DYNAMIC PLANNING FOR FAST-TRACKING BUILDING CONSTRUCTION PROJECTS

By Feniosky Pena-Mora[1] and Moonseo Park,[2] Members, ASCE

ABSTRACT: The fast-tracking delivery method has received considerable attention over the last decade, and its time saving feature has placed it as a possible alternative to the traditional more sequential method. Along with its benefits, however, fast-tracking also has greater potential to impact the project development process than the traditional method. In the literature, this is usually attributed to the increased level of uncertainty and research on fast-tracking has mainly focused on uncertainty reduction but without explicit study of the feedback processes involved in fast-tracking. However, closer observations of the project development process suggest that to effectively handle uncertainty and minimize the negative impact of fast-tracking, the feedback processes involved in fast-tracking need to be identified, and the dynamic behavior of construction resulting from those feedback processes needs to be dealt with in a systematic manner. As an effort to meet these needs, this paper presents the Dynamic Planning Methodology, a planning methodology based on system dynamics. Focusing on the dynamic behavior of fast-tracking construction, the Dynamic Planning Methodology aims to improve the planning and management of fast-tracking building construction projects by providing overlapping strategies, workforce control policies, and schedule adjustments that will minimize the negative impact of fast-tracking.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

INTRODUCTION

Under a rapidly changing business environment, the construction industry has been seeking a new method to ensure a faster and more economic project delivery. Among the various efforts to meet this challenge, the fast-tracking delivery method has received considerable attention over the last decade, and some success stories of fast-tracking with its time saving feature have been demonstrated in the literature (Huovila et al. 1994; Williams 1995).

However, despite its promise of speed, fast-tracking also has greater potential to impact the project development process than the traditional more sequential method. In reality, this popular method often results in unexpected costs and does not necessarily lead to the expected shorter project duration (Fazio et al. 1988). In the literature, these potential risks are usually attributed to the increased level of uncertainty (Russell and Ranasinghe 1991). As a result, research efforts on fast-tracking have mainly focused on uncertainty reduction. However, in dealing with uncertainty, the previous studies did not explicitly address the potential effects of feedback processes involved in fast-tracking construction. Closer observation of the design and construction process, as will be described in the following section, indicates that the feedback processes that are triggered by uncertainty, make the construction process more dynamic and unstable, possibly creating negative impact on the project performance. In particular, when a project is fast-tracked without proper planning, those feedback processes can cause the disruption of the whole project development process. For these reasons, to effectively handle fast-tracking and minimize its negative impact, the feedback processes involved in fast-tracking need to be identified, and the dynamic behavior of construction resulting from those feedback processes needs to be dealt with in a systematic manner.

As an effort to meet these needs, this paper presents the Dynamic Planning Methodology (DPM), a planning methodology developed at Massachusetts Institute of Technology. Focusing on the feedback process and dynamic behavior of fast-tracking construction, DPM aims to improve the planning and management of fast-tracking building construction projects. In order to systematically deal with the potential problems of fast-tracking construction, DPM adopts system dynamics, which has been well known for its analytic capability to solve problems involved in complex systems, since developed in the late 1950s (Richardson 1985). Based on the system dynamics model simulation and cost-benefits tradeoff analysis, DPM provides overlapping strategies, workforce control policies, and schedule adjustments that will minimize the negative impact of fast-tracking. The enhanced planning and management capability through DPM may help ensure the effective delivery of fast-tracking building construction projects without driving up costs.

[1]Assoc. Prof., Information Technol. and Proj. Mgmt., Intelligent Engrg. Sys. Lab. (IESL), Ctr. for Constr. Res. and Educ. (CCRE), Civ. and Envir. Engrg. Dept., MIT, Cambridge, MA 02139. E-mail: feniosky@mit.edu

[2]PhD Candidate, CCRE, Civ. and Envir. Engrg. Dept., MIT, Cambridge, MA 02139. E-mail: mspark@mit.edu

Note. Discussion open until May 1, 2002. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 2, 2000; revised March 1, 2001. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 127, No. 6, November/December, 2001. ©ASCE, ISSN 0733-9634/01/0006-0445–0456/$8.00 + $.50 per page. Paper No. 22211.

DYNAMICS OF FAST-TRACKING

Construction is inherently dynamic and involves multiple feedback processes that produce self-correcting or self-reinforcing side effects of decisions (Sterman 1992). These feedback processes can become more dynamic and complex under time and resource constraints, which is normally the situation in fast-tracking construction. For this reason, fast-tracking construction usually involves more diversified and dynamic feedback processes than does sequential construction.

This section identifies the feedback processes involved in fast-tracking construction and demonstrates how those feedback processes can impact the design and construction process. The feedback processes identified in this section provide DPM with conceptual foundations to systematically analyze and control the negative impacts of fast-tracking.

Design-Driven Feedbacks in Fast-Tracking

Figs. 1(a) and 1(b) represent feedback processes possibly existing in fast-tracking construction, which are either positive or negative to the project performance. Specifically, the solid arrows in Fig. 1(a) represent the feedback processes such that overlapping between the design and construction process may or may not be beneficial for the project performance. With proper planning and management, the design and construction overlapping can shorten the project duration and reduce costs, as initially planned. However, it can also delay the schedule and increase costs for various reasons. The design and construction overlapping makes the design work usually proceed

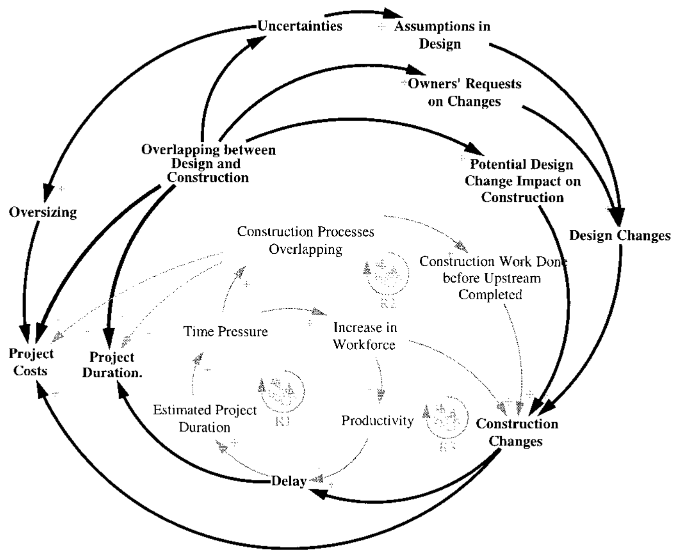

FIG. 1(a). Design-Driven Feedbacks

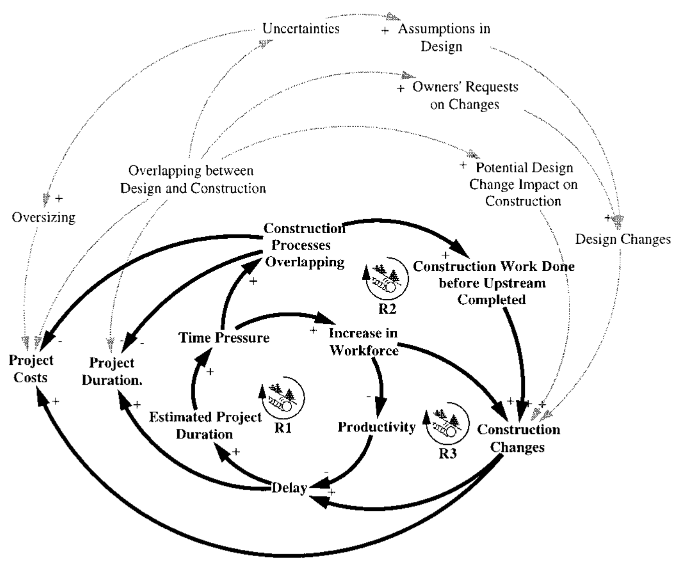

FIG. 1(b). Construction-Driven Feedbacks

with insufficient volume and poor information. Given the uncertainty in the design process, the necessity for assumptions to be made may be increased (Tighe 1991). For instance, the structural engineers may be forced to anticipate loads of a facility for the foundation design before the final layout and detailed specifications for the facility—such as exterior finishing material—have been determined. This increased level of assumption may lead to frequent design changes. In addition, with fast-tracking, design work may begin before the owner's requirements are firmly determined. In such a case, the owner's needs and the corresponding design may be altered more often than on a traditional project. Frequent design changes, driven by both the increased assumption level in design and owners' requests on design changes, in turn can produce more nonvalue-adding or corrective changes (hereinafter referred to as changes) in construction.

