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INCREASING REALISM OF CONSTRUCTION SIMULATION THROUGH INTEGRATION OF OPERATIONAL AND MANAGERIAL ASPECTS

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ABSTRACT: Current construction simulation approaches mostly focus on operation aspects of construction projects, ignoring managerial aspects which can radically change operational profiles (e.g., number of resources, expected productivity level, or daily working hours) during the course of construction. As a result, these approaches may mislead construction managers into unrealistic execution plans as well as make them difficult to find potential performance improvement areas. As an effort to address this issue, this paper establishes a comprehensive construction modeling framework which integrates operational and managerial aspects of construction projects. The proposed modeling framework will provide construction managers with more accurate, more reliable, and more realistic simulation results thus reducing the likelihoods of schedule delays and cost overruns.

Keywords: Simulation; Modeling Framework; Operational Planning; Managerial Response

1. INTRODUCTION

Schedule delays and cost overruns are the rule rather than the exception, particularly in large-scale construction projects [1][2]. These are global phenomena which have persisted over the past 70 years [3]. Among the numerous possible reasons, non-value adding activities (NVAAs) have been pointed out as the primary component that contributes to schedule delays and cost overruns in construction projects, where NVAAs are defined as activities that take time and resources (i.e., cost) but do not add any value [4]. Taking into account that 49.6% of the operational time is devoted to NVAAs [5], it is certain that successful execution of a construction project is directly related to the ability to minimize NVAAs.

To minimize NVAAs, construction researchers have strived to identify root causes of NVAAs. Koskela [4] who first coined the term of NVAAs into construction claimed that variation, defined as the difference between planned and actual production rate, is one major catalyst triggering NVAAs in construction projects. In fact, variation is a function of a highly stochastic nature of construction environments and is the major factor which sets the management of construction projects apart from project management in other fields of endeavor [6]. As such, variation is too tenacious to be completely eliminated from construction environments. Furthermore, the negative impact of variation can be dramatically amplified with higher interdependency [7]. Based on this recognition, understanding and managing the combined impact of 'variation' and 'interdependency' has been a primary concern of construction management researchers and practitioners [8].

2. CURRENT APPROACHES

CPM/PERT (Critical Path Methods/Program Evaluation & Review Techniques) is the de facto standard applied for scheduling and monitoring in the construction area [9][10]. Kelleher [11] surveyed ENR's Top 400 contractors and reported that 98% of the respondents used the CPM/PERT to some extent. Despite its wide spread application in the construction management area, the combined impact of variation and interdependency, is incompletely understood and poorly modeled through the CPM/PERT [12]. This is the main reason that high incidence of schedule delays and cost overruns occur in large-scale construction projects which are characterized by higher variation and interdependency.

In order to better understand and analyze the combined impact of variation and interdependency, several simulation-based models have been developed [12][13][14]. Conceptually rooted in Goldratt's "boy-scout hike" model [15], these models have been further developed in computer-based simulation environments which enable stochastic analysis of the combined impact of variation and interdependency in faster and more comprehensive ways. Interested readers can find further detailed information in literature [12][13][14].

These simulation models effectively visualized correlation between the combined impact and project performance and as a result, enhancing managers' intuitive understanding on construction production systems [12]. These simulation models, however, disregard managerial responses to environmental variations. In practice, if an intolerable variation takes place during construction (e.g., a significant schedule delay is expected due to erroneous execution), managers typically adopt corrective actions to annul the impact of variation (e.g., hiring more workers in order to finish the project within its expected completion date) [16]. This becomes more probable, particularly in large-scale

