Dynamic change management for construction: introducing the change cycle into model-based project management

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Abstract

In construction, rework (redoing previously completed work) has a considerable impact on project performance. As a result, construction managers often avoid rework on problematic tasks by modifying the design and specification of downstream tasks ("change"). Such a managerial action, however, can disturb the construction sequence by triggering non-value-adding change iterations among construction processes, which often contributes to unanticipated schedule delays and cost overruns. In order to address this challenging issue, different characteristics and behavior patterns of construction changes are identified, and compared to those of construction rework. Change impact on project performance is analyzed according to change characteristics, and to discovery status and time. All research findings are then incorporated into a cohesive dynamic project model. An application example of the project model demonstrates how model-based change management can enhance project performance in a real-world setting by providing effective management plans and policy guidelines. Finally, it is concluded that the model-based approach can be more effective, when combined with other managerial efforts such as reducing the process time and increasing the level of coordination among project functions. Copyright © 2003 John Wiley & Sons, Ltd.

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Introduction

Construction is inherently dynamic, involving multiple feedbacks (Sterman 1992). Nevertheless, this dynamic feature of construction has not been explicitly addressed by traditional construction planning and control tools, and problems encountered during construction are typically treated in a static manner (Lyneis *et al.* 2001). As a result, construction plans undergo continuous updates, and chronic schedule delays and cost overruns persist in construction projects in spite of advances in construction equipment and management techniques.

In this context, system dynamics researches on product development (e.g., Ford and Sterman 1997) and project management (e.g., Lyneis *et al.* 2001) provide a general and convincing framework within which to understand reasons behind the chronic managerial problems in construction projects and suggest a dynamic approach with a system view on observed management problems. Particularly, starting with Cooper (1980) and continuing with

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Richardson and Pugh (1981), Abdel-Hamid (1984), Ford and Sterman (1997), and Lyneis *et al.* (2001), significant research efforts have been made to address and develop the rework cycle embedded in the project development process. However, there are unique features of construction that require extensions to the previous researches.

First of all, construction deals with a physical manifestation, for which construction "rework" is normally accompanied by the demolition of what has already been built. As a result, rework is perceived to have a bigger impact on construction performance than "change" and, under time and resource constraints, construction managers tend to avoid rework on problematic tasks by modifying their design and specification. However, as will be discussed later, change can be more disastrous to construction performance under certain conditions. For these reasons, the rework cycle framework that has been extensively adopted for project management in other domains (Ford and Sterman 1997; Lyneis *et al.* 2001) is not sufficient to adequately address the aforesaid issues in construction management.

Second, construction is process-based work that is performed in an unfixed place by a temporary alliance among multiple organizations (Slaughter 1999). This feature, together with the fact that construction is carried out in an open environment, makes human responses to work environment and managerial decisions highly unpredictable. Therefore, to assist construction managers in making effective on-site decisions in a timely manner, a construction project model must be capable of handling control issues at the operation level as well as plans at the strategic level. Finally, construction project scope (e.g., the number of activities) greatly varies across projects, and work dependencies among construction activities are governed by physical constraints as well as the typical precedence relationships in traditional network scheduling tools like CPM (Critical Path Method, DuPont Inc. and Remington Rand, 1958), PDM (Precedence Diagramming Method, IBM Co., 1964), and PERT (Program Evaluation and Review Technique, US Navy, Booz-Allen Hamilton and Lockheed Co., 1958). Thus, a construction project model requires more flexibility in determining project scope and work dependencies than other project development models (e.g., product development or software development).

In this article, we present the dynamic project model that has been developed to be used as a planning and control tool for construction projects, focusing on effective change management. First, we identify different characteristics and behavior patterns of construction change, and compare them to those of rework. Then, we discuss the structure and equations of the dynamic project model, feedback processes triggered by construction change and rework, and important considerations in implementing a system dynamics model-based project planning and control tool. In addition, using the model structure, change impact on the construction performance is analyzed according to change characteristics, and to discovery status and time. Finally, the application of the model for a real project (the Route 3 North roadway widening in Massachusetts) is briefly discussed.

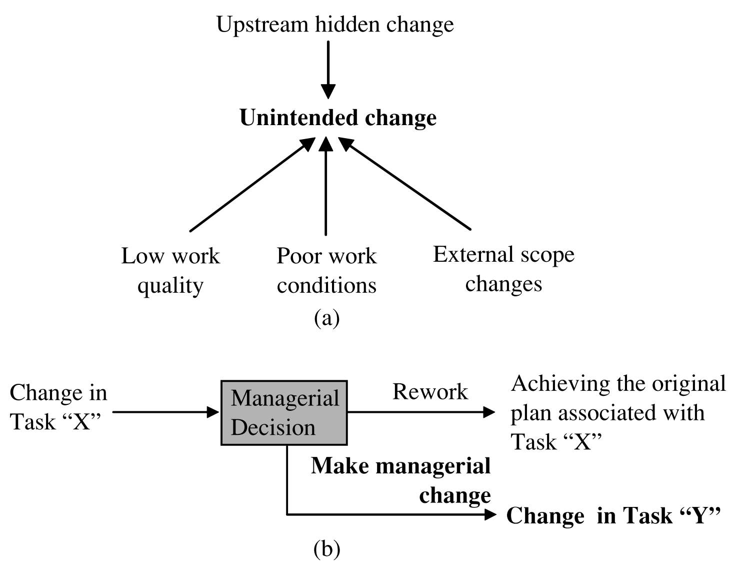
Construction change

Construction processes often involve numerous non-value-adding iterations. Some of these are inevitable, since they result from complexities and uncertainties embedded in the construction process or uncontrollable outside factors like weather conditions. Most non-value-adding iterations, however, can be reduced if they can be identified in advance and managed with a well-prepared plan. Meanwhile, a closer observation of the construction process reveals that non-value-adding iterations in construction are mainly associated with construction changes. Accordingly, reducing wasteful construction iterations requires effective change management, which should start with the understanding of different characteristics and behavior types of construction changes.

