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Modeling the Dynamics of a Tunnel Construction Project

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Abstract

Even when properly employing traditional project management techniques and tools parties involved in construction projects regularly face many unexpected issues. These issues cause low project performance and poor project outcome. This paper presents a simulation model to capture the dynamics of construction projects in the construction phase. Eight key feedback structures are formulated as dynamic hypotheses. A formal simulation model is mathematically developed in terms of stock and flow maps. The model is then calibrated for a tunnel construction project. Tests show that the simulated behavior of the model and the actual behavior of the project are similar. This implies that the model is able to simulate the dynamics of the project and, thus, to enhance project control.

Keywords

Project Management, Dynamic Modeling, Simulation, System Dynamics

1. Introduction

Large infrastructure projects are typically intricate being executed in uncertain conditions. They are dynamic systems which are (i) very complex, consisting of multiple interdependent components, (ii) highly dynamic, (iii) involve multiple feedback process, (iv) have nonlinear relationships, and (v) require both "hard" and "soft" data (Sterman, 1992). Construction project management is therefore very challenging and extremely sophisticated. Work breakdown structure, network-based techniques, and earned value method have been playing critical roles in many areas of project management: planning, scheduling and control. However, their drawbacks have been documented in many previous studies. The aim of this paper is to present a system dynamics model as a promising tool for contractors to experiment with the overall effects of project-related policies. Next, the model is calibrated for a tunnel project under construction to form a specific context and to capture the dynamics of the project.

2. Related Work

System dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems (Sterman, 2000). In the context of project management, system dynamics can be the most successful technique for building top-down holistic models (Williams, 1999). Rodrigues and Bowers (1996) listed various factors to motivate the applications of system dynamics to project management. They include: (i) a concern to consider the whole project rather than a sum of individual elements, (ii) the need to examine major non-linear aspects, (iii) a need for a flexible project model offering a laboratory for experiments with management's options, and (iv) the failure of traditional analytic tools to solve all project management problems and the desire to experiment with something new.

Most applications of system dynamics in project management have been confined to R&D and software development. Cooper (1980) developed and applied a computer simulation model to resolve a $500 million shipbuilder claim against the US Navy. In construction attempts have been made to model the dynamics of construction projects. Chang (1990) developed a construction project model based on the R&D project model by Richardson and Pugh (1981). Systems dynamics modeling has also been applied in design management (Ogunlana et al., 1998), disruption and delay (Eden et al., 2000), design and build (Chritamara et al., 2002), and contingency management (Ford, 2002). To some extent, these studies have attempted to resolve several dynamic problems encountered on complex construction projects. However, other dynamic features of large construction projects need to be further investigated.

3. Methodology

System dynamics modeling, as a part of the learning process, is interactive: a continuous process of formulating hypotheses, testing, and revision, of both formal and mental model (Sterman, 2000). This research has adopted the modeling process proposed by Sterman (2000). This disciplined process involves the following activities: (i) articulating the problem to be addressed, (ii) formulating a dynamic hypothesis or theory about the cause of the problem, (iii) formulating a simulation model to test the dynamic hypothesis, (iv) testing the model until you are satisfied it is suitable for your purpose, and (v) designing and evaluating policies for improvement. Vensim® PLE software is adopted for the tasks of system dynamics modeling such as building causal loop diagrams, stock and flow maps, an elaborate model, testing, simulation, and policy analysis. Further details of the system dynamics modeling process are available elsewhere (Richardson and Pugh, 1981 and Sterman, 2000). This paper presents the model with a focus on model formulation, validation and calibration since the whole process is rather long.

4. Key Feedback Structures

Based on previous project models and construction practice, eight key feedback structures are hypothesized about the dynamic behavior of construction projects in the construction phase. They create a conceptual framework for understanding of project behavior and a foothold for the model formulation. Basically, the four feedback structures, namely, labor, schedule, rework, and quality, are adapted from Ford (1995) and fitted into the characteristics of construction projects. The other feedback structures, namely, equipment, material, manpower-equipment interaction, and safety, are developed in this research.

Details of these feedback structures are available in Long (2003). For examples, the structure of manpower-equipment interaction (Figure 1) demonstrates adjustments so that labor progress and equipment progress are balanced. In construction, work cannot be performed in the absence of either manpower or equipment. Moreover, for smooth and efficient operation, there is need to incorporate these two resources in a logical manner. Sometimes, the labor and equipment progress rates are out of synch. Certain corrective actions are necessary. This feedback structure captures these situations and actions. When "progress of labor relative to equipment" is not equal to zero; for example, positive, it implies that labor progress is higher than equipment progress. Then, the general management policies are to reduce manpower or to input more equipment or both. These two policies are reflected in the "labor adjust" and "equip adjust" balancing feedback loops, respectively.

