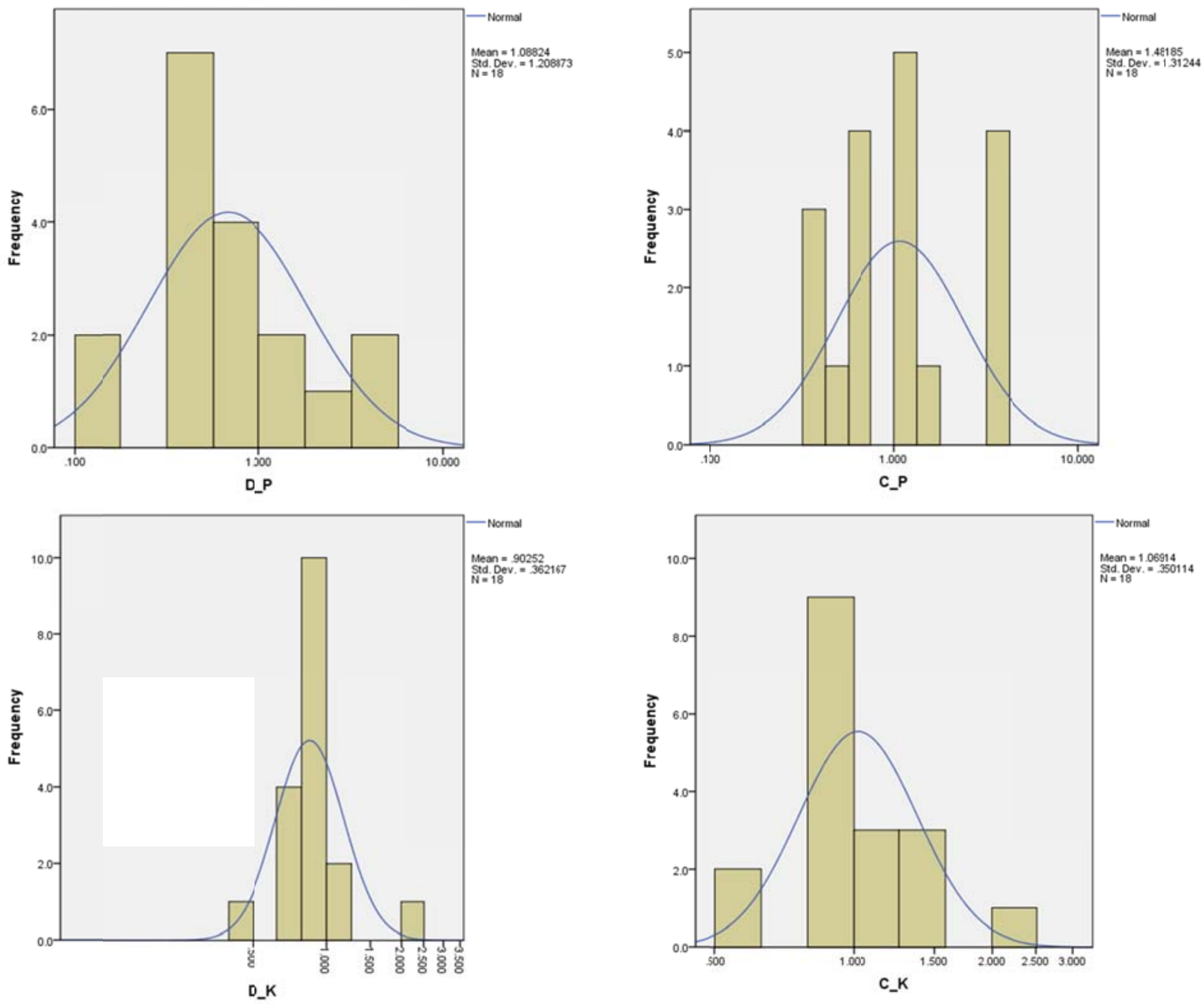


Figure 4: Examples of the cost overrun curves of the four calibration sample projects

Figure 5 reports on histogram for the estimated parameters across the 18 projects. The estimated value of parameter β came down to 1.239. It means 5%, 10% and 20% undiscovered design change decreases the construction quality of work 6%, 11% and 20%, respectively, which represents a relatively strong impact of undiscovered error on construction phase quality.