Along with the increase of design changes, the increased possibility of design changes impact on construction can also increase the potential for construction changes. With the traditional delivery method, design changes created in the design stages do not necessarily affect the construction performance, as construction may not have started. In fast-tracking, however, design changes occurring during the design stages may cause changes in construction when the construction component is already underway.

Consequently, all of the feedback processes mentioned above can contribute to an increase in construction changes, which could lead to schedule delays and cost overruns. Meanwhile, there is another phenomenon found in the fast-tracked design work that is not necessarily found on the traditional method—everyone in the design process often makes allowances for unknowns to avoid possible impacts and changes (Tighe 1991). For instance, without knowing the required capacity of an air handling unit (AHU) the mechanical engineers may size it too large to ensure adequate capacity. Likewise, the architects may assign additional space for that equipment and the structural engineer may increase the safety factor for its structural analysis due to the unknown loads that the AHU may impose on the structure. This oversizing practice increases protection, but at the same time may cause a substantial increase in the project costs due to inefficient use of resources.

Construction-Driven Feedbacks in Fast-Tracking

Fast-tracking construction also involves feedback processes within construction processes, as shown by the solid arrows in Fig. 1(b). On a fast-tracking project, as a result of the design-driven feedback processes discussed in the previous section, more changes can occur during construction that generate more work. Most of the times, the construction schedule, however, cannot be simply extended due to time constraints. One possible control action to meet the schedule is to increase work hours, either by hiring more workers or putting them to work overtime. Increased work hours can help facilitate the construction. However, once the self-reinforcing side effects of the action become dominant over self-correcting effects, the control action can result in further delays and a rise in construction costs. For example, when overtime continues beyond a certain threshold, workers will become fatigued, leading to lower productivity [denoted as R1 in Fig. 1(b)] and an increase in error rate [denoted as R3 in Fig. 1(b)], which, in turn, further delays the construction schedule and requires more use of overtime.

Another possibility to meet the schedule may lie in running the project more in parallel by overlapping activities, which forces workers to work on construction components, for which the upstream work may not yet be completed [denoted as R2 in Fig. 1(b)]. As a result, the downstream work does not have a schedule buffer that can absorb the impact of any errors and changes made during upstream work, which makes the downstream work more vulnerable to the upstream errors and changes. This can also lead to an increase in construction changes and further delays, which, in turn, requires more overlapping of the construction processes. Consequently, all of these feedback processes can produce more construction changes by self-reinforcing their vicious loop effects, which results in schedule delays and cost overruns. In contrast to the feedback processes driven by the design work, these construction-driven feedback processes can continuously create vicious loop effects throughout the construction duration.

To conclude, depending on the size, complexity, and project team, the feedback processes discussed can have a significant impact on the project performance, especially when a project is fast-tracked in a heavily constrained environment. In particular, if the increased construction cost resulting from those feedback processes exceeds the possible economic gain through the reduced project duration, the effectiveness of fast-tracking should be questioned, except in some cases (this will be discussed later). For this reason, to effectively plan and manage a fast-tracking project, the feedback process should be identified before physical execution is undertaken, and it

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

should be carefully monitored throughout the project duration. However, the dynamic state of construction caused by those feedback processes makes it difficult to anticipate or measure the construction performance resulting from any planning and managerial actions in a linear fashion. This lack of capability to deal with the dynamic state of construction necessitates a systematic and dynamic approach to the planning and management of fast-tracking construction.

SYSTEM DYNAMICS

DPM adopts the system dynamics modeling techniques to deal with the dynamic complexities involved in fast-tracking construction in a systematic manner. System dynamics was developed in the late 1950s to apply control theory to the analysis of industrial systems (Richardson 1985). Since then, system dynamics has been used to analyze industrial, economic, social, and environmental systems of all kinds (Turek 1995). One of the most powerful features of system dynamics lies in its analytic capability (Kwak 1995), which can provide an analytic solution for complex and nonlinear systems. Considering that fast-tracking construction is highly dynamic and involves multiple feedback processes, a system dynamic modeling approach is well suited to dealing with the dynamic complexity involved in fast-tracking construction projects. System dynamics modeling generally proceeds in the following five steps (Kwak 1995):

1. System understanding
2. Conceptualization
3. Model formation
4. Model validation
5. Policy analysis

System understanding is the process of deepening the modeler's understanding of the system with relevant information. In the system conceptualization step, conceptual model structures are described in the form of a causal loop diagram to show the dynamics of variables involved in the system [Fig. 1(a) and 1(b)]. In the model formation step, variables in the model structures assume quantitative attributes, based on the relationships built in the causal loop diagram. This step also includes the identification of stock and flow structures (Fig. 2), which characterize the state of the system and generate the information upon which decisions and actions are based by giving the system inertia and memory (Sterman 2000). Stocks represent stored quantities, and flows represent control quantities flowing into and out of stocks. Once the model formation is done, the completed model needs to be tested and validated in accordance with the purpose of the model. Finally, the validated model is applied to solving the given problems.

DYNAMIC MODELING

The system dynamics models for DPM described in this section have been developed using the standard modeling approach discussed thus far and have their conceptual foundation in the Ford and Sterman model (1997). The Ford and Sterman model was originally developed to explore and describe the product development phases in manufacturing, which consist of product definition, design, prototype testing, and reliability/quality. To apply the implications of their work into fast-tracking construction, DPM augments their model structure by: (1) increasing the number of development phases; (2) making it possible for a development phase to have multiple precedence relationships; (3) embedding the design work process into a generic construction process; and (4) adding subsystem model structures for resource allocation and construction performance monitoring.

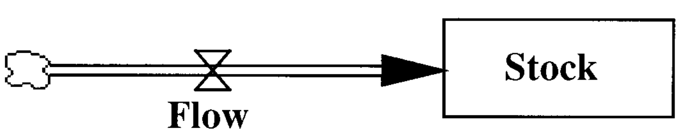

FIG. 2. Stock and Flow Structure

In addition, the DPM model aims to assist in planning and managing fast-tracking building construction projects by providing effective overlapping strategies, workforce policies, and schedule adjustments when external or internal changes happen during the project duration. To meet the modeling purposes, the model has been built to have the following functions: (1) capturing the feedback processes involved in a fast-tracking building construction project; (2) analyzing the negative impact of fast-tracking on the project performance; and (3) assessing the time and cost consequences of compressing or overlapping the design and construction processes. Some of the fundamental concepts and model descriptions are detailed below.

Effectiveness of Fast-Tracking

DPM determines the effectiveness of fast-tracking based on the economic viability of construction projects delivered by fast-tracking. This research effort recognizes that the effectiveness of fast-tracking cannot be measured solely based on economic principles, because there can be many intangible benefits. For instance, there are times when market conditions change rapidly and require owners to beat their market competitors with an earlier completion of their projects (Tighe 1991). In these cases, the market value of the shortened time is beyond the tradeoff between the possible economic gain through the reduced project duration and the increased cost to reduce the duration. Nevertheless, except for those cases, the cost-benefit tradeoff suggested in this paper can be useful to compare the effectiveness of different fast-tracking strategies, helping the project manager to establish a benchmark to compare various alternatives for effective fast-tracking.

Grouping

The DPM model is built to simulate multiple phases during the design and construction period of a building project. The model has 12 separate development phases that characterize a typical building construction project, as shown in Fig. 3. Each phase involves a specific number of tasks (hereinafter called work packages). In the model, work packages that flow through the development procedure of a project are assumed to require the same percentage of labor force and material within a certain development phase. In the model, each development phase is represented by a generic structure that can be customized to describe a specific stage of a building construction project and is connected to other development phases with dependency relationships among them.

Dependency

Dependencies involved in the development process of a building project play the role of the main constraints to construction progress. Accordingly, to effectively plan the project, these dependencies need to be identified and modeled in detail. There exist two kinds of dependencies in the development process of a building construction project—interphase dependency among development phases and internal dependency within a phase.

