A HYBRID SIMULATION MODEL FOR INTEGRATED STRATEGIC-OPERATIONAL MANAGEMENT

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ABSTRACT

Although a system integration of strategic goals and operational details is crucial to successful projects, these have been separately treated within traditional approaches. To address this issue, a hybrid simulation model is developed by combining System Dynamics (SD) and Discrete Event Simulation (DES) which have mainly been applied to strategic project management and operational project management respectively. For an illustrative purpose, being applied to a non-typical repetitive earthmoving process, the hybrid simulation model confirms that operational details could negatively affect the process performance if they are not carefully analyzed within a strategic and holistic perspective. Also, the integration of strategic goals and operational details enables to identify potential process improvement areas that traditional approaches may miss. In the non-typical repetitive earthmoving process studied in this paper, this system integration resulted in 4.45% of cost saving and 4.59% of time saving. Considering these benefits, it is concluded that the proposed hybrid simulation model has a great potential to support both the strategic and operational aspects of construction project and ultimately can improve project performance.

KEY WORDS

Hybrid Simulation, System Dynamics, Discrete Event Simulation, Management Action

INTRODUCTION

Schedule delay and cost overruns are the rule rather than the exception in a significant number of large-scale civil infrastructure projects (Sterman, 1992). These are global and chronic phenomena that have persisted over the past 70 years (Flyvbjerg et al., 2003). Analyzing 3500 projects, Morris and Hough (1987) advocated the lack of strategic analysis is a major reason for the failure of many projects. The construction industry especially has put relatively little efforts into strategic analysis (Rodrigues and Bowers, 1996). One of the main reasons for its minimal acceptance in construction management area is its lack of operational detail, which can be clearly seen in traditional approaches such as CPM networks (Williams,

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2002). For this reason, strategic analysis has been applied restrictively and separately from operational analysis. However, such an inconsistency between strategic analysis and operational analysis is a more crucial factor that brings project failures (Callahan and Brooks, 2004). To address this issue, this paper seeks to demonstrate how the mismatch triggers project failures. For this, this study first identifies what 'strategic' and 'operational' stand for and examine how these have been treated in traditional approaches. Then, this study tests whether an integration of strategic and operational analysis can actually help to enhance project management.

STRATEGIC AND OPERATINOAL ISSUES IN TRADITIONAL APPROACHES

STRATEGIC PROJECT MANAGEMENT AND OPERATIONAL PROJECT MANAGEMENT

Construction project management can be divided into two major approaches based on the primary concentration on what is being managed: strategic project management and operational project management (Lee et al., 2006). Strategic project management (SPM) is mainly concerned with how to achieve desirable project results, while operational project management (OPM) focuses on the detailed steps required to achieve the results set within the SPM. It can also be said that the SPM broadly considers long-term project behavior using a holistic view and the OPM zooms into a greater level of operational detail focusing only on one portion of the project at a time in a more quantifiable way. For its distinct focus and application level, the SPM can be defined as macro-level management that establishes the guidelines, directions, and policies that provide logically pervasive patterns to individual decisions for scheduling, budgeting and resource allocation (Rodrigues and Bowers, 1996). On the other hand, the OPM can be defined as micro-level management that provides a detailed analysis for the individual decisions.