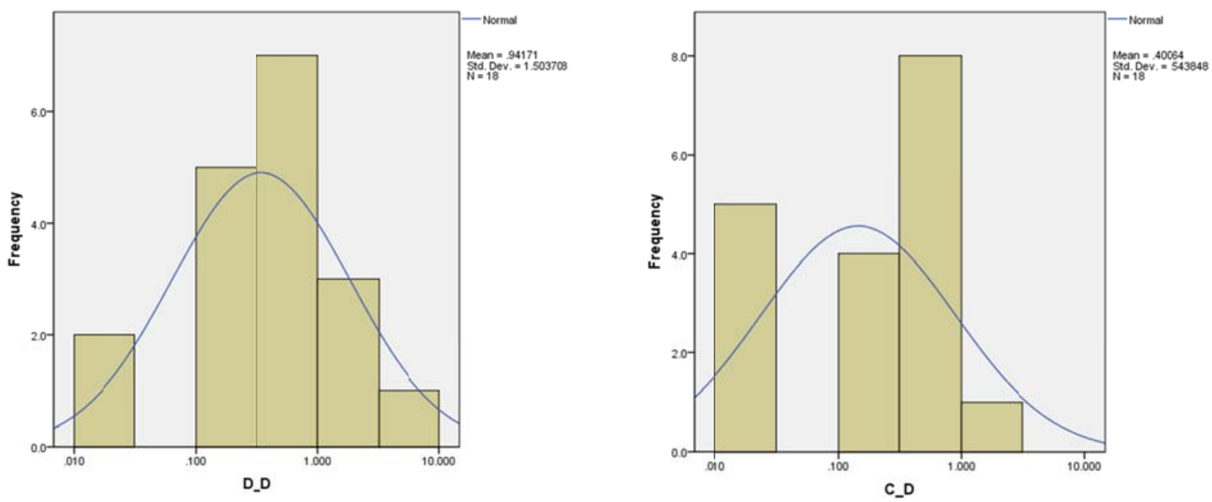


Figure 5: The calibrated parameter distributions in lognormal scale

Model Validation

To validate the model we would like to see if the model predictions, using the parameter estimates obtained in the estimation process, can provide reasonable predictions for the validation data set (15 other projects). For this assessment we first need to generate many simulated projects that draw their parameter values from distributions similar to those found in the estimated model, and then use those to create prediction ranges for the outcomes of the validation project sample. To this end we assume the project parameters are correlated lognormal random variables. The calibrated parameters of the 18 projects are used to find the best fitted random distributions for the project parameters. The variance-covariance method is used to generate 200 samples of the correlated random parameters. Each of the 15 validation sample projects is then simulated with the 200 randomly generated project parameters, given the original plans for that project. The simulation result is then compared with the actual data for those projects. Figure 6reports on the results of this test. Specifically predicted completion time and total cost fall within the 90% confidence interval produced by the empirical ensemble of 200 simulations in 90% and 97% percent of cases respectively.