Interphase Dependency

The interphase dependency captures the dependency relationship among activities that has been represented by the

J. Constr. Eng. Manage., 2001, 127(6): 445-456

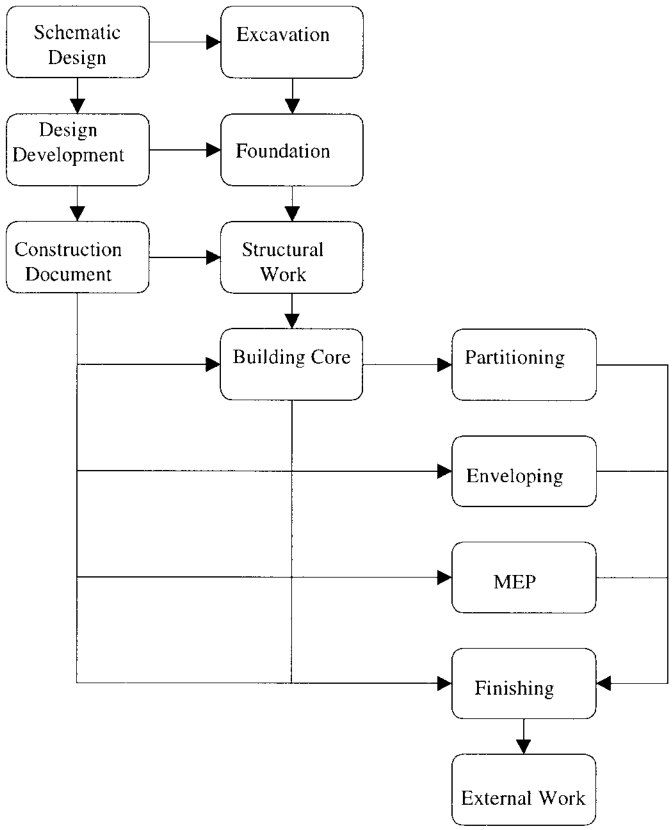

FIG. 3. Relationships of Development Phases

precedence relationship in the traditional Critical Path Method (CPM)-based methods. While the precedence relationship deals with only the start and finish of an activity in a static manner, the interphase dependency can dynamically describe the dependency relationship throughout the activity duration. Fig. 4 shows some examples of interphase dependencies in building construction projects. In the graphs, the horizontal axis represents the progress of upstream work, while the vertical axis represents the progress of downstream work.

For example, the concurrence relationship between excavation and foundation work can be represented by Graph A in Fig. 4. The downstream phase, foundation work is scheduled to start at 50% completion of the upstream phase, excavation, and thereafter foundation work can proceed in proportion to the progress of the excavation. In contrast, Graph B in Fig. 4 represents the concurrence relationship such that downstream work can start only after partial or entire completion of upstream work. In this case, there is no further dependency between the overlapped processes once downstream work gets started.

Internal Dependency

The internal dependency of a phase has not been considered in the traditional CPM-based methods. However, a construction process involves procedural or physical constraints that can create dependencies between work packages within a phase. For example, the concrete formwork requires forms to be installed, inspected for proper installation, and corrected if the installation is unacceptable. This kind of procedural constraint exists in most construction processes and can affect the development progress and time of the construction. In addition, some development phases in building construction projects, such as structural work, have physical constraints such that lower floor work should be completed before any work on the following floor, because lower floor supports those above. In the DPM model, such a constraint is simulated with

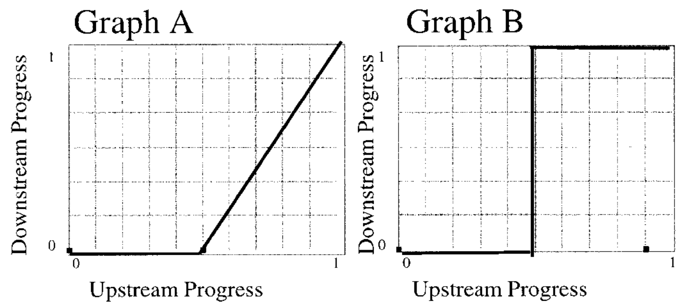

FIG. 4. Examples of External Dependency [adopted from Ford and Sterman (1997]

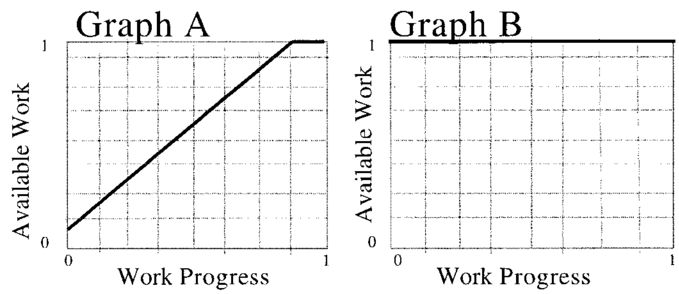

FIG. 5. Examples of Internal Dependency (adopted for Ford and Sterman (1997)]

the internal concurrency depicted in Graph A in Fig. 5. Meanwhile, the internal concurrency depicted in Graph B in Fig. 5 can be applied to the development phases that do not have physical constraints, such as partitioning, finishing, and external work. This internal concurrency relationship allows those works to proceed at any time given enough resources.

To conclude, all of the dependencies discussed in this section can constrain the design and construction process and influence the project performance. In particular, when a project is fast-tracked, they may have a significant impact on the project schedule and costs. To effectively represent these dependencies, the DPM model is designed for each work package and development phase to be linked in concurrent relationships. These concurrent relationships are embedded in each construction process model structure to be described in the following section.

Generic Structure for Building Construction Processes

The generic model structure described in this section has been developed to model building construction processes. In particular, it is designed to capture the dynamic behaviors between design and construction that are critical to the successful delivery of fast-tracking building construction projects. Fig. 6 describes a generic construction process with the stock and flow structure.

In the model structure on Fig. 6, tasks flow into and through four stocks in the unit of a *Construction Work Package* (CWP)—*CWP Done*, *CWP to be Released*, *CWP Waiting for Redesign*, and *CWP to be Corrected*. Through the performance of the *Initial Completion Rate*, tasks are initially completed and then accumulate in the stock, *CWP Done*. The work packages that reach the target quality level in *CWP Done* stock leave and pass through the process of approve rate flow into the stock of *CWP to be Released* where the work packages wait to be released. If the work packages need to be corrected due to design changes, the packages are moved to the *CWP Waiting for Redesign* and, upon the completion of redesign for the packages, to the *CWP to be Corrected* stock. Otherwise, the packages are released to the next stage. Meanwhile, work

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

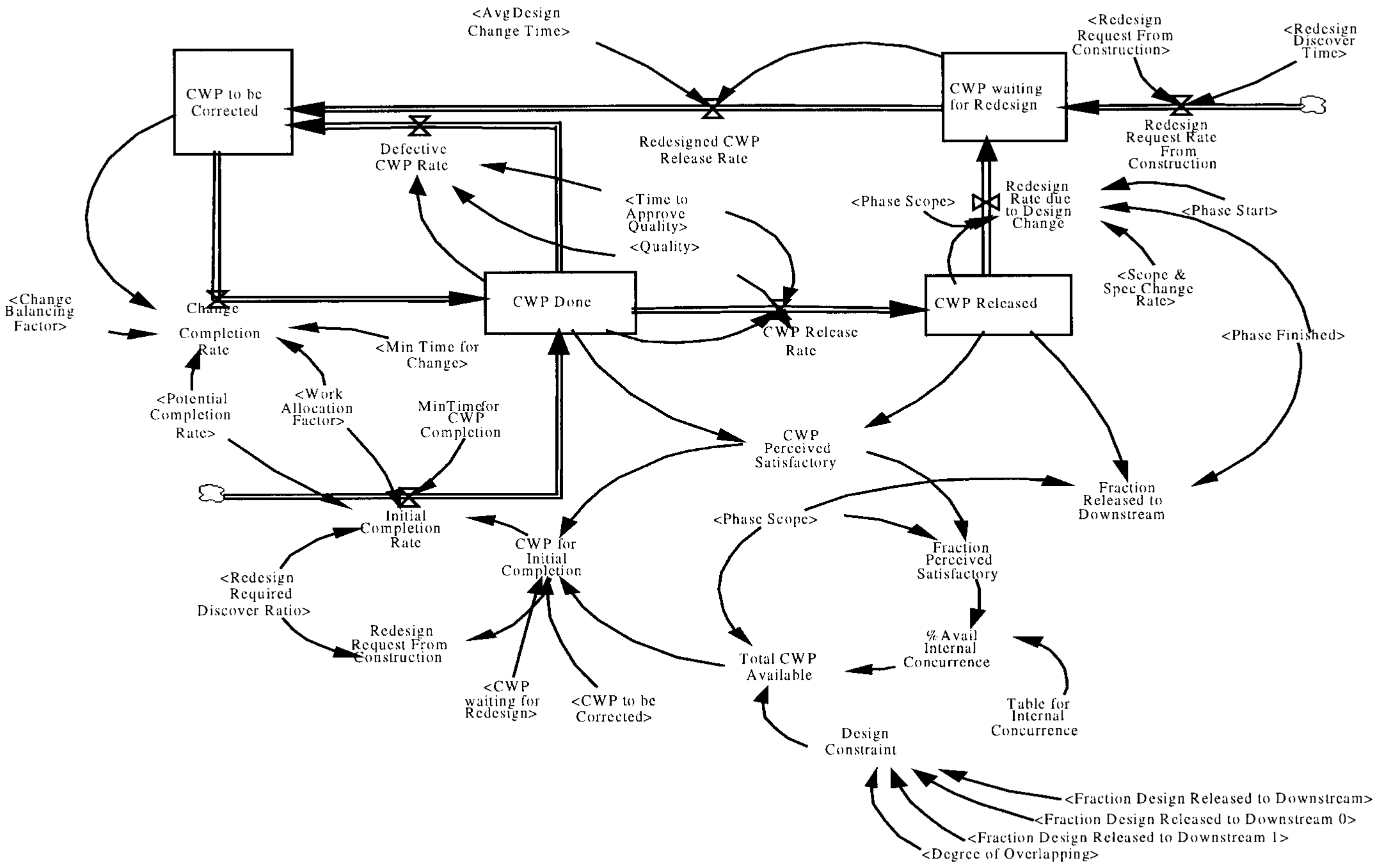

FIG. 6. Generic Structure for Construction Process [Augmented from the Ford and Sterman (1997) Development Process Model]

