Strategic-Operational Construction Management: Hybrid System Dynamics and Discrete Event Approach

Feniosky Peña-Mora[1]; Sangwon Han[2]; SangHyun Lee[3]; and Moonseo Park[4]

Abstract: A significant number of large-scale civil infrastructure projects experience cost overruns and schedule delays. To minimize these disastrous consequences, management actions need to be carefully examined at both the strategic and operational levels, as their effectiveness is mainly dependent on how well strategic perspectives and operational details of a project are balanced. However, current construction project management approaches have treated the strategic and operational issues separately, and consequently introduced a potential conflict between strategic and operational analyses. To address this issue, a hybrid simulation model is presented in this paper. This hybrid model combines system dynamics and discrete event simulation which have mainly been utilized to analyze the strategic and operational issues in isolation, respectively. As an application example, a nontypical repetitive earthmoving process is selected and simulated. The simulation results demonstrate that a systematic integration of strategic perspective and operational details is helpful to enhance the process performance by enabling construction managers to identify potential process improvement areas that traditional approaches may miss. Based on the simulation results, it is concluded that the proposed hybrid simulation model has great potential to support both the strategic and operational aspects of construction project management and to ultimately help increase project performance.

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Introduction

Schedule delays and cost overruns have chronically persisted in construction projects despite advances in construction equipment and management techniques (Park and Peña-Mora 2003). For construction cost performance, it was reported that 20 civil infrastructure projects in 17 states experienced significant cost increases ranging from around 40 to 400% (GAO 2002). This trend is not limited to projects in the United States. According to Flyvbjerg et al. (2003), cost overruns are found in 90% of all megaprojects in 20 countries ranging from Europe to Asia and such cost escalation is not a new phenomenon but has persisted over the past 70 years.

In order to minimize this situation, management actions taken during the execution stage need to be carefully examined as these actions may significantly influence project performances (Williams 2002). Depending on their effectiveness, such actions can be beneficial or detrimental to the project performance. Therefore, for successful project control, it is imperative to rigorously assess the impact that the actions will have. Especially in large-scale projects, a higher degree of project complexity can increase the difficulty of this analysis (Lee et al. 2006).

In order to take an effective management action, the action should be analyzed at both the strategic and operational levels as its effectiveness is mainly dependent on how well the strategic perspective and operational details of a project are balanced (Schultz et al. 1987). For example, given the strategic perspective of the project without operational details, beneficial actions could be identified but not properly taken. Conversely, given operational details without strategic perspective, detrimental actions might be taken. Such a mismatch between strategic analysis and operational analysis is one of the main reasons for project failures (Callahan and Brooks 2004). Thus, for successful construction project management, both strategic and operational approaches are simultaneously required (Lee et al. 2006).

To address this issue, this paper seeks a way of combining both strategic and operational analyses. For this, we first examine and identify the scope of "strategic" and "operational" analyses and how they have been treated in traditional construction project management approaches. Then, we identify limitations of the traditional approaches and propose an integrated model which can overcome these limitations. For a systematic integration, we develop a hybrid simulation modeling framework that can support both strategic and operational aspects of construction projects. Finally, we validate and simulate the model, analyze the simulation results, and demonstrate how the hybrid model can be helpful to enhance construction project performance.

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Strategic and Operational Issues in Traditional Approaches

Construction project management can be divided into two major approaches in terms of the primary concentration on what to manage: 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 within the context of the company's strategic objectives, while operational project management (OPM) focuses on the steps required to achieve the project objectives. It can also be said that SPM broadly considers long-term project behavior using a holistic view, whereas OPM zooms into a greater level of operational details focusing only on one portion of the project at a time in a more quantifiable way. Thus, the SPM can be defined as macrolevel management actions that establish 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 microlevel management actions that provide a detailed analysis for each individual decision.

Traditional Construction Project Management Approaches

In order to reduce complexity of a construction project, traditional construction management approaches have subdivided a construction project into smaller parts (i.e., activities). This is attributed to a common belief that although each construction project is unique, its constituent activities are common so that project managers' past experience can be easily applied. Thus, it was believed that the more details are incorporated, the more rigorous the management model could be developed. Together with such beliefs, most traditional approaches have focused on individual activities (Ondash et al. 1988) and operational issues rather than strategic issues (Rodrigues and Bowers 1996).

Among the traditional construction management approaches, the most widely utilized formal scheduling technique is the critical path method (CPM) (Senior and Halpin 1998). Tavakoli and Riachi (1990) and Kelleher (2004) surveyed ENR's top 400 contractors and revealed 92.6 and 98% of respondents used the CPM to some extent, respectively. This clearly indicates the broad adoption of the CPM in the architect/engineer/contractor (A/E/C) industry and how it has continued to increase over the last 10 years. Despite this continuing popularity, its drawbacks have been continuously addressed by numerous research efforts. For example, Martinez and Ioannou (1997) claimed that it assumes all activities have fixed durations that are known at the beginning of the project. However, in practice, it is almost impossible to gather all required information at inception due to uncertainties inherent in construction projects. In order to address this issue, the PERT (Program Evaluation and Review Technique) is often accompanied (CPM/PERT). Unlike the CPM, which considers only one fixed activity duration, the PERT uses three duration factors (i.e., optimistic, pessimistic, and most likely) in order to approximate an empirical distribution of an activity duration (Moder et al. 1983). In this approach, it is expected that the project completion time is normally distributed because of the central limit theorem (the sum of a large number of independent, identically distributed random variables will approximate a normally random variable). However, contrary to this assumption, activity durations are not identically distributed nor are they all independent. Further, in practice, project failures are more often observed than project successes (Morris and Hough 1987). For example, the General Accounting Office (GAO 2005) reviewed 27 courthouse projects constructed from fiscal year 1998 to fiscal year 2005.