TRADITIONAL CONSTRUCTION PROJECT MANAGEMENT APPROACHES

Construction industry has traditionally subdivided the project into smaller parts (activities) according to a Work Breakdown Structure (WBS) and assumed management can be enhanced by carefully handling these individual activities. Based on this assumption, most traditional approaches (e.g., network based models or discrete event simulation models) have focused on operational issues (Morris and Hough, 1987) since these could be easily analyzed by discrete models which have comprised the majority in the construction management area (Walsh et al., 2002)). These approaches also assume a highly stable project environment such as well defined project goals, logistics, and constraints (Lee et al., 2006). Given such detailed information at the beginning stage, traditional approaches can provide a precise estimation for the project (Rodrigues and Bowers, 1996). However, unlike the premise used in traditional approaches, due to the degree of uncertainty, deviations from plans can often be introduced during execution and these deviations may cause project managers to face quite a different construction environment than what was initially planned. To deal with these deviations, construction managers usually adopt control actions such as reallocation of cost, schedule, resource, or even project goals for better project performance. Thus, for more realistic project estimation, such management actions need to be incorporated to project management models. In order to incorporate the management actions, project models should be equipped with the capability to capture feedback effects since project performance and management actions constitute a feedback loop. However, such feedback has not been extensively considered in discrete model based traditional approaches since these models assumed the highly ordered project environments stated above. As a result, traditional approaches sometimes provide unrealistic project estimations especially in cases of highly unstable execution environments (Williams, 2004). To address this issue, system dynamics models have been recently introduced due to their very good demonstration of the effects of feedback loops (Martin and Raffo, 2001). Unlike focus on operational issues exhibited by traditional approaches, these models have mostly dealt with strategic issues (Lyneis et al., 2001). However, these are inherently limited in their ability to represent operational details (Rodrigues and Bowers, 1996). Such incapability is the main deterrent to transfer valuable insights to analyze the operational issues (Williams, 2002). To summarize, SD models and discrete traditional models have been successfully but separately applied to analyze strategic issues and operational issues respectively.

A HYBRID APPROACH FOR STRATEGIC-OPERATIONAL PROJECT MANAGEMENT

As addressed so far, SD and discrete traditional models have their own strengths and weaknesses. These models only support some aspects of a project at a cost to other aspects. We have also addressed system integration of strategic analysis and operational analysis as decisive factor for project success. These arguments led us to the possibility of enhanced modeling capabilities to support both strategic and operational aspects of a construction project through combining SD and traditional models. Despite this potential benefit, only few attempts have been made to integrate SD models and traditional models in the construction management area. Lee et al. (2006) initiated the study of hybrid SD and traditional models and provided a theoretical framework for integrated strategic and operational project management. Based on this framework, this study pursues implementation of integrated strategic-operational project management through combining SD modeling and DES modeling, one of the most advanced of traditional approaches.

MODEL DEVELOPMENT

CASE: EARTHMOVING PROCESS

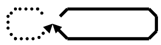
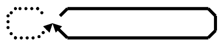
For an illustrative purpose, an earthmoving process is adopted. In this research, the earthmoving process is defined as iterations of moving earth and dumping to an off-site location as part of construction of a new highway. As the earthmoving process progresses, the iteration distance gets longer and the iterations continue until the planned area is completely filled with earth. An earthmoving process is selected for the several reasons. First, earthmoving is a non-typical repetitive process that usually requires management actions such as timely movement of resources to maintain work continuity (El-Rayes and Moselhi, 1998). In addition, the earthmoving process is a representative process considered as an indicator of the success or failure of many civil projects as a whole (Smith et al., 2000).

Based on these recognitions, numerous examples of earthmoving processes exist in the literature including Martinez et al. (1994) and Smith et al. (1995).

TRADE-OFFS IN THE EARTHMOVING PROCESS

The fact that travel distance gets longer makes it difficult for construction managers to optimize the process performance. Since the process simultaneously necessitates loaders and trucks, the overall production rate is determined by the lesser of the truck circulation rate (the number of trucks divided by truck iteration time) and the loader circulation rate (similarly, the number of loaders divided by loader iteration time). The example portrayed in the following table supposes 2 loaders and 4 trucks assigned for the process (Table 1).

Table 1. Overall Production Rate in Earthmoving (given 2 loaders and 4 trucks)

Phase	**Graphical Description**	**Loader Iteration Time**	**Truck Iteration Time**	**Loader Circulation Rate**	**Truck Circulation Rate**	**Overall Production Rate**
Earlier Phase		1 min	1 min	**2 units/min**	4 units/min	**2 units/min**
Middle Phase		1 min	2 min	**2 units/min**	**2 units/min**	**2 units/min**
Later Phase		1 min	4 min	2 units/min	**1 units/min**	**1 units/min**

* Dot line represents loader circulation while straight line stands for truck circulation

