



Inter-phase feedbacks in construction projects



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ABSTRACT

Understanding diverse performance trajectories of projects is of interest to operations researchers and practitioners. Interactions between multiple phases of a project are commonly assumed to be important in project dynamics, yet the strength of these feedback mechanisms has not been rigorously evaluated. In this study we use data from 15 construction projects to estimate the feedbacks between design and construction phases. The estimated factors reveal that undiscovered design rework diminishes construction quality and production rate significantly and construction completion speeds up the detection of undiscovered design rework. Together, these feedbacks can explain as much as 20% of variability in overall project costs. Comparison of model predictions with a separate set of 15 projects shows good predictive power for cost and schedule outcomes and their uncertainty. The estimation and prediction framework offers a template for using data from multiple cases to estimate both case-specific and industry-wide parameters of project models, and for leveraging those estimates for project planning.

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1. Introduction

Projects are critical to how modern organizations structure work. Moreover, faster product life cycles and increasingly global supply chains require firms to organize many steps of once routine operations, such as manufacturing and production processes, as projects (Gunasekaran and Ngai, 2012). Therefore, project management is increasingly an important part of operations management research and practice. Related operations literature has largely focused on designing algorithms for efficiently planning the execution of a project and offering decision support based on this algorithmic framework (Tavares, 2002). Besides this academic literature, practitioner knowledge communities, such as the Project Management Institute, have elicited and codified best practices and offer various training and certification options to individuals and organizations (Williams, 2005).

Despite the importance of projects and the management tools designed and applied by the research and practitioner communities, many projects fall short of their targets. From software (Moløkken and Jørgensen, 2003) to construction (Mansfield et al.,

1994), infrastructure (Flyvbjerg et al., 2003), and military applications (Drezner et al., 1993), delays, cost overruns, and quality problems have plagued many projects. For example, Standish Group's biennial surveys of the IT industry have found significant cost and budget overruns and cancellations in the majority of surveyed projects and a Procter & Gamble survey found that 15% of authorized projects cost over 50% more than the original budget (Scott-Young and Samson, 2008). Similarly, the U.S. General Accounting Office found cost overruns between 40% and 400% in a sample of 20 large infrastructure projects across 17 states (General Accounting Office, 2002). In fact, disagreements over projects' fates instigate many legal disputes (Callahan et al., 1990), some of them in the billions of dollars, and may even play a role in national politics (Pear et al., 2013).

Significant delays and cost overruns have motivated a more critical look at the assumptions that underlie operations research on projects. Specifically, the conventional project management paradigm is based on the decomposition of total project work into smaller, sequentially dependent tasks and algorithmic planning of the optimal sequencing and resource allocation within a project (Pollack, 2007). However, there is an increasing realization that projects include many uncertainties and structural, dynamic, and socio-political complexities (Checkland and Winter, 2006; Geraldini et al., 2011). These complexities require a more systemic approach that is able to incorporate organizational and

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psychological antecedents to project performance (Hong et al., 2004; Bendoly and Swink, 2007; Hagen and Park, 2013) as well as feedback loops and nonlinearities that may trigger unintended consequences of the conventional approach to project planning (Ackermann et al., 1997; Williams 2005; Lyneis and Ford, 2007; Mingers and White, 2010).

In response, research into understanding the root causes of project challenges has followed two complementary directions. Several empirical studies in this domain have used surveys of clients, contractors, and design personnel to assess the magnitude of cost and schedule overruns and their root causes (Mansfield et al., 1994; Assaf et al., 1995; Chan and Kumaraswamy, 1997; Flyvbjerg et al., 2003; Sambasivan and Soon, 2007; Scott-Young et al., 2008). A few common themes emerge from these studies. First, the quality and the extent of early design and planning are key to project performance. Second, factors that influence the quality of task implementation, from experience to technical complexity, are critical contributors to overall performance. Third, late changes requested by clients often lead to many ripple effects that cost the project beyond the direct cost of those changes. Finally, the leadership and team structure and incentives moderate the impact of project-specific factors on performance. Nevertheless, different survey designs, and recall and other biases associated with retrospective studies, complicate the quantitative integration of these findings to tease out different causal mechanisms responsible for project performance and to provide quantitative decision support.