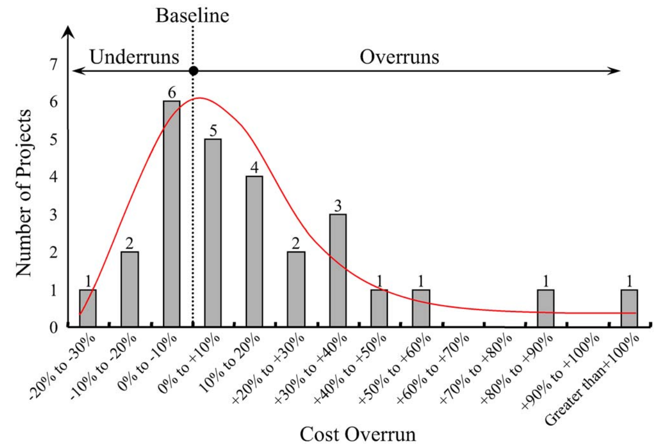

Fig. 1. Cost overruns of courthouse projects

The courthouse projects are all constructed in a quite similar manner because the *U.S. Courts Design Guide* sets courthouse construction standards. Because of this similarity, if the central limit theorem is applicable in these projects, we would observe the same probability of project success and failure. However, in Fig. 1, comparison between actual costs and estimated costs at the design stage of these projects indicates that project performance has a long tail (higher probability of project failure). Thus, for more realistic project estimation, more rigorous statistical analysis needs to be incorporated into the project model.

Another significant element ignored by CPM/PERT is managerial actions taken during execution. In practice, once deviations are met, project managers usually adapt their execution plan with corrective actions for the deviations rather than adhere to their initial plan (Rodrigues and Bowers 1996). Suppose that foundation work in a construction project is due to finish at around 60 days (Fig. 2). This work consists of three subactivities: *excava-*

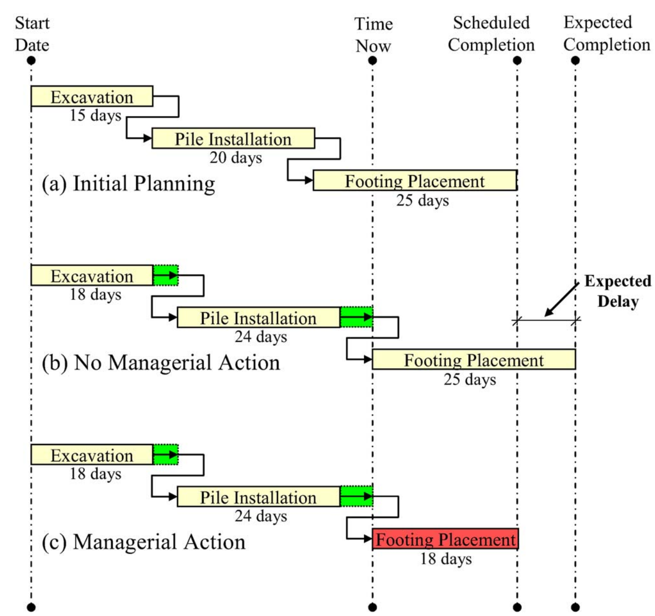

Fig. 2. Management actions in foundation work

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tion, *pile installation*, and *footing placement*. Further, suppose that the subactivity durations were initially expected to be 15, 20, and 25 days, respectively, but due to firmer ground than the manager's initial expectation, *excavation* and *pile installation* took 18 and 24 days, respectively. Imagine that the construction manager is now about to execute the remaining activity, *footing placement*. Recognizing the schedule slippage, the project manager will try to take a management action (i.e., assigning more workers and adopting an overtime policy) in order to ensure finishing the foundation work near the scheduled completion date. Otherwise, the manager will need to pay a significant penalty for the late completion. As such, in practice, managers would not just overlook the schedule slippage (Williams 2004), but take action in order to correct deviations or enhance their project performance.

To address this issue, project managers have regularly and frequently but *reactively* updated their schedules with these corrective actions. As a result, a revised schedule accounts for previous deviations but is still vulnerable to future deviations. In this context, even though a CPM/PERT schedule is regularly and frequently revised, its reliability may not be yet fully guaranteed until project completion at which all deviations can be identified. In other words, CPM/PERT does not account for the intrinsic dynamics on a project schedule since it does not provide a mechanism to explicitly represent feedback between performance and management actions, which is a major source of the dynamics of a system (Williams 2002). As a result, it is observed in nearly all construction projects that the final CPM/PERT schedules have been significantly changed from the initial schedules and incorporate additional time or costs which are completely unpredicted by the initial schedules. Thus, for getting more reliable project estimations, a project model needs to incorporate a mechanism to deal with management actions proactively.