packages that do not reach the target quality level pass through the process of *Defective CWP Rate* flow from the stock of *CWP Done* to the stock of *CWP to be Corrected*. These work packages are then corrected or improved through *Change Completion Rate* process and returned to the stock, *CWP Done*. The following example supports the understanding of the model structure described above. When the finishing work on the first floor is done, it is inspected for quality assurance. Work that does not reach the target quality is corrected and again inspected. Work that satisfies the quality objectives allows its succeeding work to start unless there are design changes on the work during that period. If design on the work has been changed during the period, the work should be corrected based on the revised design. Correction work cannot proceed until design change is completed. Once the design change is done, the work is corrected and inspected again.

In addition, as seen in the model on Fig. 6, *Total CWP Available* is determined by phase scope and several constraints, including internal concurrence dependency, design constraints, and interphase concurrence dependency. Internal concurrence dependency is given to the model according to the feature of the concerned work. *CWP for Initial Completion* is the *Total CWP Available* less CWP accumulated in all of the stocks of the generic development structure. In addition, every construction work package is dependent on the required design work, which can be modeled using percentages of each design process, schematic design, design development, and construction document. Also, each CWP has different external dependency, which is decided by the interphase concurrency between the focal phase and relevant upstream phases.

The generic model structure in Fig. 6 is used to simulate the building construction process, which was grouped into 12 work-breakdown-structures in the previous section. The model structure is customized to each building construction process. In addition, submodel structures, including resource and performance models to be described in the following sections, are incorporated into each of the customized building construction process model structures.

Resource Model Structure

Resource model structures in this section are used to simulate resource acquisition and allocation in fast-tracked building construction projects. The management of resources under time constraints causes most of the difficulties found during fast-tracking projects. In addition, building construction projects usually involve many delays in the process of resource acquisition and allocation and the estimation of resource. To rigorously plan and manage fast-tracked building construction projects, the process of resource management during construction needs to be identified and modeled in detail.

Estimation of Required Workers

The DPM model adopts three main policies regarding labor control—fixed headcount, flexible headcount, and overtime. Basically, required workers are estimated based upon the volume of work to be done, the time horizon to completion, productivity, and quality, regardless of labor policy. In the case of a fixed headcount policy, the initially estimated labor resource level is maintained throughout the project duration. However, when a flexible headcount policy or overtime is applied to the simulation, the required worker level continuously changes, based on the volume of work to be done, the time horizon to completion, productivity, and quality at every time step.

Estimation of Schedule

The model in Fig. 7 represents the process of completion date projection. The projection is done based on the remaining

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

work amount and normal construction work rate, as determined by current workforce, productivity, and workweek. Time delay is involved in the process, because it takes a certain amount of time to gather data and to report it to managers, which plays an important role in characterizing fast-tracked project behaviors. Such an information delay exists, because people do not change their minds immediately on the receipt of new information, and reflection and deliberation often take considerable time (Sterman 2000). The simulation results of the model provide a basis, on which decisions for resource allocation and management will be made.

Flexible Headcount Labor Policy

The labor control model in Fig. 8 is applied to simulate the adjustment of the current workforce to the desired workforce level by hiring new workers. In this model structure, the desired effective workforce is calculated based on the remaining work, the expected productivity of performing that work, and whatever is critical to the phase between the available time to completion and the minimum time for the phase work. Once a desired effective workforce is obtained, it is adjusted through the hiring process, which involves a time delay.

The simulation result of this model provides the required workforce level to finish the project on time. In addition, this model structure makes it possible to analyze the causes and the effects of delays in labor control, such as increasing or decreasing personnel for an activity. This feature is valuable, especially when the project is fast-tracked, because in fast-tracking, delayed labor adjustment to the desired workforce level has greater impact on the project performance due to the tight schedule in which the work is done.

Overtime Labor Policy

The labor control model in Fig. 9 simulates the process of adjusting the current workweek to a desired workweek level

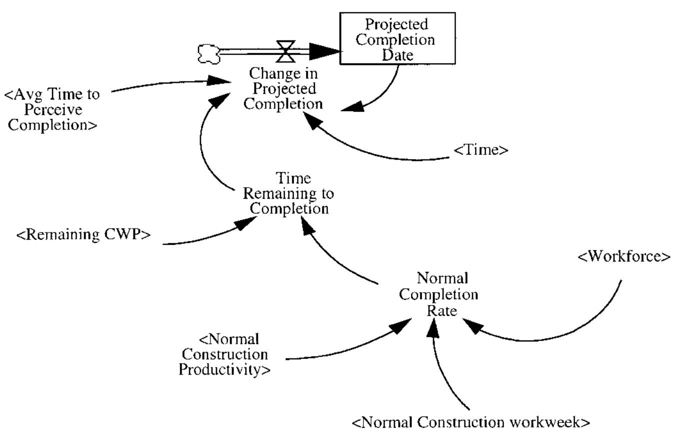

FIG. 7. Perceived Completion Time Model

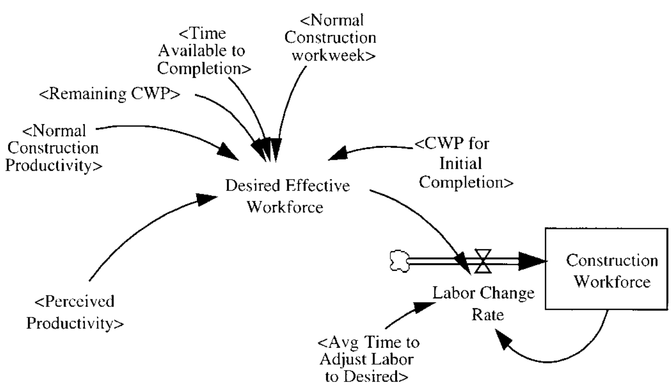

FIG. 8. Labor Hiring Model

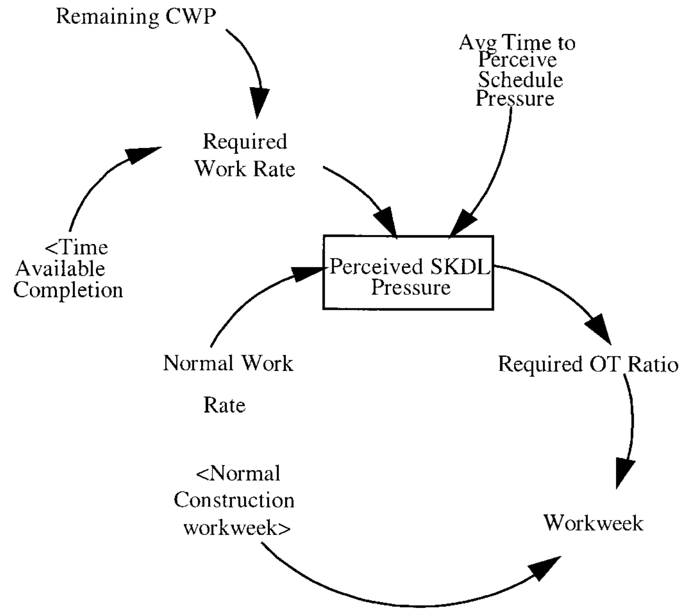

FIG. 9. Overtime and Workweek Model

by adopting an overtime policy. First, a required work rate is calculated, based on the remaining work and available time to completion. Then, the schedule pressure is determined by comparing the calculated required work rate against the normal work rate that is calculated based on current head count and workweek. In the model, it is assumed that when the required work rate is greater than the normal work rate, contractors or project managers perceive the schedule pressure with a time delay. According to the perceived schedule pressure, the overtime ratio and workweek are determined.