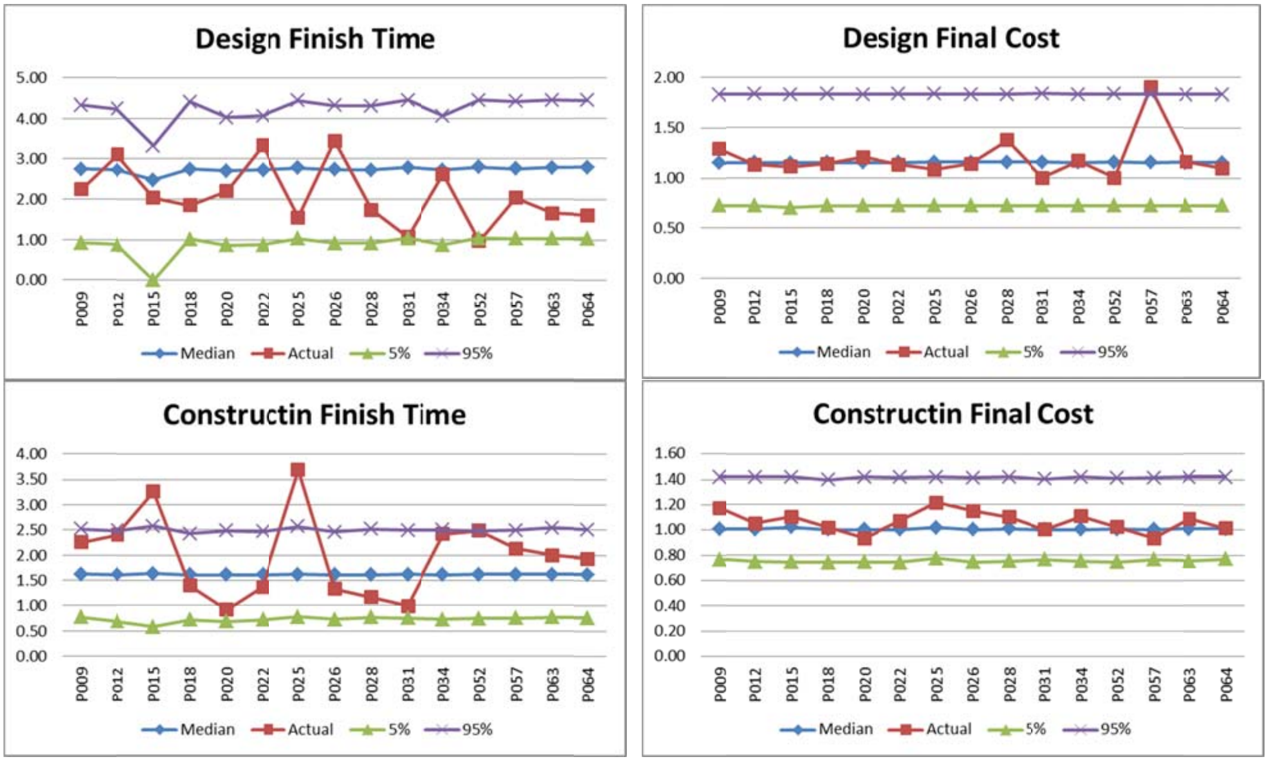


Figure 6: Validation results on the finish time and final cost

Impact of parameter β on payoff function

To investigate the significance of the parameter beta, sensitivity analysis is performed on the payoff function by changing the parameter beta. The payoff value is scaled by the payoff of the optimal solution at Beta= 1.239. The payoff value is the average of the simulated payoffs of the 33 projects. Figure 7 demonstrates that the payoff is convex with a sharp corner around the optimal beta. The sharp corner is the evidence of the meaningfulness of the optimal beta.

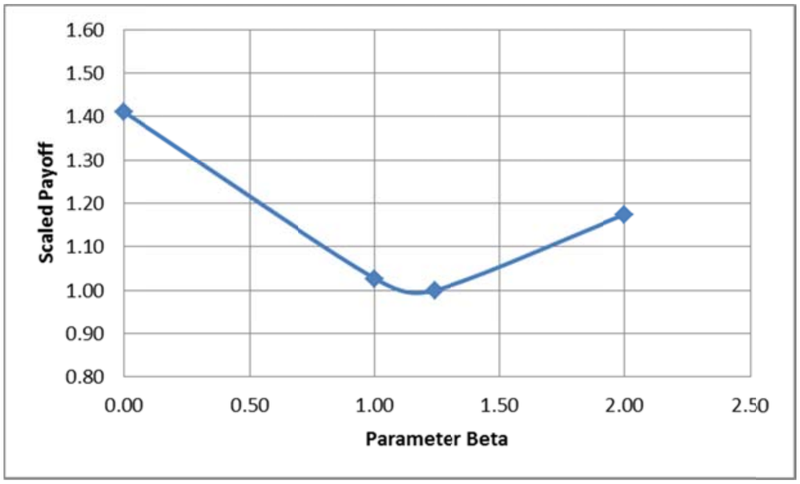


Figure 7: Behavior of the payoff function on Beta

Conclusion and discussion

In this paper we reported on an empirical estimation of a project model to data from 18 construction projects, followed by validation against a set of 15 projects. Overall the model performs very well in both matching the predicted projects, and providing reliable estimate ranges for the validation sample. This suggests the model can be used as a prediction and planning tool for other projects with similar characteristics. Moreover, we were able to estimate the impact of design phase undiscovered rework on construction phase quality. This paper therefore provides one of the first estimates for a feedback mechanism that has been hypothesized as influential by many previous researchers but has been hard to capture empirically.

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