Simulation-Based Approaches

As addressed in the previous section, traditional approaches have two principal limitations in terms of (1) lack of statistical analysis and (2) lack of management action. In order to overcome these limitations, simulation models have been extensively adopted in the construction management area. Simulation models in the construction management area can be divided into two major approaches: Discrete event simulation (DES), which has occupied the mainstream of construction simulation and system dynamics (SD), which has recently been introduced to the construction simulation area.

With the ability to incorporate various kinds of statistical distributions in order to estimate activity durations, DES models can overcome the lack of statistical analysis, one limitation of traditional approaches. In addition, DES models directly replicate construction processes so construction managers can easily analyze their logistics. As DES models can provide detailed information for execution, they have been mainly utilized to analyze operational issues like earthmoving or pipe installation. However, due to their narrow focus, sometimes these provide unrealistic estimations because process performance is significantly affected by its project contexts (i.e., schedule urgency) which are determined by other concurrent processes. However, DES models, analyzing construction processes with an event-oriented view, lack the capability to incorporate feedback structures between process performance and its project contexts (Martin and Raffo 2001).

To address this issue, control theory-based SD models have been introduced to analyze project environments because of their very good representation of feedback effects. In addition, SD models are effective to incorporate management actions, which is another limitation of the traditional approaches. Unlike the focus on operational issues exhibited by DES models, SD models have mostly dealt with strategic issues (Lyneis et al. 2001). Such differences make SD models represent construction processes in quite a different manner than DES models do.

The difference between DES and SD models is examined in a construction context with an earthmoving example. In DES models, the earthmoving process is subdivided into manageable smaller subactivities (i.e., *Load, Haul, Dump, Return,* and *Back track*) and directly replicated to the model. In order to incorporate uncertainty that might exist in the subactivities, these models apply statistical distribution like *Normal* distribution or *Triangular* distribution to the subactivities after analyzing previous empirical data since it is believed that such subactivities are common so that project managers' past experiences can be easily applied. Then, according to precedence relationships and process logistics, the whole earthmoving process is estimated in terms of cost performance, schedule performance, and resource profile. Finally, these models try to optimize the execution plan by varying input variables (i.e., number of trucks). As these models still form discrete breakdown structures, these can provide each subactivity's detailed information for the optimal execution. On the other hand, as will be shown later in more detail, SD models try to identify process feedback mechanisms of the earthmoving rather than reproduce the process itself. Through analyzing interactions among process variables, SD models capture overall process dynamics and estimate how these dynamics will affect process performance over time (i.e., as process progresses, haul distance gets longer, thus lowering process performance). Then, based on the feedback analysis, existing problems (occasional process interruption due to lack of trucks) that the process involves are revealed and suggestions of how to overcome the discovered problems (i.e., assigning more trucks) are offered. As such, SD models more effectively provide a policy guideline to enhance process performance but have greater difficulties in providing information as detailed as that provided by the DES models. One main reason is that SD models do not generally form a breakdown structure of discrete subactivities, but analyze the process as a continuous stream of work. For this reason, SD models are inherently limited in their ability to generate operational details for project execution (Williams 2002).

To summarize, DES models have mainly dealt with operational issues without aggressively considering project feedback structure and focused on the efficiency of process logistics in terms of time, cost, and resource usage. On the other hand, SD models have mainly addressed strategic issues by analyzing project feedback structures and examined the effectiveness of control policies against a continuously changing project environment. SD models and DES models, so to speak, have been successfully but *separately* applied to analyze strategic and operational issues respectively but each with their limitations. However, incorporation of management actions to a construction project model requires both project strategy and operational details. First, project strategy sets project objectives and drives management actions during the execution of the project in order to realize the project goals. Depending on the effectiveness of the project strategy, management actions can be beneficial or detrimental to project behavior and are judged by whether they are helpful in attaining project objectives. Thus, project strategy needs to be incorporated and evaluated for successful management actions. Also, operational details are required for actual implementation of management actions. If these are not sup-

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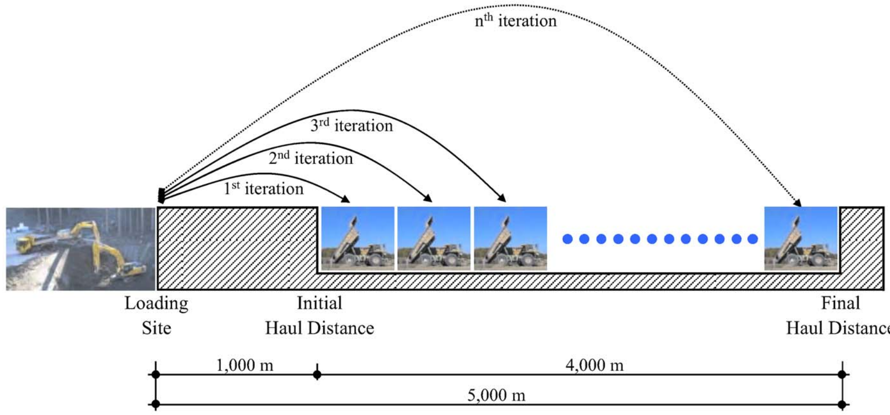

Fig. 3. Pictorial representation of the earthmoving process

ported, it would be difficult to detect the detailed information required for taking the management actions (e.g., specific timing, responsibility, resource deployment, and so on). As such, for robust project management, both project strategy and operational details need to be integrated into a comprehensive modeling framework and it is expected that systematic integration of SD modeling and DES modeling can support both strategic and operational aspects of a construction project.