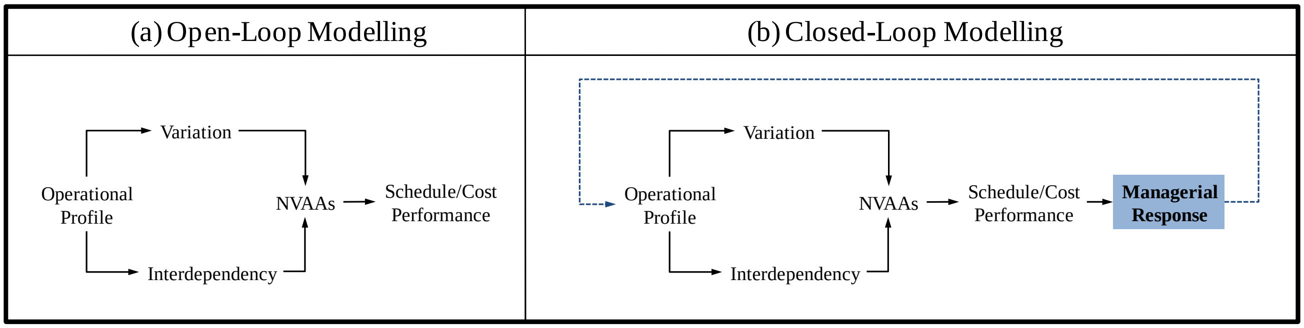


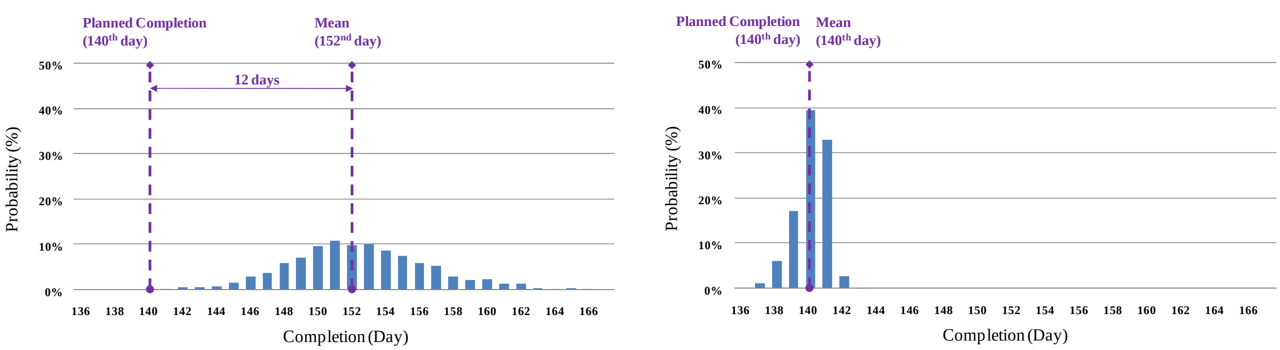
Figure 1. Open-Loop Modeling vs. Closed-Loop Modeling

complex fast-track construction projects where negative impact of variation can be dramatically amplified through higher interdependency [7]. Such managerial actions can radically change operational profiles (e.g., number of assigned resource) making their effects apparent in forecasting project performance [17].

From the perspective of modeling, current construction simulation models assume variation and interdependency as 'exogenous independent system variables', which are set before the execution of the model and unchanged during the running of the model while they have been conceived as the two most important factors governing project performance. Unlike this assumption, in practice, both variation and interdependency can be highly affected by managerial actions taken during construction. This implies that both variation and interdependency should be converted into 'endogenous interdependent variables' from 'exogenous independent system variables' by incorporating the managerial actions. In other words, construction production systems should be understood and modeled as 'closed-loop systems' (Figure 1-(b)), not 'open-loop systems' (Figure 1-(a)) on which current construction simulation models are mostly based.

incorporating managerial responses to schedule variation which is defined as difference between cumulative planned progress and cumulative actual progress. The framework forecasts project completion date at every time step, based on cumulative productivity (i.e., cumulative work done divided by time spent) and the remaining work. If the difference between the forecasted and the planned completion date is out of tolerance, managerial actions would be taken to expedite the progress and to finish the project within or on the planned completion date. Among numerous actions for expediting delayed progress in construction, this paper focuses on the three most popular control actions; 1) adopting overtime, 2) increasing overlapping between activities (i.e., reducing safety buffer between activities), and 3) hiring more workers.