In the model, the overtime ratio ranges from 1.0 to 2.0, which means that according to the degree of the schedule pressure, construction workers can work up to 80 hours per week, given the 40 hours of a normal workweek. In addition, considering that the overtime ratio can vary depending on construction conditions and policies, the model is designed to have a different overtime ratio range based on a DPM user's manipulation. This model structure will calculate how many additional work hours are required to meet the schedule. When the construction progress is behind schedule, contractors or project managers start to feel the schedule pressure.

Performance Model Structure

The performance of building construction work is usually assessed in terms of time, quality, and costs. The model structures in this section deal with these factors, focusing particularly on changes in workers' productivity under given work environments. To do this, the performance model structures will simulate how other associated variables affect productivity and how construction workers perceive changes in those variables.

Workweek and Effect of Fatigue

The workweek component of the model simulates the size of the average workweek based on the schedule pressure and overtime ratio with a normal workweek (40 h/week) and a range from no work to the maximum work in a week (0–80 h). The values of the workweek over the recent past are used to represent workers' fatigue, which in turn affects the quality of work and productivity. In the model structure of Fig. 10, the initial value of the average workweek (40 h) changes as the perceived workweek change is accumulated in the stock of perceived workweek. This perceived workweek change is

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

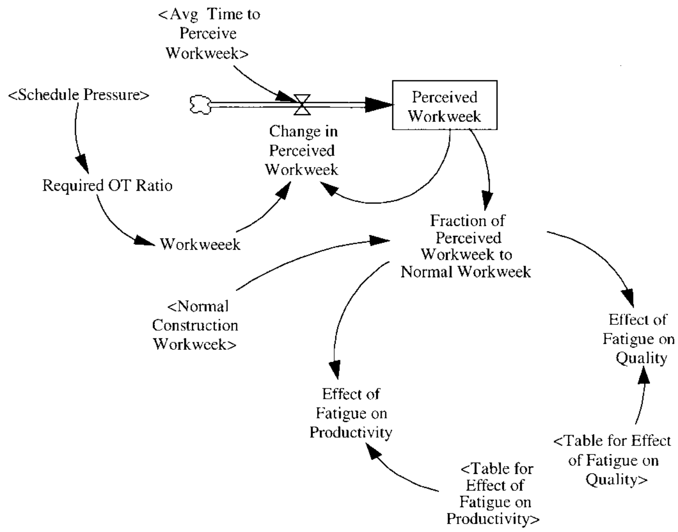

FIG. 10. Workweek and Effect of Fatigue Model [Augmented from the Ford and Sterman (1997) Fatigue Model]

determined by the normal workweek time and the current workweek.

As the schedule pressure increases, the workweek grows within the maximum workweek size. However, workers do not perceive the actual amount of increase in workweek due to a delay and information adjustment. If the schedule pressure continues to grow, the perceived workweek increases, which increases workers' fatigue and, in turn, lowers productivity and quality. The workweek component obtained from the simulation of the model structure will be a basis for calculating the current construction rate, while the degree of workers' fatigue level will be used to measure the workers' productivity and the construction quality.

Productivity

One of the most important things to obtain a reliable simulation result is to have a realistic productivity estimate, given construction conditions. Normally, construction site managers do not consider flexible labor productivity when they schedule the project or hire new workers. The productivity of workers, however, varies depending on the work environment and construction progress over time. For example, workers' productivity is usually low in the beginning of construction due to the lack of knowledge on the work environment. But, productivity tends to increase as construction progresses and workers become familiar with the environment. Some previous studies on simulation-based construction planning apply various productivity patterns to the simulation of the construction process. However, they simply apply a different productivity level according to construction stages, rather than dynamically handling changes in workers' productivity throughout the construction process. For example, Bernold (1989) classified the productivity pattern according to three development phases—start-up, transient, and termination—and applied them into his simulation model. Although his model could simulate more realistic productivity than did the previous simulation models, the model did not capture dynamic changes in productivity according to changes in construction conditions.

In contrast, DPM aims to help the project manager estimate labor productivity in a more plausible way during construction, focusing on changes in workers' response to the given construction conditions. The model in Fig. 11 simulates the productivity of each development phase, based on workers' experience, effect of schedule pressure, and effect of fatigue. The more experience with a specific phase on a project, the more efficiently workers can work. In the model, it is assumed that workers gain experience as the project progresses. Meanwhile, schedule pressure can help increase productivity to a certain degree, as productivity tends to be low when progress is ahead of schedule. Additionally, productivity is considered to decrease when workers' fatigue is accumulated. The estimated productivity based on the model structure will be a basis for the calculation of the construction rate, project completion, and required labor acquisition.

To summarize, this section presented some of the fundamental concepts and descriptions of the DPM model. The complete DPM model consists of 1,053 variables, which have resulted from an effort to replicate the feedback processes existing in real fast-tracking building construction processes and to implement the model functions required to achieve the research goals. To test its applicability and usefulness, the DPM model has been simulated with a sample project, which will be presented in the following section.

MODEL SIMULATIONS

In this section, the applicability and usefulness of the DPM model presented thus far is tested. For the model test, DPM is simulated with a real world project, which is an office building construction project being developed by Daewoo Corporation. The project has been carried out by fast-tracking, aiming to reduce time to market in Warsaw, Poland. But, it has experienced a lot of problems including some of the fast-tracking problems discussed earlier in this paper. As a result, this project could not be completed by its completion date

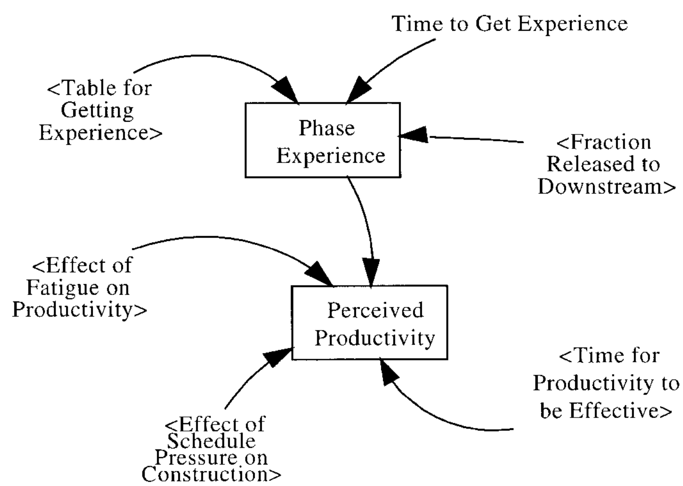

FIG. 11. Perceived Productivity Model

TABLE 1. Description of Sample Project

Project phases	Schedule (weeks)	Turnover (m^2/week/worker)	Hard costs (millions of dollars)
Schematic design	8	9.3	—
Design development	12	6.25	—
Construction document	18	4.2	—
Excavation	32	4.5	8
Foundation	24	3.5	7
Building core work	56	0.6	25
Structural steel work	56	0.7	40
Partitioning	56	0.7	5
Enveloping	44	0.9	30
MEP	56	0.7	40
Finishing	60	0.9	10
External work	24	4.25	1

Note: Project name: Warsaw Daewoo Center; Location: Warsaw, Poland; Owner/Developer: Daewoo Corp., Korea; Total building area/floor: 30,000 m^2/40; Delivery method: Fast-tracking/construction management; Estimated project duration: 156 weeks.

J. Constr. Eng. Manage., 2001, 127(6): 445-456

(September 1999). A brief description of the project is presented in Table 1.

Simulation of Sequential Delivery Method

In this section, the sample project is simulated within the scenario that represents the traditional sequential method such that the project is carried out with flexible labor policy and no overlapping between design and construction. This case will be compared to the fast-tracking cases to be described in the following section. Some of the simulation results are as follows.