Despite this potential benefit, only few attempts have been made to integrate strategic approaches and operational approaches in the construction management area. Lee et al. (2006) initiated the study of hybrid SD and DES models and provided a theoretical framework for integrated strategic and operational project management. Based on this framework, this study pursues the implementation of an integrated strategic-operational project management model by combining SD and DES modeling.

Model Development

To demonstrate implementation of the concept of integrated strategic-operational construction management, an earthmoving process is selected as an application example. In this research, the earthmoving process is defined as iterations of moving soil and dumping it to an off-site location as part of construction of a new highway. These iterations are repeated until the planned area is completely filled with soil. However, as the earthmoving process progresses, the iteration distance gets longer as does the time required for an iteration (Fig. 3). This makes this process a nontypical repetitive process. According to Voster and Bafna (1992), repetitive processes can be divided into two main categories: typical and nontypical. Typical repetitive processes are characterized by having identical durations in all repetitions. On the other hand, nontypical repetitive processes do not have identical durations due to variations in the quantities of work and/or productivity (Moselhi and El-Rayes 1993). Considering this categorization, the earthmoving process can be classified as a nontypical repetitive construction process as all repetitions of the process do not have identical durations due to the increase in distance as the iterations progress.

The earthmoving process was selected for several reasons. First, the earthmoving process is a nontypical repetitive process which usually requires construction managers to take management action (i.e., timely movement of resources) to maintain work continuity (El-Rayes and Moselhi 1998). Therefore, the earthmoving process could be a natural candidate to incorporate management actions to its modeling. In addition, the earthmoving process is one of the representative processes considered as indicators of the success or failure of many heavy construction projects as a whole (Smith et al. 2000). Finally, based on this recognition, the earthmoving process has been used to determine the effectiveness of previous DES-based models, including Martinez et al. (1994), Smith et al. (1995), and AbouRizk and Mather (2000). Thus, the earthmoving process is very appropriate to highlight how this study is different from traditional approaches and this study's contribution.

Trade-Offs in the Earthmoving Process

The most important thing we should notice in the earthmoving process is that travel distance gets longer as the process progresses. As will be discussed later, this is the main reason that optimization of process performance is difficult. The process performance (hereafter called *overall production rate*) can be 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) since the process simultaneously necessitates loaders and trucks. Table 1 shows how the overall production rate is calculated over time in the process. The example portrayed in Table 1 supposes two loaders and four trucks assigned for the process.

When the truck iteration time is 1 min (*Earlier Phase*), the truck circulation rate is 4 units/min and the loader circulation rate is 2 units/min. At this time, the overall production rate is governed by the loader circulation rate (which is the lesser of both circulation rates). As time goes by, travel distance increases and consequently the truck iteration time also increases to 2 min (*Middle Phase*). In this phase, although the truck circulation rate decreases to 2 units/min, the loader circulation rate remains at 2 units/min as the loaders travel a relatively constant distance. Finally, if travel distance increases further, truck iteration time increases to 4 min (*Later Phase*) and the truck circulation rate decreases to 1 unit/min. At this point, the truck circulation rate begins to restrict the overall production rate. As shown in this example, 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, whereas the loader circulation rate is almost constant. Therefore, the key concern is to find a proper number of trucks that can maintain a balance between the truck circulation

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Table 1. Overall Production Rate in Earthmoving (Given Two Loaders and Four Trucks)

Phase	Graphical description	Loader iteration time (min)	Truck iteration time (min)	Loader circulation rate	Truck circulation rate	Overall production rate
Earlier phase		1	1	**2 units/min**	4 units/min	**2 units/min**
Middle phase		1	2	**2 units/min**	**2 units/min**	**2 units/min**
Later phase		1	4	2 units/min	**1 units/min**	**1 units/min**

Note: Dotted line represents loader cycle and solid line represents truck cycle.

rate and the loader circulation rate since careful selection of equipment fleets for the process can yield substantial savings in both time and cost (Farid and Koning 1994).

If trucks are not sufficiently assigned, the cost performance might be improved through minimizing 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 redundantly 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) (see Fig. 4). However, no matter how many trucks are assigned in current DES based models, the process cannot avoid a certain amount of lower cost performance or process disruption due to the trade-offs.