Figure 2 shows comparison of stochastic simulation results (1,000 runs) between the open-loop modeling and the closed-loop modeling case. While the open-loop modeling case (Figure 2-(a)) exhibits a wide symmetric distribution with the mean value of 152nd day which is 12 days delayed from the planned completion date (140th day), the closed-loop modeling case (Figure 2-(b)) yields



(a) Open-Loop Modeling (b) Closed-Loop Modeling

Figure 2. Simulation Results Comparison of Open-Loop and Closed-Loop Modeling

3. COMPREHENSIVE MODELING FRAMEWORK

Founded on the concept of the 'closed-loop modeling', a comprehensive construction modeling (COCOMO) framework was developed. The COCOMO framework was further developed from Alarcón and Ashley [13] by

a narrow symmetric distribution with the mean value of 140th day which is the planned completion date.

These simulation results show that managerial actions can bring positive effects to annul the combined impact of variation and interdependency, and increase the surety of meeting the planned completion date. These positive effects are the direct reasons why construction managers closely monitor their project performances and take corrective actions when needed. In this sense, the closed-

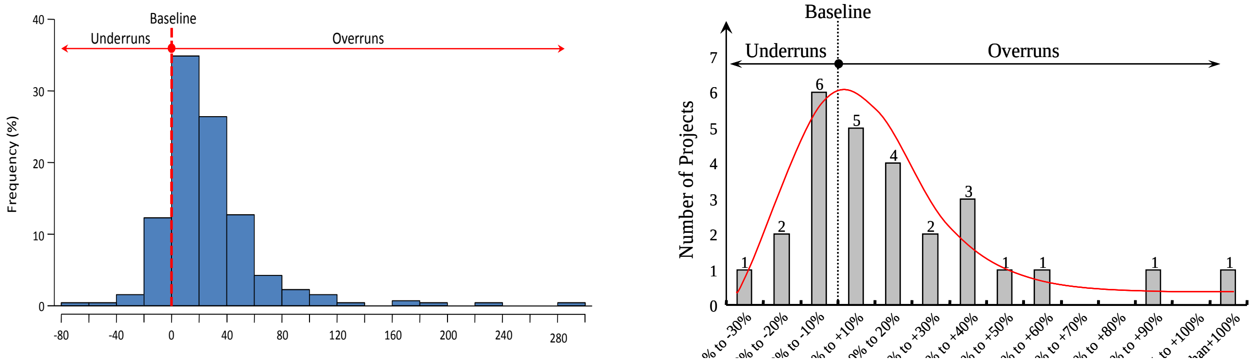


Figure 3. Real Observation

loop modeling is meaningful in terms of incorporating managerial responses as well as operational profiles. However, the simulation results in Figure 2-(b) are closer to construction managers' expectation from managerial actions, rather than to project realism. As shown in Figure 3-(a) and (b) in common, real observation shows that overruns are the norm while underruns seldom occur [3][18]19].

This inconsistency between the model results and real observation suggests that important modeling elements were missing in the proposed model. Review of literature and interview with construction practitioners identified that managerial actions do not always bring intended positive effects on project performance, but sometimes can trigger unintended negative effects. Particularly under high schedule pressure, these actions can often negatively affect project performance [20][21][22]. For example, overtime may increase workers' fatigue, accordingly decreasing productivity [23]. Also, increasing overlapping may make construction environments more prone to generate non-productive time and to demoralize supervision [22]. Finally, hiring more workers may trigger congestion problems and require much coordination effort [27]. In addition to these problems, these actions may result in quality deterioration under high schedule pressure.

Based on this recognition, the concept of the closed-loop modeling was modified by embracing the possibility that managerial responses can bring unintended negative effects on project performance. As shown in Figure 4, managerial actions are regularly taken in order to increase the surety of meeting the scheduled completion date, changing operational profiles (i.e., mostly increasing production rate); however, these actions can trigger further variation due to productivity loss, demoralization, or coordination problems as well as increase interdependency which can amplify the negative impact of the variation. Therefore, effectiveness of managerial actions might be much lower than the managers expected.