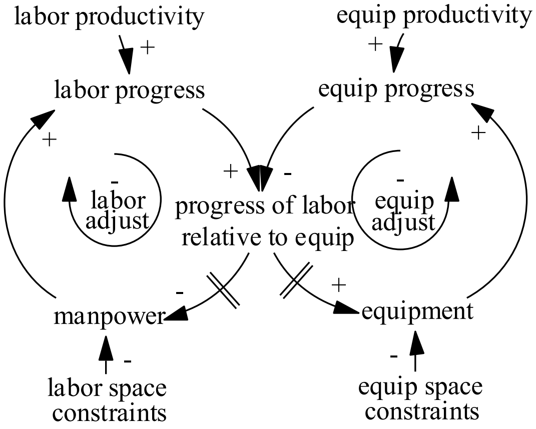

Figure 1: The Structure of Manpower and Equipment Interaction

5. The Case Study

The model is calibrated for a tunnel project to devise realistic model boundary, assumptions, parameterization and validation. The project used in this research is a road tunnel project built through a huge pass in Vietnam. The main transport tunnel is a two-way road 6,247m long, 11.9m wide and 7.5m high. At the time of the data collection, the project has been under construction for 28 months being scheduled to be finished within 48 months of construction. The first of the two main contracts, worth US$43 million and covering the 3,857m northern part of the tunnel, is used in this research. The contract has suffered time delays, cost overruns and other problems. The current tempo of construction has been slower than expected. In addition, several labor strikes have occurred due to increasing working hours (overtime), lowering pay and dangerous work conditions. From the interview, it was revealed that the contract was less profitable than initially expected and even must face cost overruns. The owner was also expected to give three more months for extension of time.

Data collection included project documents and records, field observations and structured interviews. Data was collected on (i) project information, (ii) problems encountered (budget status, schedule status, rework, etc.), (iii) actual performance (work accomplished, progress, resources, working time, etc.), and (iv) common management policies. Project managers were involved in structured interviews to gain insight into the problems encountered and to obtain soft data (worker behavior, effect of worker's fatigue on productivity, etc.) that could not be obtained from project documents.

6. Model Boundary

The model is bounded in the construction phase and for the main contractor. An important assumption is that tasks are uniform in size, replaceable and small enough to be flawed or correct but not partially flawed (Ford, 1995). Moreover, this assumption is more accurate when task size is small. Thus, relatively small parts of construction work are designated as tasks. As a characteristic of the system dynamics approach, the model boundary assumes continuous flow of the project environment, process and organization during the construction stage. For example, probability of rework discovery can be considered as a constant to describe the average probability during the construction stage for simulation.

Resources of project implementation are divided into manpower, equipment and materials. Manpower is classified into unskilled workers, skilled workers and management team. This assumption is reasonable even though manpower is categorized into more types in practice. Equipment is assumed to consist of major equipment and supportive equipment. Major equipment implies indispensable and/or productive equipment that directly contributes to reduction in tasks remaining and is costly. It cannot be replaced or is difficult to replace with workers. Supportive equipment implies portable and other equipment and tools that are indirectly involved in the progress of work and are less costly. Again, there are many kinds of equipment and plant during the construction stage. However, that assumption is acceptable in managing projects at the strategic level. Materials are aggregated into a single material type. This reflects an assumption that different materials such as concrete and rebar are combined in certain proportion to reinforced concrete. Other primary model assumptions are available in Long (2003).

7. The Model Structure

The model consists of several variables and equations. It is preliminarily divided into the six subsystems scope, progress and rework, resources, performance, cost breakdown and objectives control. Also, each subsystem can be divided into sectors or sections. These subsystems and sectors are interrelated in the form of shared parameters. Progress and rework can be grouped into a subsystem since they have a special interrelation. When a project work is performed, rework is likely to occur. Resources consist of manpower, equipment and material. The resources subsystem models the distribution of quantities over time. Labor productivity, equipment productivity, experience, safety, quality of practice, work-month, and supervision are grouped into a subsystem - performance. Project costs are broken down into material, manpower and equipment costs. Project objectives are, of course, many. However, contractors and other parties seem to focus primarily on time, cost and quality. The model, therefore, focuses on these main objectives aggregated into objectives control subsystem. Figure 2 displays progress and rework subsystem as an example. The main equations of this subsystem are given in the Appendix section.