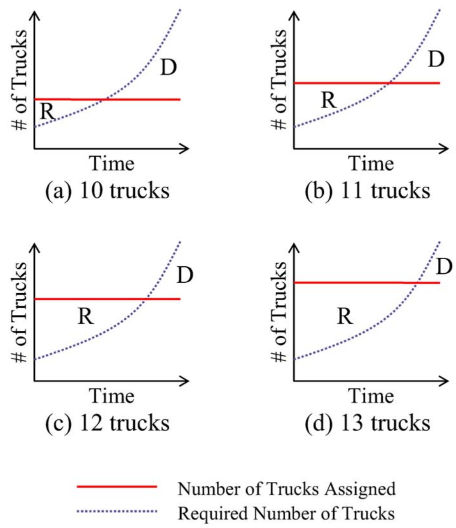

Fig. 4. Trade-offs in the earthmoving process

Missing Link: Management Action

In order to investigate what dynamics generate the trade-offs, this study analyzes process feedback structure using a stock and flow diagram (Fig. 5), which characterizes the state of a system and generates information upon which decisions or actions are based (Sterman 2000). A stock represents ("Soil Moved" in Fig. 5) stored quantities and a flow ("Production Rate") represents control quantities flowing into and out of stocks. In the earthmoving process, as more soil is moved, travel distance increases as does the iteration time (ⓐ and ⓑ in Fig. 5). Increased iteration times lower the truck circulation rate and ultimately decrease the overall production rate (ⓒ and ⓓ). Even though the production decreases, soil continues to be moved, though at a lower rate, fur-

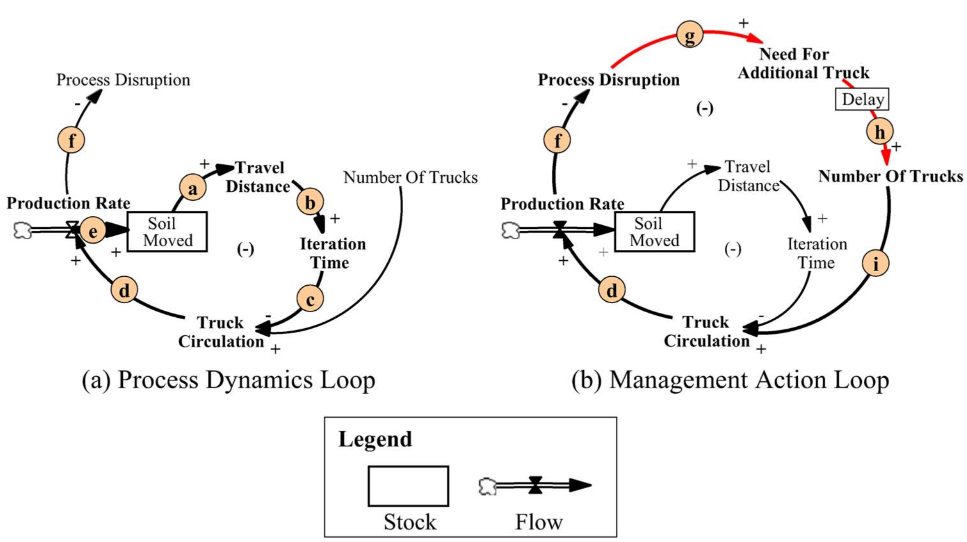

Fig. 5. Process feedback in the earthmoving process

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Table 2. Comparison of Deterministic Simulation Results [Adapted from Martinez et al. (1994)]

Fleet configuration		STROBOSCOPE (A)		Intermediate model (B)		Comparison (B/A)	
Loader	Truck	Duration	Total cost	Duration	Total cost	Time ratio	Cost ratio
3	5	219.19	132,609	219.17	132,598	0.9999	0.9999
	6	182.67	119,281	182.65	119,271	0.9999	0.9999
	7	156.58	109,762	156.57	109,756	0.9999	0.9999
	8	136.99	102,609	137.01	102,621	1.0001	1.0001
	9	122.93	97,977	123.01	98,039	1.0007	1.0006
	10	113.29	95,729	113.34	95,772	1.0004	1.0004
	11	106.83	95,403	106.88	95,444	1.0005	1.0004
	12	102.81	96,748	102.88	96,810	1.0007	1.0006
	13	100.79	99,681	100.83	99,721	1.0004	1.0004

ther increasing the travel distance (e–a). As a result, as more soil is moved, the production rate always decreases and the process would face occasional process disruptions (f).

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). Whether the construction manager takes management action ultimately depends on the manager's strategic objectives. In this study, we assumed that the process can acquire additional trucks and that the manager's strategic objective is to finish the project with minimum operation cost and time. Based on these assumptions, as the construction manager faces increasing chances of process disruption, the manager will try to acquire additional trucks to increase the production rate (g). In addition, we assumed a certain amount of time is required for an additional truck to be assigned to the process once it is ordered (h). By incorporating management actions (g and h), the process forms another loop (f–g–h–i–d) and this loop will enhance the process performance by adjusting the number of trucks.

Model Building Process

In order to rigorously examine the impact of these management actions on schedule and cost performance, we developed a hybrid simulation model. The model is built using the *Extend* simulation environment (Imaginethat, Inc. 2002) which is capable of supporting both SD modeling and DES modeling. As current DES based models do not incorporate management actions, they cannot be directly compared with the proposed hybrid model for examination of the impact of the management actions. Thus, for a clear comparison, we will first develop an *intermediate model*, which mimics current DES-based models in terms of omitting the management actions. Then, we will further develop a *hybrid model* by incorporating the management actions to the *intermediate model*. By developing the model in this manner, we can first fairly measure the impact of our management actions via comparing the *intermediate model* to current DES models and then to the *hybrid model*.

Intermediate Model

This section discusses the model building process and validation of the *intermediate model* that has been developed based on the literature available for STROBOSCOPE (Martinez et al. 1994).