Rooted in the modeling concept shown in Figure 4, the enhanced closed-loop model was further developed and simulated 1,000 times again and Figure 5 shows its stochastic simulation results. Unlike the simulation results of the open-loop modeling (Figure 2-(a)) and the closed-loop modeling (Figure 2-(b)), Figure 5 shows a right-skewed distribution which is well matched with real observation shown in Figure 3-(a) and (b). Also, its mean value is 145 days which is 5 days delayed from the planned completion date. These simulation results are significant in terms of not just yielding a right-skewed distribution which is shown in real observation but also explaining the possibility of schedule delays despite construction managers' best effort to keep the planned completion date.

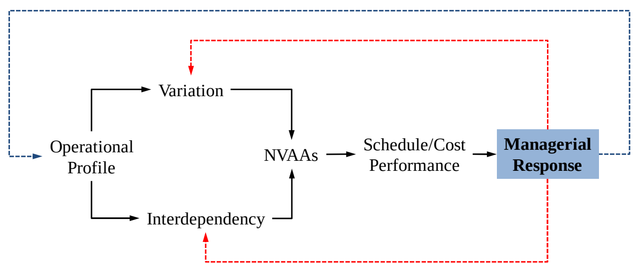


Figure 4. Enhanced Closed-Loop Modeling

Also, these simulation results corroborate that construction performance is not simply governed by the combined impact of variation and interdependency but also significantly affected by effectiveness of managerial actions to annul the combined impact. Therefore, in order to increase realism of construction simulation, it should incorporate both operational and managerial aspects and analyze their complex interactions. Then, it can be utilized as a 'realistic' test-bed to assess and analyze the current performance, to forecast trajectories of future performance, and to simulate the effectiveness of control actions under different what-if conditions.

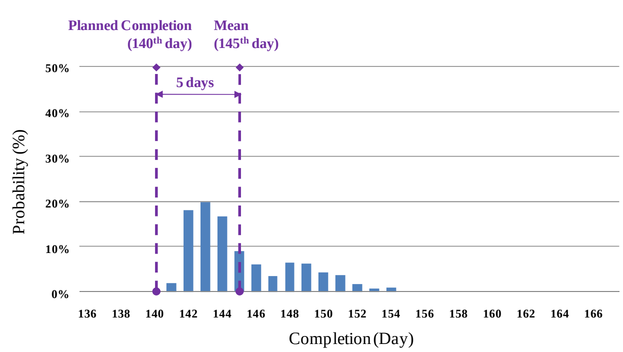


Figure 5. Simulation Results of the Enhanced Closed-Loop Modeling

4. CASE STUDY: THE BIF PROJECT

To validate the applicability of the COCOMO framework, a building project at the University of Illinois was selected and analyzed as a case study project. The title of this project is Business Instructional Facility (BIF) project and it was selected for two major reasons. First, the BIF project, like other university building projects, had been undertaken with an extremely strict deadline where construction managers were willing to take schedule recovery actions at the sacrifice of cost or even quality. Second, the BIF project involved several repetitions of "trades" (e.g., concrete work, steel work, mechanical/electrical/plumbing (MEP) work, masonry work, and windows/doors work) where the combined impact of variation and interdependency were apparent. For these reasons, the BIF project was ideal to examine managerial responses as well as the combined impact of variation and interdependency.