When the truck iteration time is 1 minute (*Earlier Phase*), the truck circulation rate is 4 units/min and the loader circulation rate is 2 units/min. As time goes by, travel distance increases and consequently the truck iteration time also increases to 2 minutes (*Middle Phase*). In this phase, while the truck circulation rate decreases to 2 units/min, the loader circulation rate remains at 2 units/min since the loaders travel a relatively constant distance. Also, if travel distance increases further, truck iteration time increases to 4 minutes (*Later Phase*) and the truck circulation rate decreases to 1 units/min. At this point, the truck circulation rate begins to restrict the overall production rate. Thus, for cost-effective management, it is necessary to synchronize the truck circulation rate with the loader circulation rate. However, the difficulty lies in that the truck circulation rate continuously decreases while the loader circulation rate is almost constant. Therefore, for process optimization, the key concern is to find the optimal number of trucks that can maintain a balance between the truck circulation rate and the loader circulation rate. If trucks are not sufficiently assigned, the cost performance might be improved through a decrease in redundant trucks in the earlier stages. However, this would result in a process disruption due to a truck shortage at later stages and will delay the schedule performance and ultimately adversely affect the cost performance due to the extended duration. On the other hand, if trucks are exceedingly assigned, the process disruption can be prevented and thus schedule performance could be enhanced, especially at later stages. However, at earlier stages, some trucks will be redundant, causing negative cost performance. Thus, there are certain trade-offs between the schedule performance and cost performance when setting a number of trucks in the earthmoving process. To deal with these trade-offs, current DES based models seek the optimal truck number that conceptually minimizes the summation area of *R* (Redundant Trucks) and *D* (Deficient Trucks) (Figure 1). However, no matter how many trucks are assigned in these approaches, the process cannot avoid a certain amount of lower cost performance or process disruption due to the above mentioned trade-offs.

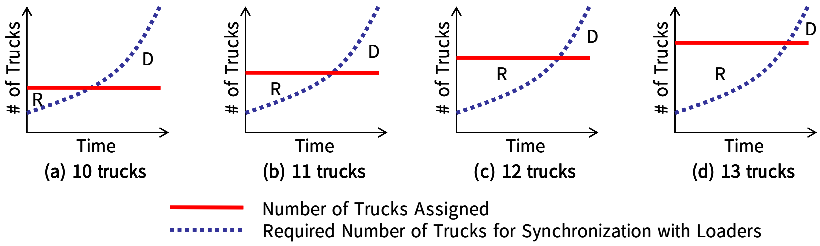


Figure 1. Trade-offs in the Earthmoving Process

THE MISSING LINK: MANAGEMENT ACTIONS

To effectively deal with these trade-offs, the process dynamics that generate them need to be analyzed through identifying feedback structures (Figure 2). In the earthmoving process, as more earth is moved, travel distance increases as does the iteration time (A-B in Figure 2). Increased iteration times lower the truck circulation rate and ultimately decrease the overall production rate (C-D). Even though the production decreases, earth continues to be moved, though at a lower rate, further increasing the travel distance (E-A). As a result, as more earth is moved, the production rate always decreases and the process would face occasional process disruptions (F).