Intermediate Model Building

In the earthmoving process, each iteration consists of subtasks named *Load*, *Haul*, *Dump*, and *Return*. Using available trucks and loaders, a certain amount of soil is loaded into a truck (*Load*) and the truck travels to a planned dumping site (*Haul*). Arriving at the site, the truck dumps the loaded soil (*Dump*) and returns to the loading site to be reloaded for the next iteration (*Return*). Such iterations continue until the soil completely fills the planned area of the new load. As shown in Fig. 3, the planed length is 4,000 m and the cross section is 12.5 m^2. The initial iteration distance is 1,000 m and the final distance is 5,000 m. For other simulation data and equations for this process, we adopted those utilized in Martinez et al. (1994).

Intermediate Model Validation

Before incorporating management action processes, we need to validate the *intermediate model* to remove any modeling bias between the current DES modeling and the *intermediate model*. For this, we compare the *intermediate model* simulation results with STROBOSCOPE results under both deterministic and stochastic contexts.

For testing the *intermediate model*'s validity in a deterministic context, the simulation results under various loader–truck configurations are compared with STROBOSCOPE. As shown in Table 2, the simulation results are highly consistent with the STROBOSCOPE simulation results with a maximum deviation of only 0.07%. Therefore, it is suggested that the *intermediate model* is highly reliable in the deterministic context. Also, Table 2 indicates that when three loaders are allocated, the optimal number of trucks is eleven, giving rise to the lowest cost in both models ($95,403 in STROBOSCOPE and $95,444 in the *intermediate model*, close results within 0.04%).

Further, we examined the simulation results under the stochastic context as well because uncertainty is ubiquitous in executing a construction process such as earthmoving. It is assumed that the amount of soil to be loaded per truck as well as each subtask time incorporates randomness. Detailed descriptions for these stochastic features for this process can be found in Martinez et al. (1994). Table 3 shows summary statistics of simulation results of STROBOSCOPE and the *intermediate model* and that their simulation results are quite similar to each other.

So far, we have examined the validity of the *intermediate model* under deterministic and stochastic contexts and showed its simulation results are highly consistent with the known simula-

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Table 3. Summary Statistics of STROBOSCOPE and the Intermediate Model [Adapted from Martinez et al. (1994)]

	STROBOSCOPE (A)		Intermediate model (B)		Comparison (B/A)	
Measurement	Duration	Cost	Duration	Cost	Time ratio	Cost ratio
Sample size	100	100	100	100	1.0000	1.0000
Minimum	115.70	103,323	115.65	103,275	0.9995	0.9996
25% quartile	116.59	104,112	116.55	104,081	0.9997	0.9997
Mean	116.89	104,386	116.82	104,318	0.9994	0.9994
Median	116.87	104,367	116.86	104,351	0.9999	0.9998
75% quartile	117.24	104,701	117.13	104,600	0.9990	0.9990
Maximum	118.01	105,387	118.24	105,591	1.0020	1.0019
Standard deviation	0.47	417.9	0.47	418.0	1.0013	1.0002
95% UCL	116.98	104,468	116.91	104,400	0.9994	0.9994
95% LCL	116.78	104,285	116.76	104,269	0.9999	0.9998

tion results. These results suggest that the *intermediate model* is a valid model and could be used to simulate the effect of management actions.

Hybrid Model with Management Action

Based on the *intermediate model* validated in the previous section, this section will develop the *hybrid model* by incorporating management actions.

Hybrid Model Building

In the section entitled "*Trade-offs in the Earthmoving Process*," we argued that it is important to synchronize the truck circulation rate with the loader circulation rate for optimal cost effectiveness. We also explained that management actions can enhance cost effectiveness of the process in the section entitled "*The Missing Link: Management Action*." For incorporation of these actions into the model, we first need to evaluate the process continuously in order to determine when such actions should be adopted. For this, the *MatchFactor* variable, initially proposed by Smith et al. (1995), is elaborated in this study and calculated as follows

$$\text{MatchFactor} = C_L/C_T = (N_L/T_L)/(N_T/T_T) \tag{1}$$

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.

Smith's study regarded the *MatchFactor* as a *static* variable, which determines whether an appropriate number of trucks is *initially* allocated for maximum process efficiency. However, the study presented in this paper, extending Smith's idea, considers this index a *dynamic* variable, which continuously changes through the entire process because the truck circulation rate continuously decreases as explained in the section entitled "*Trade-offs in the Earthmoving Process*." Similar to Smith's study, in the study presented in this paper, when *MatchFactor* is one, the process is perfectly cost effective. In addition, *MatchFactor* greater than one indicates that the number of trucks is insufficient and less than one means truck redundancy. This index is continuously evaluated over the entire process in order to trigger management actions. Whenever this index 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.

Hybrid Model Validation

The *hybrid model* is developed from the *intermediate model* by incorporating management actions. Though the *intermediate model* is validated under various modeling contexts, since management actions are newly incorporated system elements into the *hybrid model*, these need to be further validated. From the modeling point of view, the main difference between the *hybrid model* and the *intermediate model* is that the former can provide information for taking management actions (i.e., when and how many additional trucks should be ordered and when these will be actually assigned to the process) by continuously evaluating *MatchFactor*, whereas the latter cannot. Therefore, if the information can be fed to the validated *intermediate model* and the model is simulated with this information, this can be used for validating the *hybrid model*. If the *hybrid model* is valid, its simulation results would correspond to the *intermediate model* results which are simulated with the information for taking management actions.