Workforce

As a result of the simulation, the project is completed at week 200 with project costs of $197.19 million. The graph in Fig. 12 shows the number of workers per week for each phase and the accumulated workers. As shown in the graph, the cu-

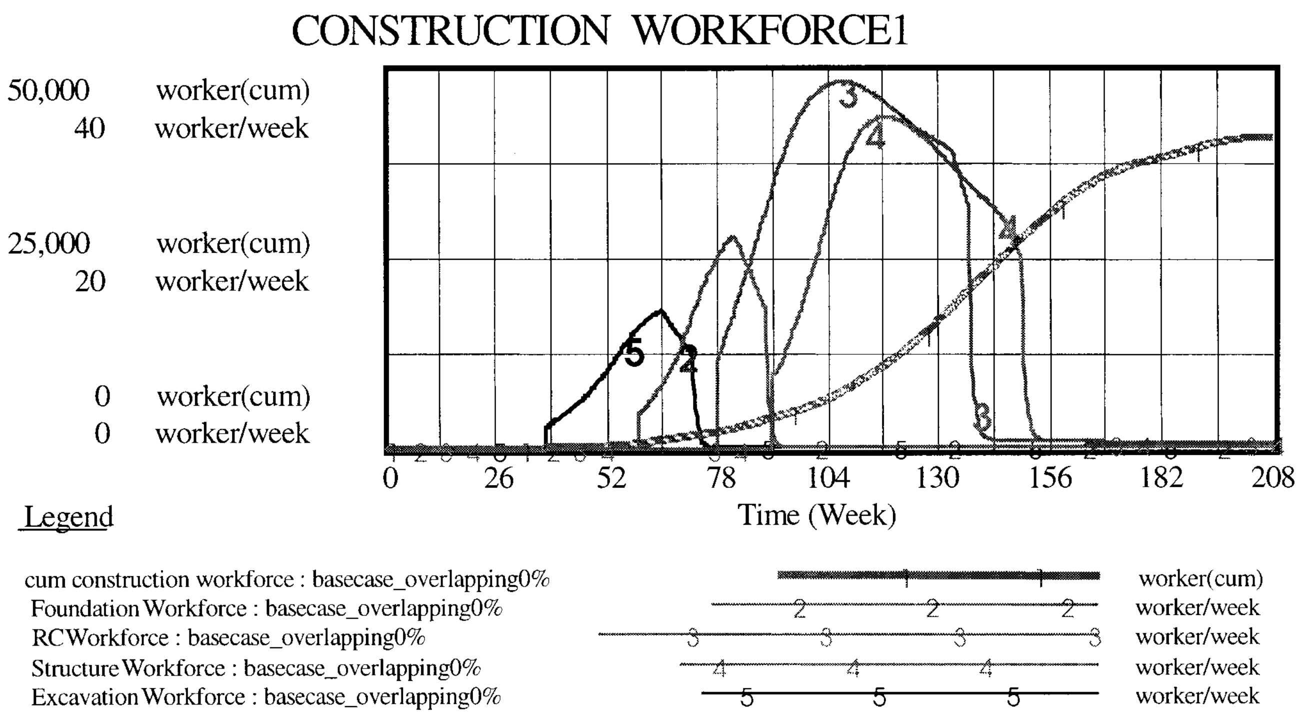

FIG. 12. Workforce during Construction

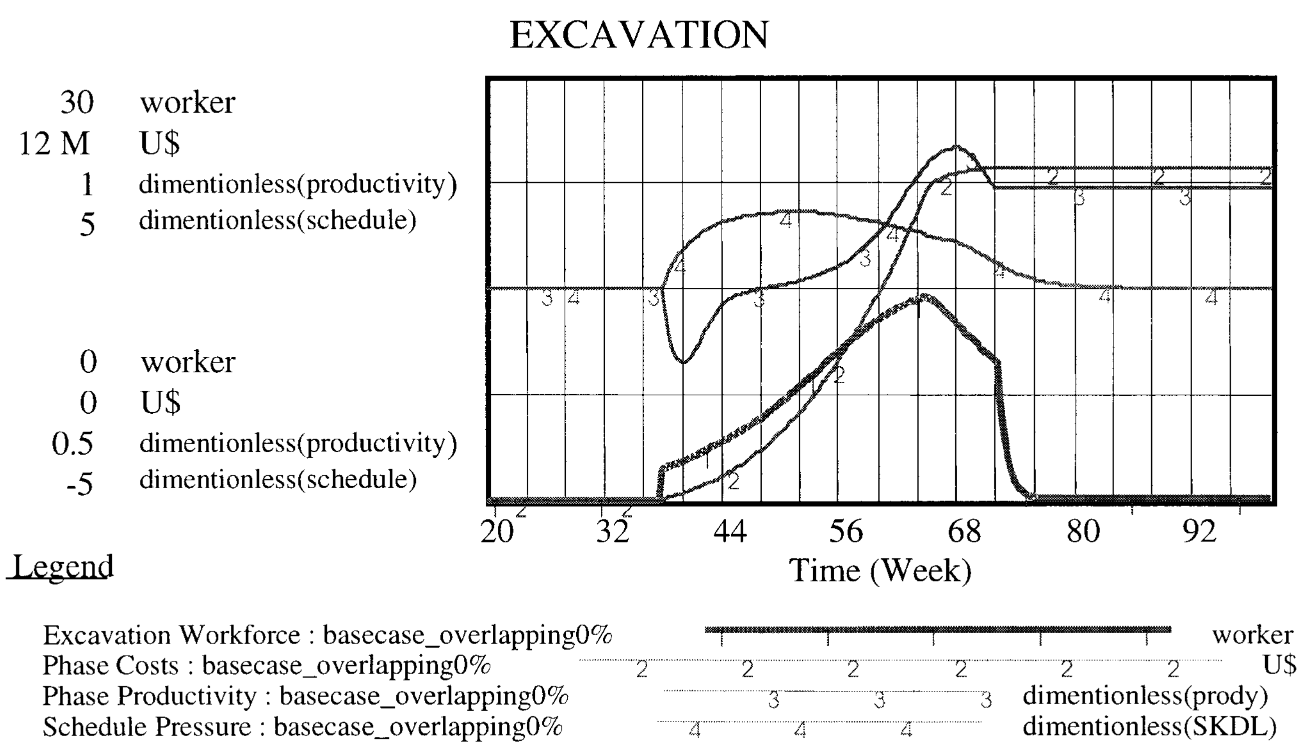

FIG. 13. Workforce Excavation Work

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

mulative number of workers involved in the project reaches 40,605 with an S-shaped curve.

For a detailed analysis, the simulation result of required workforce for the excavation work phase is presented in Fig. 13 together with that of schedule pressure and productivity. Fig. 13 shows how the schedule pressure and the productivity influence the required workforce level and construction costs. For instance, schedule pressure significantly increases from the beginning of the phase and smoothly decreases after half of the phase has progressed. This is because in the initial stage of the phase, excavation proceeds slowly due to low productivity and the fact that construction usually commences with a relatively small number of workers. As the workers are getting familiar with the work environment, productivity continuously increases, which lowers the schedule pressure together with the already increased number of workers. As a result of the synergetic effect of relevant components, the number of required excavation worker continuously varies throughout the period. In particular, the required number of workers is getting more at its peak in week 65 as the excavation work proceeds.

Productivity

Going to a more detailed level, the productivity in the model simulation is determined by the function of schedule pressure, experience level with a phase, the effect of fatigue, and the normal productivity. Fig. 14 shows the interrelationships among these factors that influence the productivity of the excavation work.

The experience level increases as the phase progresses with an S-shaped curve. There is no effect of workers' fatigue, because overtime is not applied to the base case. Although workers' experience level continuously increases, the productivity drops in the later part of the phase as schedule pressure decreases. Consequently, the productivity for the excavation work continuously increases at different rates by week 68 and thereafter drops, as schedule pressure effects become dominant in the system.

To summarize, this section explored the basic dynamics of the sample project within a sequential delivery scenario. The synergetic effect of interactions among construction components makes the construction process highly volatile to the work environment. As shown in the simulation results, workers' productivity continuously varies over time as relevant components, including learning effect and schedule pressure, are changed, which requires the different number of workers throughout the period. The simulation results obtained thus far will be compared to fast-tracking cases (described in the following section) to measure the sensitivity of the sample project's performance thus assisting in effectively fast-tracking the project.

Simulation of Fast-Tracking

As discussed in the first section, the ripple effects of the feedback processes involved in construction can become greater under time and resource constraints. For this reason, fast-tracking construction usually involves more diversified and dynamic feedback processes than does the sequential construction that requires a systematic and dynamic approach to the planning and management of fast-tracking construction. The sensitivity study to be done in this section will support these arguments and provide an insight into the effective planning and management of fast-tracking building construction projects. To do this, the sample project is simulated with various scenarios. First, to quantify the impact of fast-tracking, the project is simulated with different overlapping alternatives. Then, simulations are done to examine the effect of labor control policies on the construction. In addition, model behaviors under different construction settings, such as different hiring time and inspection time, are examined to measure the effect of project components on the fast-tracking construction. Finally, an efficient overlapping strategy between design and construction, and policies for the effective fast-tracking of the sample project are suggested based on the cost-benefit analysis.