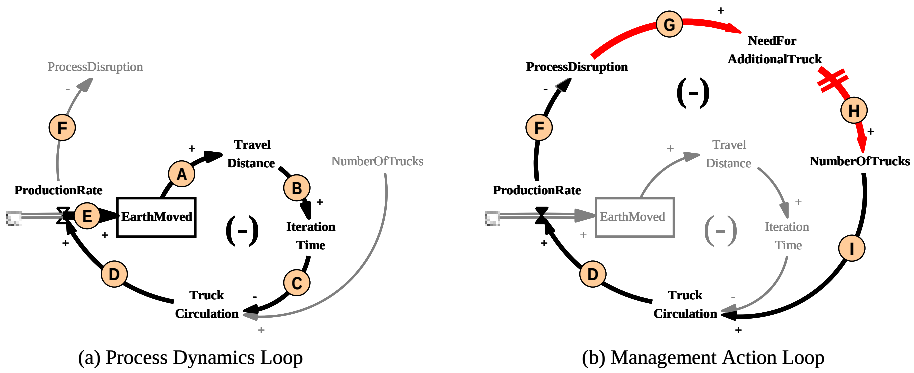


Figure 2. Process Feedback in the Earthmoving Process

In this situation, a construction manager, facing process disruptions, would not simply overlook it (Williams, 2004) but would take management action such as timely movement of resources to ensure work continuity (El-Rayes and Moselhi, 1998). As the construction manager faces increasing chances of process disruption, the manager will try to acquire additional trucks to increase the production rate with certain amount of time delay (G-H). By including these management actions, the process forms another loop (F-G-H-I-D) and this loop will allow the process to avoid the above mentioned trade-offs and ultimately enhance the process performance dramatically. To rigorously examine the impact of these management actions on the process performance, we developed a hybrid simulation model.

MODEL BUILDING

For building simulation models, we utilized the Extend™ simulation environment (Imaginethat Inc., 2002) which is capable of supporting both SD and DES modeling.

PROCESS LOGISTICS

In the earthmoving process, each iteration consists of sub-tasks named *Load*, *Haul*, *Dump*, and *Return*. Using available trucks and loaders, a certain amount of earth is loaded into a truck (*Load*). Then the truck travels to a planned dumping site (*Haul*). Arriving at the site, the truck dumps the loaded earth (*Dump*) and returns to the loading site to be reutilized for the next iteration (*Return*).

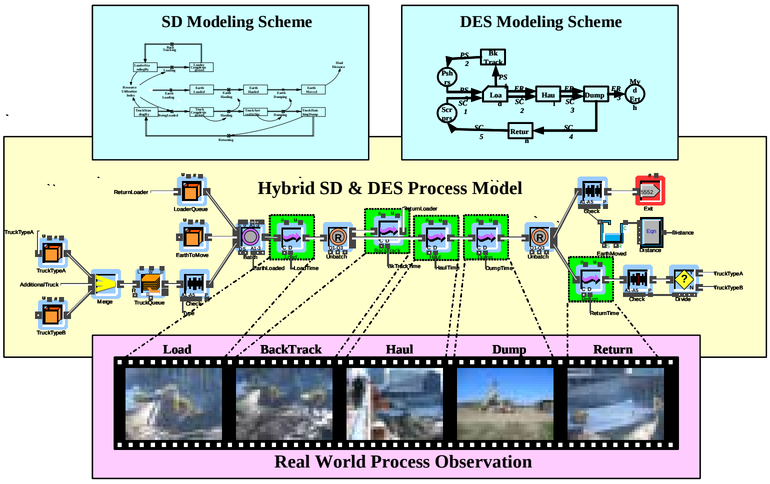


Figure 3. Earthmoving Process Model

Since the *Load* task requires a loader and a truck simultaneously, *Batch* node checks truck and loader availabilities. If a loader and truck are available, the *Load* task begins and *LoadTime* is calculate based on the type of truck, its power, and capacity. Once the *Load* task finishes, the truck and the loader will be unbatched. The loader returns to its resource pool (named *LoaderQueue*) to be involved in the next iteration. On the other hand, the truck travels to the dumping site during *HaulTime*. Similar to *LoadTime*, *HaulTime* is estimated based on the type of truck, its power, and current iteration distance. After dumping earth to an appropriate place, the truck and earth are segregated because the earth is left at the dumping site, while the truck returns to the loading site for the next iteration. The simulation engine checks the truck type and integrates the volume of the earth dumped into *EarthMoved* block (Figure 3). These iterations continue until the required length is filled with the dumped earth. Detailed data for this process is adopted from the literature (Martinez et al., 1994).