Its construction began on May 15th 2006 and its substantial completion was forecasted to be May 13th 2008 at that time. This schedule could give the University approximately three months to check over the project and arrange everything in time for the start of classes in August of 2008. As of March 18th 2008, its actual progress, despite the construction management team's best effort, has been significantly delayed. Several reasons of the schedule delay in the BIF project were identified through examining relevant project documents as well as interviewing key project personnel including construction manager, project manager in the University, designer, and several superintendents. The identified reasons include 1) design errors, 2) frequent change orders, 3) long RFI (Request for Information) and approval time, 4) lack of constructability, and 5) lack of management team's experience. For example, 4 inch concrete blocks were initially designed to be placed between double-paned windows of its exterior walls, but were later found to be insufficient to support structural loads on the walls. It took 6 months to redesign the walls (i.e., variation), and no drywall installation could be executed for the interior of the building during that time (i.e., propagation of variation through interdependency).

Due to all above-mentioned reasons, as of March 18th 2008, the substantial completion date of the BIF project has been pushed back to August 1st 2008. This is the absolute deadline which cannot be further extended, giving the University only three weeks to move into the new building. Under this schedule pressure, construction management team has regularly revised the schedule with corrective actions. The management team has crashed everything possible in the schedule to meet the absolute deadline as close as they can. In addition, in order to avoid any potential delay, they have attempted to start all remaining activities as early as possible, even though some activities had extra float time. Some out-of-sequence activities were also undertaken. For example, interior walls were installed before the steel roof was fireproofed. On fireproofing the steel roof, the interior walls had to be protected and this significantly increased extra work, accordingly introducing further variation.

Figure 6 shows summary history of schedule revision in the BIF project from November 15th 2006 to November 1st 2007. While the schedule has been revised every month, Figure 6 shows schedule revision of every three months in order to avoid visual complexity. Figure 6 shows that impact of variation (e.g., design errors) was not apparent at earlier stage (Figure 6-(A)). On the mid-stage where numerous trades were interdependently undertaken, its impact became more apparent due to the interdependency among several activities (Figure 6-(B)). Because of this compounding effects through interdependency, schedule variation has repeatedly occurred and the substantial completion date has been pushed back in spite of construction managers' continuous effort to keep the deadline. Furthermore, the more the schedule was revised, the lazier S curve its progress showed. This pattern means that the remaining activities should be undertaken in more time-compressing environments (Figure 6-(C)) where schedule recovery actions can trigger unintended side-effects (e.g., productivity loss or quality degradation) due to higher schedule pressure. Considering this unreliable execution environment at the later stage, it seems that the probability of finishing this project before the deadline is not too high unlike construction management team's expectation.

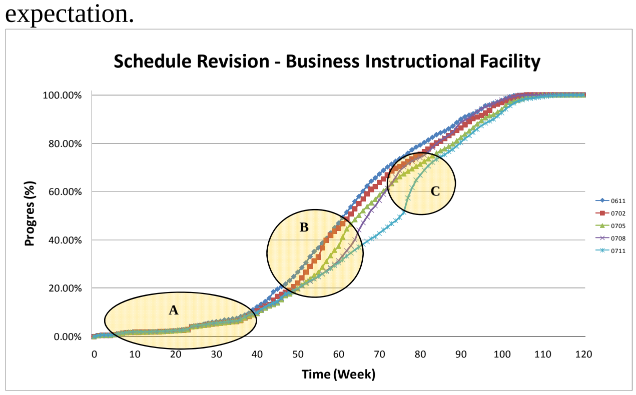


Figure 6. History of Schedule Revision in the BIF Project

5. SIMULATION RESULTS

In order to accurately forecast the completion date of the BIF project, all relevant data was gathered by interviewing key project personnel as well as reviewing project document including schedule revision history. As previously addressed, major reasons of schedule variation were identified as 1) design errors, 2) frequent change orders, 3) long RFI (Request for Information) and approval time, 4) lack of constructability, and 5) lack of management team's experience. Also, it was identified that overtime, shift-work, and increasing overlapping had been extensively utilized for recovering the delayed schedule. With this input data, initial simulation result was obtained. Then, parameters used in the model were calibrated by comparing the reported cumulative progress and the simulation result. Finally, trajectory of future progress was forecasted based on the current trend.