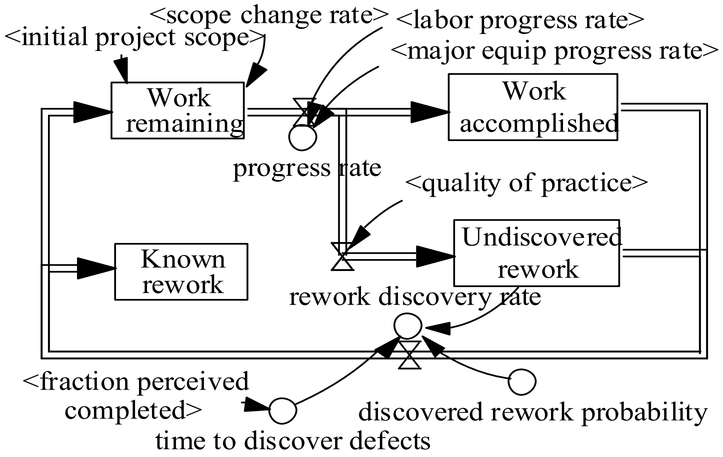

Figure 2: Progress and Rework Subsystem

8. Model Behavior

An important characteristic of system dynamics is that it focuses on behaviors of variables over time rather than their values. Exact parameter values and simulation output are not as important as an intuitive understanding of the impacts of the model's structure on its behavior (Ford, 1995). A series of simulation results over time help understand the model behavior. The input for the base run was obtained from the tunnel project. In the base run, the project is finished after nearly 52 months of the construction. In comparison with the 48-month construction of initial project deadline, the project is delayed 4 months. In the model, one task is equivalent to 0.3857 m length of the tunnel and hence the contract studied has 10,000 tasks. The behavior of the variables from the simulation is practical and meaningful.

During the simulation, work remaining decreases gradually while work accomplished and known rework have S-shaped growth (Figure 3). Undiscovered rework seems to have "overshoot and collapse". It can be explained that at the first months of construction, waiting time for inspection is longer than in the last months. This is reflected in the variable - time to discover defects – as a lookup function. That is, near the end of construction stage, flawed work is increasingly discovered.

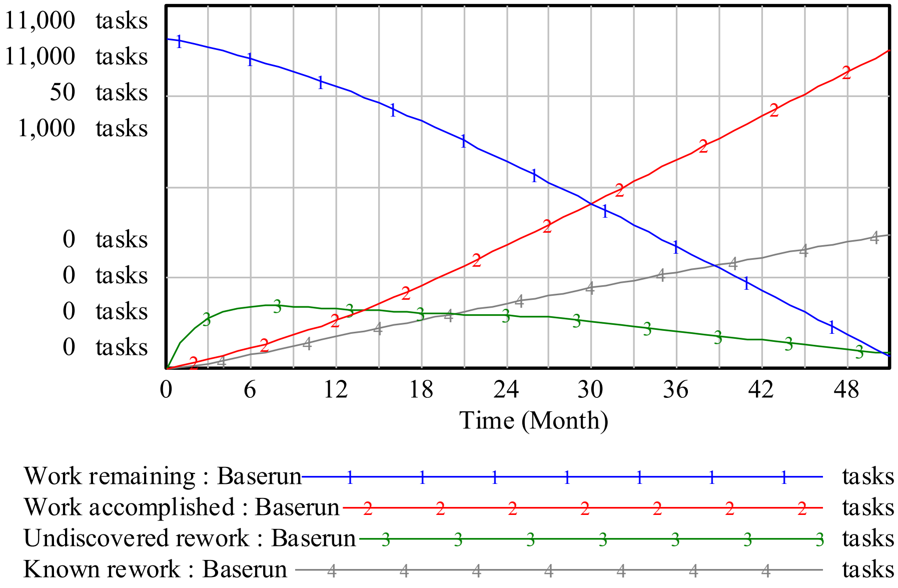

Figure 3: Behavior of Work and Rework

9. Model Testing

In system dynamics modeling, a variety of specific tests have been developed to uncover flaws in models and to improve them. Sterman (2000) summarized twelve main tests and their various purposes. They are: boundary adequacy, structure assessment, dimensional consistency, parameter assessment, extreme conditions, integration error, behavior reproduction, behavior anomaly, family member, surprise behavior, sensitivity analysis, and system improvement. The full procedures for these tests are available in Long (2003) and they confirm the suitability and consistency of model structure and behavior with the case study project.

10. Conclusions

Infrastructure projects interact with various aspects – social, economical, managerial, technological and environmental. These aspects are dynamic in nature and hence their impacts on project behavior are also dynamic. Traditional techniques center on the static side of project management. Thus, it is difficult to capture the behavior of construction projects at a holistic overview. Therefore, the model presented in this paper facilitates contractors to more easily understand the dynamics of projects.

When the model is calibrated in the tunnel construction project, the simulated behavior and historic behavior are similar as long as an appropriate parameterization is undertaken. This implies that the model can simulate the dynamics of the project. The understanding of the project dynamics and the process of project control are obvious. The contractor can consequently use the model to formulate and evaluate policies for project performance improvement by properly changing the values of parameters and/or model structures.

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12. Appendix

Work remaining = INTEG (-progress rate + rework discovery rate + scope change rate, initial project scope) (tasks)
Work accomplished = INTEG (progress rate - rework discovery rate, 0) (tasks)
Undiscovered rework = INTEG (progress rate*(1-quality of practice)-rework discovery rate, 0) (tasks)
Known rework = INTEG (rework discovery rate, 0) (tasks)
progress rate = MIN (labor progress rate, major equip progress rate) (tasks/month)
rework discovery rate = (Undiscovered rework/time to discover defects)*discovered rework probability (tasks/month)