MANAGEMENT ACTION PROCESS

As previously discussed, to achieve process optimization, it is important to synchronize the truck circulation rate with the loader circulation rate. Such synchronization can be attained by proper management actions. In order to incorporate management actions into the process, we first need to identify when the action should be taken. For this, the *MatchFactor* variable, initially used by Smith et al. (1995), is elaborated in this study. The Smith study determined whether an appropriate number of trucks had been allocated for process efficiency using an index calculated as follows:

$$MatchFactor = C_L / C_T = (N_L / T_L) / (N_T / T_T)$$

Where C_L = Loader circulation rate, C_T = Truck circulation rate, N_L = Number of loaders, T_L = Loader cycle time, N_T = Number of trucks, and T_T = Truck cycle time

Extending their idea, this study uses *MatchFactor* as the main decision variable to trigger management actions. Whenever the *MatchFactor* variable reaches a certain threshold set by the construction manager, the simulation engine assigns an additional truck with a certain amount of adjustment delay. Using this control mechanism, we simulate how such management actions impact the process performance.

SIMULATION RESULTS ANALYSIS

In terms of taking the management action there could be two main decision factors: 1) how many trucks need to be initially allocated and 2) how quickly additional trucks can be assigned when required. To examine these factors, the process is simulated with: 1) 5 to 13 initial trucks and 2) zero (ideal case) to 24 working hours of adjustment delay.

SCHEDULE PERFORMANCE

Figure 4-(a) shows the effect of two decision factors on schedule performance. As expected, the schedule performance gets better with a shorter adjustment delay and more initial trucks. In addition, Figure 4-(a) indicates that when one of the decision factors gets worse, the sensitivity of the schedule performance to the other factor significantly increases. For example, when more than 11 trucks are initially assigned, sensitivity to changes in the adjustment delay is minimal. However, if the process begins with fewer than 8 trucks initially, the sensitivity to changes in the adjustment delay dramatically increases. The reason for this is that when the initial number of trucks is high enough, there are fewer opportunities for adjustment and consequently the impact of adjustment delay remains insignificant. However, if the process does not have enough trucks initially, the opportunities for adjustment increase and the impact of adjustment delay becomes significant. Thus, when trying to enhance the schedule performance, if it is difficult to control both decision factors, a construction manager should focus on one decision factor, whichever is easier to control, and try to reduce sensitivity to the other factor.

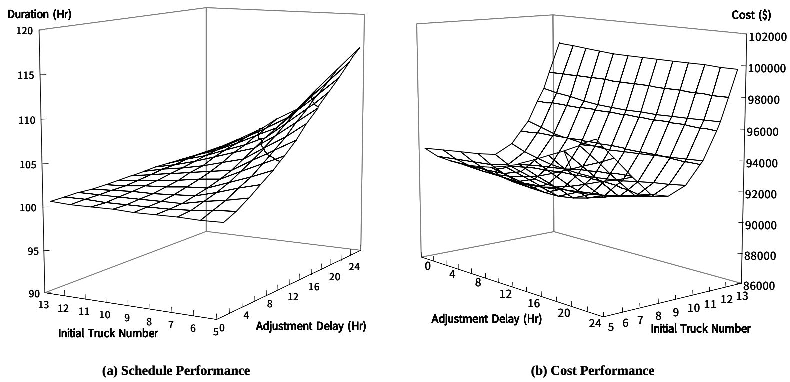


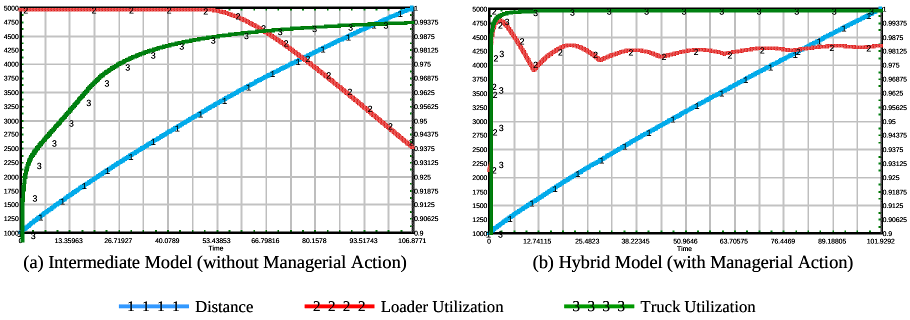
Figure 4. Response Surface for Cost and Schedule Performance