Figure 7 shows comparison of 1) initial schedule, 2) actual cumulative progress so far, 3) expected future progress (by the management team), and 4) simulated progress (by the proposed COCOMO framework). As represented in Figure 7, the actual progress is much behind the planned progress. The project started to be delayed when 5% of the project was completed (Figure 7-(A)). This is mainly because numerous activities started to be concurrently undertaken from this point. Due to the combined impact of variation and interdependency, the project was significantly delayed. Although about 45% of progress was initially planned on the 280th working day (Figure 7-(B)), only about 25% was actually completed. So far, about 50% of the project has been completed (Figure 7-(C)) and the construction managers are planning to expedite the remaining activities as much as possible. The most recently revised schedule expects the completion date to be August 1st 2008 (Figure 7-(D)). However, the simulation results obtained from the COCOMO framework shows a more pessimistic prediction saying its completion date would be late November 2008, unless the management team changes the project control policies (Figure 7-(E)). The reason for this pessimistic prediction is attributed to unintended side effects that can be triggered by adopting recovery actions in a time-compressing environment. Since such a completion date cannot be accepted, it is expected that construction management team would take more and more recovery actions in order to meet the deadline and these actions would lead them to working in a more chaotic and less-productive environment.

Eventually, the BIF project was barely finished just before the start of fall 2008 semester with three-shift work. While the teaching units including classrooms were opened for classes of fall 2008 semester, the faculty members' movement to the new building was postponed. Also, two of water pipes were ruptured after opening the building, requiring substantial rework and working on weekends had continued for one more month. This shows that recovery of schedule variation can be much more difficult than construction managers expected, especially when the recovery actions can trigger further variation due to interdependency and unintended side-effects. However, construction managers (at least in the BIF project) tended to underestimate these negative effects and accordingly, encountered schedule variation again and again in spite of their continuous revision effort. This case study shows that the proposed COCOMO framework, unlike managers' optimism, can assess project performance from a more objective perspective and the framework has a great potential to support construction managers in making their critical decisions by providing a more accurate, more comprehensive, and more realistic prediction.

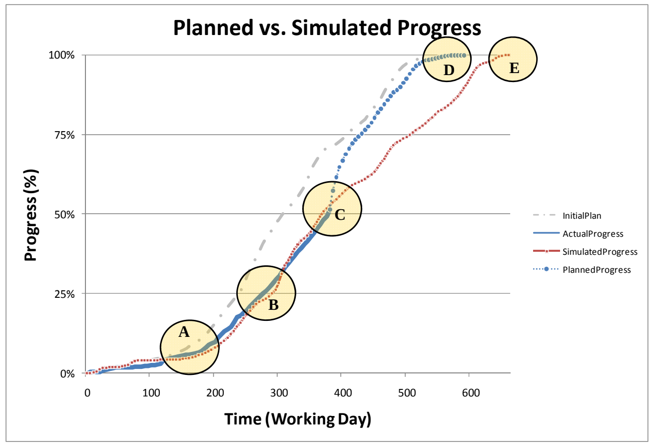


Figure 7. Comparison of Planned vs. Simulated Progress

6. CONCLUSIONS

Rooted in the concept of the open-loop modeling, current construction simulation models have mainly focused on operational aspects without explicit consideration on managerial aspects. Accordingly, these models often provide construction managers with unrealistic prediction of project performance. This paper confirmed that construction production system should be understood and modeled as a closed-loop model by incorporating managerial responses to environment variations. Also, this paper showed that managerial actions taken especially under high schedule pressure may bring unintended side-effects triggering further variation on project performance. These findings lead us to a conclusion that construction performance is governed not only by the combined impact of variation and interdependency but also by the effectiveness of managerial responses to the combined impact. The case study in this paper confirmed that effort required for schedule recovery can be much greater than that construction managers expected due to compounding effect through interdependency and unintended side-effects. For this matter, the proposed COCOMO was proven to be capable of providing more accurate, more comprehensive, and more realistic prediction required for successful execution of construction projects.

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