A second research stream has applied simulation modeling to understanding project dynamics and improving project management (Lyneis et al., 2007; Mingers et al., 2010). From task interdependence, to design and implementation quality, testing, and intermittent change requests, projects involve tightly interconnected factors that interact over time to determine project performance. Starting with a model that informed the arbitration of a ship-building project lawsuit (Cooper, 1980), this line of modeling has grown to be one of the most successful areas of system dynamics (SD) practice (Lyneis et al., 2007). The rework cycle—the phenomenon of low work quality resulting in rework and change orders that extend required resources and duration—is at the core of project models and has ample empirical support (Hanna et al., 1999; Hanna and Gunduz, 2004; Ibbs, 2005; Moselhi et al., 2005; Alnuaimi et al., 2010; Jarratt et al., 2011). Moreover, from early on the modelers identified the importance of disaggregating these models to include multiple phases or task groupings (Lyneis et al., 2007). Formulating multi-phase project models was discussed in detail by Ford and Sterman (1998) and many applications have used different variants of this formulation in different industries (Lee et al., 2009; Park et al., 2011; Khoueiry et al., 2013). In this formulation each phase of the project is modeled with a separate rework cycle, with the knock-on effects of the quality and progress of each phase on the successive phases. Different effects could be conceived in this setup, the most prominent of which are the impact of early phase quality on later phase productivity, the effect of early quality on later quality, and the effect of later completion of tasks on the discovery of errors in earlier phases. These effects could then activate endogenous rework, schedule pressure, and morale feedback loops within different phases, leading to much variability in project performance, quality, and costs (Ford et al., 1998; Lyneis et al., 2007). However, the strengths of these feedback mechanisms have been assumed based on qualitative knowledge or single case study estimates. Rigorous and multi-project empirical estimates are lacking in the literature, partly due to limited data. Yet such estimates are critical for understanding the relative impact of different dynamic mechanisms that underlie project performance heterogeneity.

A few statistical studies have analyzed the latent impact of

design error on the construction phase. Burati et al. (1992) reported that design defects are responsible for 79% of total change costs, and 9.5% of total project cost. Cusack (1992) showed that documentation errors increase project costs 10%. Hanna et al. (2002) found that design errors lead to 38%–50% of change orders in the projects they studied. And recently, Lopez and Love (2012) showed that the average of direct and indirect costs for design errors is about 7% of contract value. Nevertheless, estimates that clearly delineate the different causal pathways through which design errors influence the quality and productivity of construction work are lacking.

Moreover, the impact of these feedbacks is most relevant in the context of their interaction with other feedback mechanisms in the project dynamics. For example, design quality problems may lead to construction delays exacerbating burnout and morale problems, which can lead to further deterioration of construction quality and a more salient rework problem. Capturing such interactions is necessary for understanding the many instances of late and failed projects and requires a dynamic modeling framework that provides reliable estimates of the interacting factors.

In this study we develop a system dynamics model of project dynamics, empirically estimating both project-specific parameters and industry-wide inter-phase feedbacks. In light of the important roles these feedback effects play in many project models, a reliable quantitative estimate will deepen our theoretical understanding of the causal pathways in project performance, allow us to assess the relative role of these feedbacks in project performance heterogeneity, and strengthen the practical models for project planning and project dispute resolution. Moreover, our methodological approach provides a blueprint for estimating and using project-specific and industry-wide parameters of dynamic models across other contexts, such as software, energy, infrastructure, military, and aerospace projects.

2. Data and methods

In this study, we quantify the design-construction feedback relationships in design-bid-build (DBB) construction projects. In contrast to concurrent design and construction, DBB is a project delivery method in which design services to produce construction documents (CD Design) are performed separately from, and before, actual construction. Moreover, in the construction phase a design firm—usually the same firm that was hired for the design phase—is hired to provide inspection and design services during construction. While overlapping design and construction is common in construction projects due to their time savings (Ford and Sterman, 2003a,b), the institution owning the projects in our sample opted for DBB to reduce the risk of unanticipated iterations.

A generic dynamic model with two phases of design and construction is developed based on the SD literature. Historical data from 30 building construction projects is used to estimate and validate the model. The model is calibrated with 15 randomly selected projects and the other 15 projects are used for validation. The calibration process is used to estimate three distinct effects: (1) impact of design quality on construction quality, (2) the effect of design quality on construction productivity, and (3) the effect of construction progress on error discovery rate in design. The validation process verifies the feasibility of using simple SD models to estimate the likely distribution of project outcomes for new projects, a key step in project planning activities.

2.1. Data

A sample of thirty small-to-medium-sized projects was selected from a public university construction project archive. Data from

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