Design and Construction Overlapping

By simulating the model with different overlapping alternatives, the impact of fast-tracking is examined. Table 2 summarizes the result of the simulations for each case in which their policies were changed. The simulation results in Table 2 can be explained using the feedback processes represented in Fig. 1(a) and Fig. 1(b). Increasing the overlapping degree between the design and construction created more changes in design and construction than those in the sequential method, which led to delays and counterbalancing the time reduction achieved by the increased overlapping. As a result, the initially

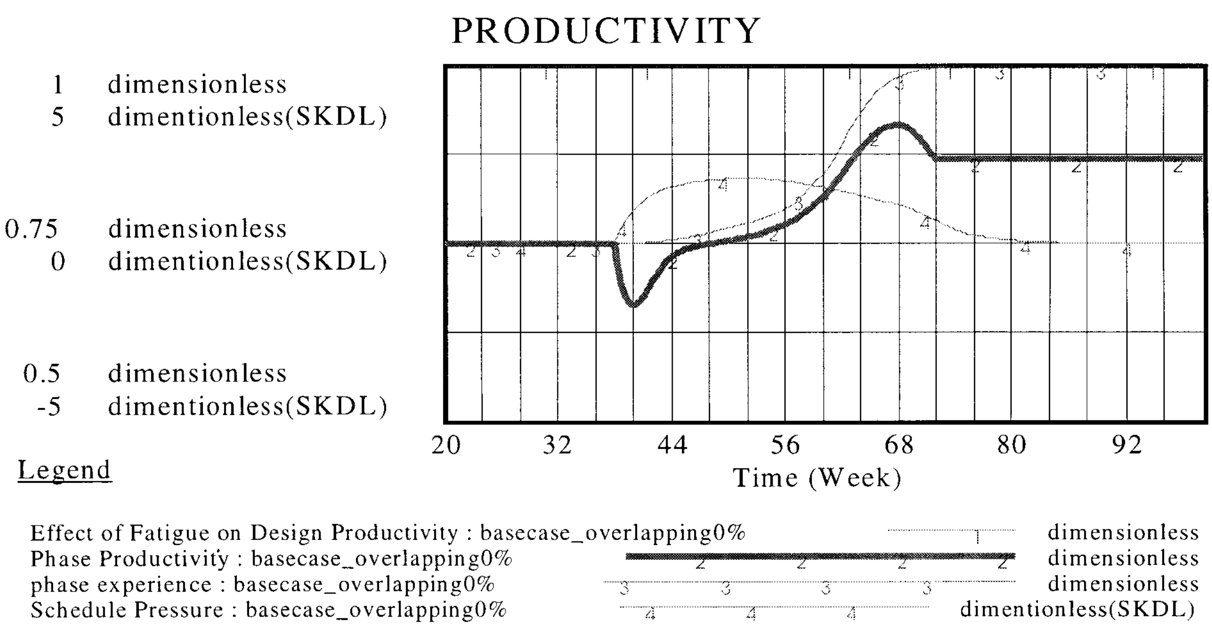

FIG. 14. Productivity of Excavation

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

TABLE 2. Effect of Design and Construction Overlapping

Degree of overlapping	0% (base)	25%	50%	75%	100%
Costs					
Value (millions of dollars)	198.19	199.44	201.88	205.96	210.73
Change from base (%)	0	0.63	1.86	3.9	6.3
Duration					
Value (weeks)	205.2	199.7	194.5	188.7	179.5
Change from base (%)	0	−2.6	−5.2	−8.0	−12.5
Workers					
Value (persons)	40,966	41,083	41,265	41,793	42,520
Change from base (%)	0	0.28	0.73	2.0	3.8
Design changes					
Value (cwp)	22,002	24,971	31,309	39,385	42,052
Change from base (%)	0	13.4	42.3	79.0	91.1
Construction changes					
Value (man*hour)	35,702	39,670	47,547	58,850	68,118
Change from base (%)	0	11.1	33.1	64.8	90.7

expected time reduction was not achieved, which could make the vicious feedback processes in Figure 1(b) dominant in the construction system. As a result, the project was completed with a relatively small amount of time reduction, compared to a significant increase in design and construction changes. (Table 2 shows that 100% overlapping resulted in 12.5% of time reduction, 91.1% of increase in design changes, and 90.7% of increase in construction changes.) In addition, to examine the trends of the model behaviors, the numbers in Table 2 are normalized with a maximum value of 100% in case of overlapping 100%. Normalized curves in Fig. 15 show that as the degree of overlapping is increased, project duration shortens in a near linear fashion. However, project costs and cost-increasing factors, including number of workers, changes in design, and construction increase nonlinearly.

This sensitivity study implies that more than 50% of overlapping between the design and construction may not be cost effective, and if more than 50% of overlapping is required by outer factors, more attention should be paid on reducing the cost impact.

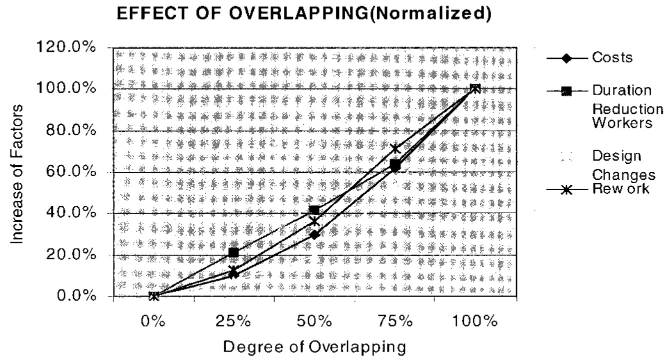

FIG. 15. Effect of Design and Construction Overlapping

TABLE 3. Effect of Labor Policies

Degree of overlapping	Fixed HC (base)	Flexible HC	Overtime
Costs			
Value (millions of dollars)	198.19	197.19	208.7
Change from base (%)	0	−0.5	5.3
Duration			
Value (weeks)	205.2	200.25	208
Change from base (%)	0	−2.4	13.6
Workers			
Value (persons)	40,966	40,703	38,243
Change from base (%)	0	−0.6	−6.6
Design changes			
Value (cwp)	22,002	21,722	26,714
Change from base (%)	0	−1.2	21.4
Construction changes			
Value (man*hour)	35,702	34,090	51,961
Change from base (%)	0	−4.5	45.5

Labor Policies

Simulations are done to examine the effect of labor control policies on the performance of the sample project by adapting a base case with different assumptions for labor control policies. The base case has a fixed head count labor control policy and 0% overlapping. Table 3 summarizes the results of the simulations for each case.

As a result of the simulation, flexible labor policy is found to be most efficient in terms of schedule and costs for the sample project. In the case of overtime, there are more design and construction changes than in the base case, which leads to schedule and cost overrun. Overtime is typically adopted to meet the schedule, however, it is demonstrated here that overtime can result in more schedule overrun due to the dynamic behaviors of schedule pressure, productivity, and quality. Fig. 16 shows the result of the simulations normalized to compare each case when numbers for the base case are set as 1.0.

The effectiveness of labor control policies can vary depending on the nature of a project, including the delivery method. However, the sensitivity study done in this section implies that the construction performance greatly depends on labor control policies. In particular, it implies that while overtime may not be helpful to shorten the construction duration, flexibility in labor control may contribute to reducing the construction duration and costs.

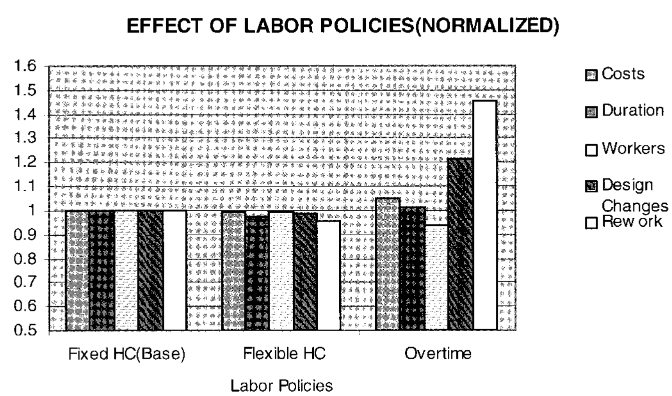

FIG. 16. Effect of Labor Policies

Time Variable

In addition to overlapping and labor control policies, there are many other construction components to affect the construc-

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

TABLE 4. Effect of Changes in Time Variables

Degree of overlapping	BASE[a]	ADC = 1[b]	AQA = 1[b]	ALH = 8[b]	ASP = 4[b]
Costs					
Value (millions of dollars)	197.19	197.16	196.13	196.64	197.83
Change from base (%)	0	0	−0.54	−0.28	0.32
Duration					
Value (weeks)	200.25	200	189.5	193	198.25
Change from base (%)	0	−0.13	−5.4	−3.6	−1.0
Workers					
Value (persons)	40,703	40,575	39,326	41,777	41,545
Change from base (%)	0	−0.4	−3.3	2.6	2.0
Design changes					
Value (cwp)	21,722	24,218	24,708	22,219	23,657
Change from base (%)	0	11.5	13.7	2.2	8.9
Construction changes					
Value (man*hour)	34,090	38,170	39,228	36,799	37,671
Change from base (%)	0	11.9	15.0	7.9	10.5