In order to feed the information to the *intermediate model*, a "*Program*" block is embedded in the *intermediate model*, which can provide certain items (*Trucks* in this case) at user-defined times. This block is programmed to assign additional trucks using the information obtained from the *hybrid model* simulation results (i.e., time and amount of newly ordered trucks). Taking advantage of the *Program* block, we simulated the *intermediate model* again with the information for taking management actions and compared the results with the *hybrid model* simulation results. Simulation results of both models are identical. This suggests that the *hybrid model* is valid and could be used to analyze the impact of management actions to the process performance.

Simulation Results Analysis

In this section, the *hybrid model* simulates the effect of the management action of truck adjustment that a construction manager may take in the earthmoving process. Simulating the *hybrid model*, we will assess the impact of the management action to the process performance and analyze how we can enhance the performance.

Experimental Design

In terms of taking the management action, there could be two main decision factors: (1) how many trucks should be initially

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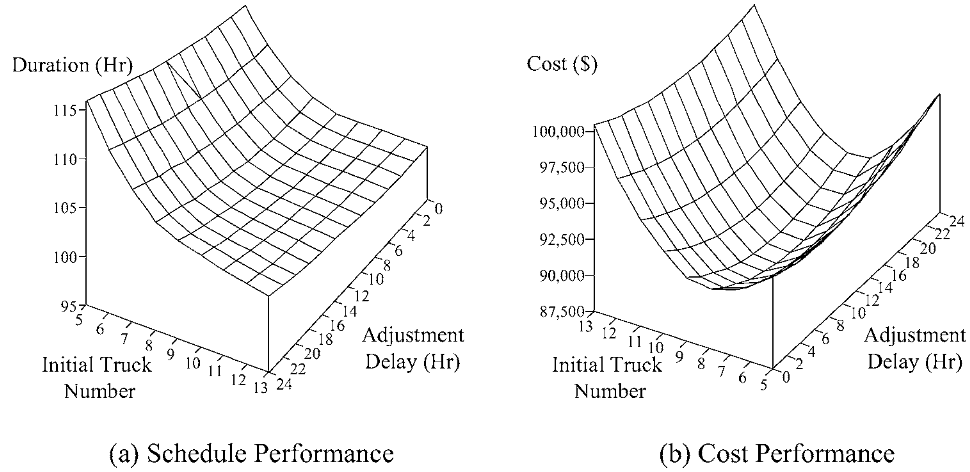

Fig. 6. Response surface for cost and schedule performance

allocated and (2) how quickly additional trucks can be assigned when required. To examine these factors, the process is simulated with: (1) 5–13 initial trucks and (2) zero (ideal case) to 24 working hours of adjustment delay.

Response Surface Analysis

In order to analyze the effects of the initial number of trucks and adjustment delay on cost and schedule performance, we utilized a response surface methodology (Myers and Montgomery 2002). Fig. 6(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. Fig. 6(a) shows schedule performance is primarily dependent on initial truck numbers. Although adjustment delay also affects the schedule performance, its impact is not as significant as that initial truck number's impact. Also, Fig. 6(a) shows the sensitivity of increasing initial trucks on the schedule performance. When the initial truck number is less than 8, its sensitivity is significant, but decreases when the initial truck number is greater than 8. Unlike the schedule performance, the cost performance produces a convex curve in terms of initial number of trucks [Fig. 6(b)]. When 8 trucks are initially assigned to the process, the cost performance is optimal in all cases of adjustment delay. This is because redundant trucks can cause idling cost and too few trucks can interrupt the process and consequently lower the cost performance. In addition, the cost performance produces a convex curve in terms of adjustment delay while its sensitivity is not as significant as the impact of initial truck numbers. Generally, it is believed that the shorter the adjustment delay, the better the cost performance that can be obtained because shorter adjustment delays can be helpful in minimizing process disruptions caused by the truck shortage. Contrary to this general perception, the simulation results show 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 h of adjustment delay. This implies that the cost performance is not in proportion with managerial efforts to improve decision factors. In the traditional approaches, it is often assumed that the process performance could be linearly enhanced with managerial efforts and 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 resource levels will enhance schedule performance, but degrade cost performance. However, as shown in Fig. 6(b), the simulation results demonstrate that if the impact of these actions is not carefully analyzed within 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 increase project performance.

Table 4 details summary statistics of the simulation results of the *intermediate model* and the *hybrid model*. The *intermediate model* was simulated with three loaders and eleven trucks and the *hybrid model* was simulated with eight initial trucks and 10 h of adjustment delays. An examination of the results of the two simulations reveals important differences. Also, we further checked differences of the simulation results using statistical hypothesis tests ($H_0\!:\boldsymbol{\mu}_{\text{Intermediate}}=\boldsymbol{\mu}_{\text{Hybrid}}$ and $H_1\!:\boldsymbol{\mu}_{\text{Intermediate}}>\boldsymbol{\mu}_{\text{Hybrid}}$). The test results indicate that the null hypothesis is clearly rejected ($p=0.001$, $\alpha=0.01$). In addition, the test results show that the management actions could result in time saving of 4.22–4.45% (95% confidence interval) and cost saving of 4.02–4.25% (95% confidence interval) over the optimal simulation results of the *intermediate model.* As the probability of Type I error (i.e., rejecting H_0 and accepting H_1 even though H_0 is true) is denoted by α (significance level of the test), the probability that these improvements might be within the range of statistical error is less than 0.01.