COST PERFORMANCE

The cost performance produces a convex curve in terms of initial number of trucks (Figure 4-(b)). When 8 trucks are initially assigned to the process, the cost performance is optimal in all cases of adjustment delay. These results are consistent with our initial expectation that more trucks will cause idling cost and fewer trucks will interrupt the process and thus lower the cost performance. Also, it produces a convex curve in terms of adjustment delay. Generally, it is believed that the shorter the adjustment delay, the better the cost performance because shorter adjustment delay can be helpful in minimizing process disruptions caused by the truck shortage. Contrary to this, Figure 4-(b) shows that there is a certain threshold that gives a maximum cost performance. For example, when 8 trucks are initially assigned, the lowest cost performance is found at 10 hours of adjustment delay. Therefore, management should optimize the adjustment delay rather than try to reduce it as much as possible.

IMPLICATIONS

Figure 4-(b) implies the crucial point that the cost performance can not be in proportion to managerial efforts to improve decision factors (e.g., the initial number of trucks and adjustment delay in the earthmoving). In the traditional approaches, without a careful examination of the process dynamics, it is often hypothesized that the process performance could be linearly enhanced with managerial efforts. In addition, it is assumed that there exist certain trade-offs between schedule performance and cost performance. As a result, construction managers take control actions with the belief that increasing input resources will enhance schedule performance, but degrade cost performance. However, as shown in Figure 4-(b), the simulation results confirm that if the impact of these actions is not thoroughly analyzed from a strategic and holistic view, the overall process performance may suffer *because* of our own best efforts (e.g., excessive number of trucks and shortest possible delay). Thus, in order to take effective management actions, it is crucial to align our operational efforts consistently with our strategic directions. In this context, the hybrid simulation model, integrating strategic and operational aspects, can help construction managers take effective management actions and ultimately reduce the chance of project failures.



(a) Intermediate Model (without Managerial Action)

(b) Hybrid Model (with Managerial Action)

Figure 5. Simulation Results

Finally, the simulation results demonstrate that effective management actions could result in cost savings of 4.49% and time savings of 4.63% over the optimal simulation results absent management actions. When the management actions are omitted, the results clearly show ineffectiveness in that some trucks are redundant at earlier phases (potential cause for degraded cost performance) and are deficient at later phases (potential cause for process disruption) (Figure 5-(a)). However, when the management actions are implemented, trucks are fully utilized during the whole process and loaders are utilized at around 98.25% during the same period (Figure 5-(b)). In addition, the production rate is stabilized unlike when the actions are omitted. While the management actions generate 1.75% of wasted loader utilization, the wasted loader utilization plays a significant role as a buffer for hedging a process disruption from truck shortage. Such simulation results vividly demonstrate how management actions can enhance process performance.

CONCLUSIONS

Since project failures could be ascribed to a mismatch between strategic perspectives and operational efforts, both strategic and operational issues need to be considered simultaneously when taking managerial actions. To address this issue, this study developed a hybrid simulation model that can support both the strategic and the operational aspects of a construction project through integrating SD and DES. For illustrative purposes, we applied the model to a non-typical repetitive earthmoving process and examined how management actions can impact the process performance. Through a series of response surface analyses, the hybrid model demonstrated that process performance is not proportionally enhanced with managerial efforts, but follows a convex curve like Figure 4-(b). In addition, the existence of the convex curve suggests that construction managers should not try to increase their management efforts recklessly but rather attempt to find an appropriate level of effort with a strategic and holistic perspective. Also, the analyses indicated that the hybrid simulation model can help construction managers find potential process improvement areas (e.g., cost savings of 4.49% and time savings of 4.63%) that traditional project management approaches may miss. Finally, in order to be applied to a real project, additional considerations are still required such as side effects or ripple effects caused by the management actions. Though these are challenging issues, we believe that further exploration of these issues is necessary for discovering the complexities and dynamics of construction projects and ultimately reducing the chance of project failures.

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