[a]Base case: ADC = 2; AQA = 2; ALH = 16; ASP = 8. unit: weeks.
[b]ADC: Average design change time, AQA: Average Quality Approve Time; ALH: Average Labor Hiring Time, ASP: Average Schedule Perception Time

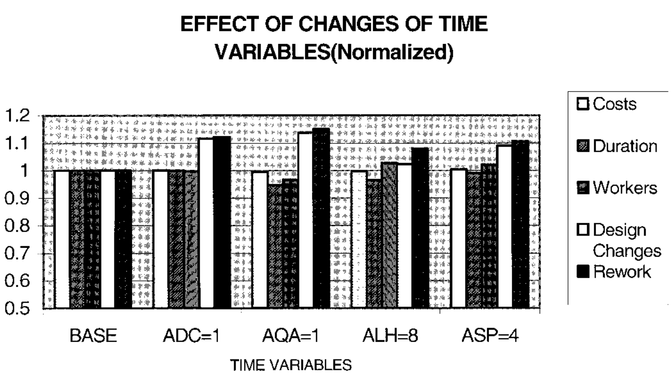

FIG. 17. Effect of Changes in Time Variables

tion performance. In this section, simulations are done to analyze the effect of some important time variables for the key process on the case of flexible head count and 0% overlapping. Table 4 summarizes the results of the simulations for each case.

Generally, shortening the required time for a certain activity, such as quality approval and labor hiring, is found to facilitate project duration but does not necessarily reduce project costs. In particular, average labor hiring time and quality approval time greatly affects the construction performance. Additionally, reducing quality approval time decreases the number of workers and shortens project duration, while reducing the labor hiring time increases the number of workers. Fig. 17 shows the result of the simulations normalized to compare each case when numbers for the base case are set to 1.0.

The above sensitivity study shows that reducing a required time for a certain activity helps facilitate the construction schedule in fast-tracking. This implies that to achieve effective fast-tracking, the decision-making process in design and construction should be shortened, and information flow among project functions should be streamlined to support that.

Cost-Benefits Analysis

In this section, the effectiveness of various fast-tracking alternatives for the sample project is determined based on the criteria discussed earlier in this paper among the selected construction settings. Given the different construction settings, the DPM model analyzes the trade-off between the increased costs to reduce project duration and the possible capital gain through shortened duration. For the sample project, possible capital gain to be achieved through earlier completion is assumed $10 million/year. Under this assumption, the selected construction settings are simulated and some of the cases are listed in Table 5.

The result shows that cases with 50% of an overlapping option are favorable alternatives in terms of the trade-off. Case 2, which has 1 week as the average quality approval time and 16 weeks as the average labor hiring time, is most efficient among them. Meanwhile, Case 7 has the shortest project duration, despite a negative trade-off. As shown in Table 5, all cases with 100% overlapping have a negative number of trade-offs. These results imply that when a project is fast-tracked by more than 50%, fast-tracking may not be effective. If more than 50% of overlapping is required by other factors, labor control should be flexible during the project duration and quality approval and labor hiring time should be shortened as much as possible to reduce the negative impact of fast-tracking.

To summarize, this section has demonstrated how the use of the DPM model can help the project manager assess the time and cost consequences of overlapping the design and construction processes and establish policies. The effectiveness of fast-tracking policies can vary depending on the nature of a project. In addition, delivery systems adopted to carry out a project are also closely related to effective fast-tracking poli-

TABLE 5. Trade-Off of Alternative Policies

Des.	DO[a]	FH[b]	QAT[c]	LHT[d]	PD[e]	PC[f]	Trade-off
Base	0	—	2	16	205.2	198.2	0.00
Case 1	50	—	1	16	181.7	201.7	0.94
Case 2	50	●	1	16	180.7	199.2	3.69
Case 3	50	●	1	8	175.5	201.9	1.97
Case 4	50	●	1	4	174.2	202.5	1.61
Case 5	100	—	1	16	179.5	210.73	−7.54
Case 6	100	●	1	8	159.0	212.0	−5.00
Case 7	100	●	1	4	158.0	212.9	−5.70

Note: Unit %, weeks, millions of dollars.
[a]DO: Degree of overlapping.
[b]FH: Flexible headcount.
[c]QAT: Average quality approval time.
[d]LHT: Average labor hiring time.
[e]PD: Project duration.
[f]PC: Project costs.

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.

cies. However, the model behaviors and sensitivity studies discussed in this section have some general guidelines for the effective fast-tracking of building construction projects. That is: (1) the planning and management requires a systematic and dynamic approach due to the diversified and dynamic feedback processes involved in the fast-tracking construction; (2) the synergetic effect of those feedback processes makes the construction process highly volatile to the work environment, making worker productivity continuously varying throughout the construction process, which requires dynamic and flexible labor control; and (3) the decision-making process in design and construction should be shortened, because time delays can magnify the ripple effects of the feedback processes under time and resource constraints.

CONCLUSION

Accelerating a project is fascinating. At the same time, it is challenging. Fast-tracking may shorten delivery time and lower project costs. Fast-tracking, however, also involves the potential to affect the project development process. Closer observation of the design and construction process in this paper revealed that to effectively plan and manage a fast-tracking project, feedback processes should be identified before physical execution is undertaken, and they should be carefully monitored throughout the project duration. However, it is difficult to handle those feedback processes and the dynamic behavior of construction resulting from them in a linear fashion, which requires a systematic and dynamic approach to the planning and management of fast-tracking construction. As an effort to meet these needs, DPM has been developed. Although the research results should be validated and further developed using more sample projects, the methodology developed so far has demonstrated its applicability and usefulness in dealing with the dynamic complexity of fast-tracking construction. The enhanced planning and management capability through DPM may help ensure the effective delivery of fast-tracking building construction projects without driving up costs.

ACKNOWLEDGMENTS

The authors would like to thank Margaret Fulenwider and Sanghyun Lee for their invaluable feedback. The authors also would like to acknowledge the contribution to this research by David N. Ford, Assistant Professor at Texas A&M University, Joe Peck, Corporate Planning and Scheduling Manager, Bill Lemoine, Vice President, and John Foster, Senior Project Manager at Modern Continental Co., and Philip Helmes, Vice President at InteCap Inc. Finally, the authors would like to acknowledge the support for this research received from InteCap Inc., the National Science Foundation CAREER Award and the White House PECASE Award CMS-9875557.

REFERENCES

Bernold, L. E. (1989). ‘‘Simulation of nonsteady construction processes.’’ *J. Constr. Engrg. and Mgmt.*, ASCE, 115(2), 163–178.

Fazio, P., Moselhi, O., Theberge, P., and Revay, S. (1988). ‘‘Design impact of construction fast-track.’’ *Constr. Mgmt. and Economics*, 6(2), 195–208.

Ford, D., and Sterman, J. (1997). ‘‘Dynamic modeling of product development processes.’’ *Working Paper 3943-97*, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Mass.

Huovila, P., Koskela, L., and Lautanala, M. (1994). ‘‘Fast or concurrent: The art of getting construction improved.’’ *Proc., 2nd Workshop on Lean Construction*, Santiago, Chile, 143–158.

Kwak, S. (1995). ‘‘Policy analysis of Hanford Tank Farm operations with system dynamics approach.’’ PhD thesis, Dept. of Nuclear Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

Richardson, G. (1985). ‘‘Introduction to the system dynamics review.’’ *Syst. Dyn. Rev.*, 1(1), 1–5.

Russell, A., and Ranasinghe, M. (1991). ‘‘Decision framework for fast-track construction: A deterministic analysis.’’ *Constr. Mgmt. and Economics*, 9(5), 467–479.

Sterman, J. (1992). ‘‘System dynamics modeling for project management.’’ Sloan School of Management, Massachusetts Institute of Technology, ⟨http://web.mit.edu/jsterman/www/⟩.

Sterman, J. (2000). *Business dynamics: System thinking and modeling for a complex world*, McGraw-Hill, New York.

Tighe, J. (1991). ‘‘Benefits of fast tracking are a myth.’’ *Int. J. Proj. Mgmt.*, 9(1), 49–51.

Turek, M. (1995). ‘‘System dynamics analysis of financial factors in nuclear power plant operations.’’ MS thesis, Dept. of Nuclear Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

Williams, G. (1995). ‘‘Fast-track pros and cons: Considerations for industrial projects.’’ *J. Mgmt. in Engrg.*, ASCE, 11(5), 24–32.

J. Constr. Eng. Manage., 2001, 127(6): 445-456

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/07/19. Copyright ASCE. For personal use only; all rights reserved.