Fig. 7 clearly represents how management actions brought these enhancements. When the management actions are omitted [Fig. 7(a)], the simulation results reveal ineffectiveness in that some trucks are redundant at earlier phases (potential cause for degraded cost performance) and are insufficient at later phases (potential cause for process disruption). However, when the management actions are implemented [Fig. 7(b)], trucks are fully utilized during the whole process and loaders are utilized at around 98.5% during the same period. Although the management actions generate 1.5% of idling loaders, this plays a significant role as a buffer for hedging a process disruption due to truck shortage. Such simulation results provide a demonstration on how management actions can enhance process performance.

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Table 4. Summary Statistics of the Intermediate Model and the Hybrid Model

	Intermediate model (A)		Hybrid model (B)		Comparison (B/A)	
Measurement	Duration	Cost	Duration	Cost	Time ratio	Cost ratio
Sample size	100	100	100	100	1.0000	1.0000
Minimum	115.65	103,275	110.47	98,804	0.9552	0.9567
25% quartile	116.55	104,081	111.41	99,679	0.9559	0.9577
Mean	116.82	104,318	111.76	100,002	0.9567	0.9586
Median	116.86	104,351	111.78	99,986	0.9565	0.9582
75% quartile	117.13	104,600	112.03	100,313	0.9564	0.9590
Maximum	118.24	105,591	113.02	101,233	0.9558	0.9587
Standard deviation	0.47	418.0	0.51	465.6	1.0880	1.1139
95% UCL	116.91	104,400	111.86	100,093	0.9568	0.9587
95% LCL	116.76	104,269	111.68	99,895	0.9564	0.9581

Conclusions

As project failures could be ascribed to a mismatch between strategic policy and operational efforts, both strategic and operational issues need to be considered simultaneously when taking management 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 the integration of SD and DES modeling. For a proof of concept purpose, we applied the model to a nontypical earthmoving process example and examined how management actions can impact the process performance. Through a series of response surface analyses, the simulation results indicated that the *hybrid* model can help construction managers find potential process improvement areas. Although DES models have been extensively applied to simulate the earthmoving process, these are limited to explicitly discover this improvement area. However, this study utilizing a hybrid approach could visibly discern the area through analyzing the process feedback structure as represented in Fig. 5.

In practice, increasing project complexity makes it more difficult to take effective control actions. In this circumstance, this research would help construction managers successfully control their projects by simulating the impact of their actions in advance. For example, when construction managers face a lower progress rate than planned, their intuition would not always provide a systematic means of compensating for the delayed schedule. The reason is that performance enhancement does not always follow our general perception, as shown in the earthmoving case. In such a case, this research could provide a reliable mechanism of supporting project control.

Although this research is a meaningful step toward integrated strategic-operational construction project management, additional considerations are still required to be fully utilized in real construction projects. This study does not extensively consider side effects or ripple effects caused by the management actions. These may make strategic decision processes more complex and less reliable. The writers believe that further exploration of these challenging issues is necessary to discover the complexities and dynamics of construction projects and ultimately increase project performance.

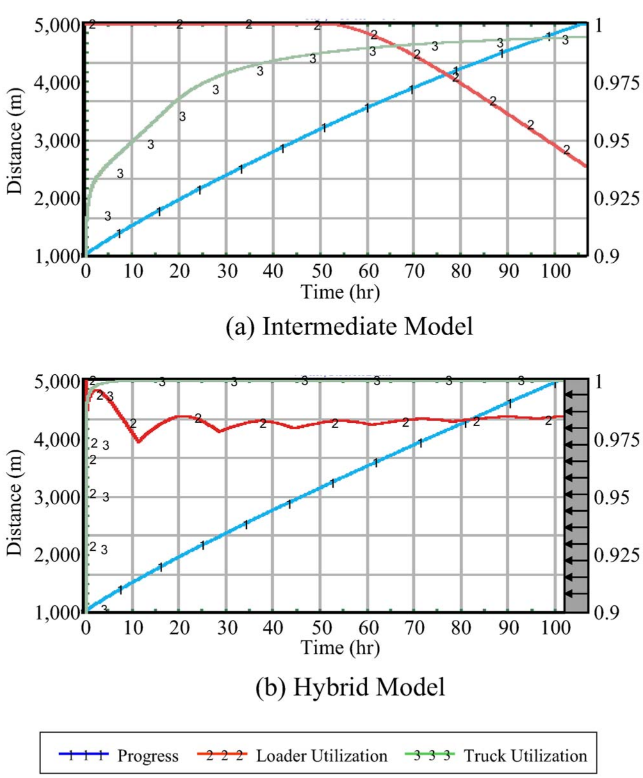

Fig. 7. Simulation results

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