Unintended change

Construction changes refer to work state, processes, or methods that deviate from the original construction plan or specification. During the construction process changes take place either unintentionally ("unintended change") or on purpose ("managerial change"). Unintended changes occur without the intervention of managerial actions. As shown in Figure 1(a), they result from low work quality, poor work conditions or external scope changes. In addition, unintended changes can be also caused by upstream "hidden changes" (unintended changes that have been inspected but not found). For example, suppose that an unintended design change was released to the construction process and it was not discovered before construction. In this case, the design

Fig. 1. (a) Unintended and (b) managerial change processes



change (upstream hidden change) can cause subsequent unintended changes in construction.

Managerial change and rework

In contrast to unintended changes, managerial changes are implemented by managerial decisions during quality management. To minimize the impact of the changes that have already occurred, managerial changes are made on succeeding tasks by adopting a different method or process from that in the original plan and specification. For this reason, once implemented, they can trigger subsequent changes in other tasks. Meanwhile, managerial change needs to be distinguished from rework, which is the other available option during quality management. Having found already-made changes, rework is done on the problematic task so as to achieve what has been originally intended in the original plan and specification. Accordingly, rework does not trigger subsequent changes in other tasks.

Behaviors of managerial change and rework

As illustrated in Figure 1(b), when an already-made change is discovered during quality management, the discovered change results in either managerial change or rework, depending on managerial decisions. Both managerial change and rework are mainly done in the form of “adding”, “removing” or “replacing (removing and adding)”. However, given the same problem, managerial change and rework have different behavior patterns because of their different characteristics discussed previously.

The following examples demonstrate their different behavior patterns. Case I and Case II in Figure 2 illustrate that, given the problems (a concrete hump and excess concrete pouring respectively), rework would be done by removing the problem, while change would be done by adding some more concrete. In Case III in Figure 2, where floor tiling has been finished with less than the required thickness, both managerial change and rework have the same behavior pattern (replacing). However, rework would be done on the problem area by removing what has been constructed and adding a new layer, while change would be made on the adjacent floor area that has been finished before (replacing tiles on the smaller area requires less resource). In addition, in Case IV in Figure 2, where some of the piles have not been correctly positioned, rework would be re-driving (adding) piles, while change would be keeping the current pile position.

Tradeoff of change option and rework option

In construction, “change option” (implementing managerial changes) is more common, since “rework option” (implementing rework) is perceived to have a

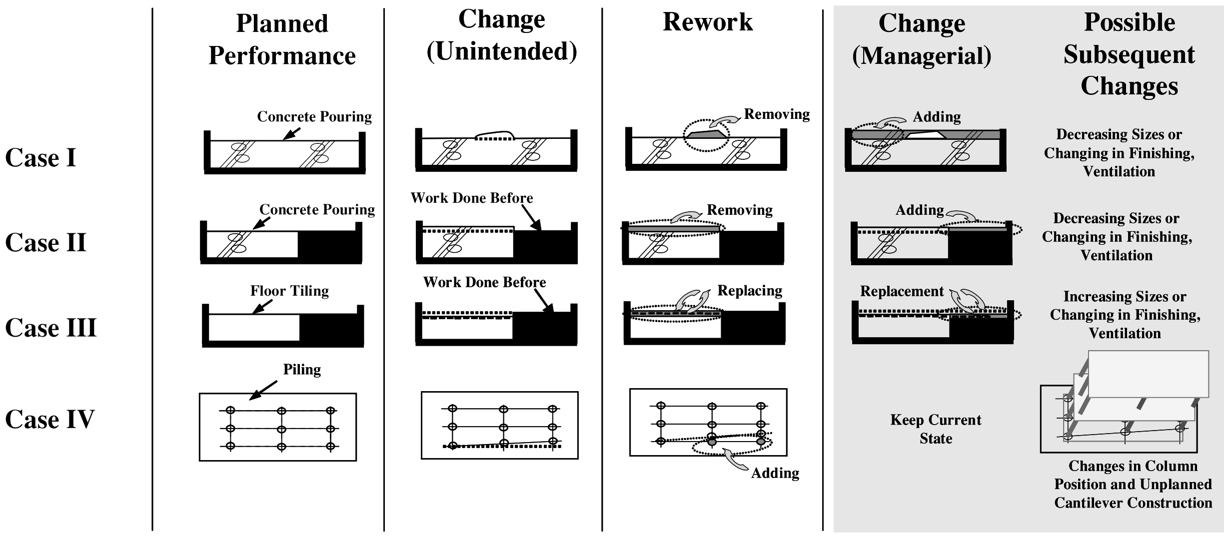


Fig. 2. Behaviors of managerial change and rework

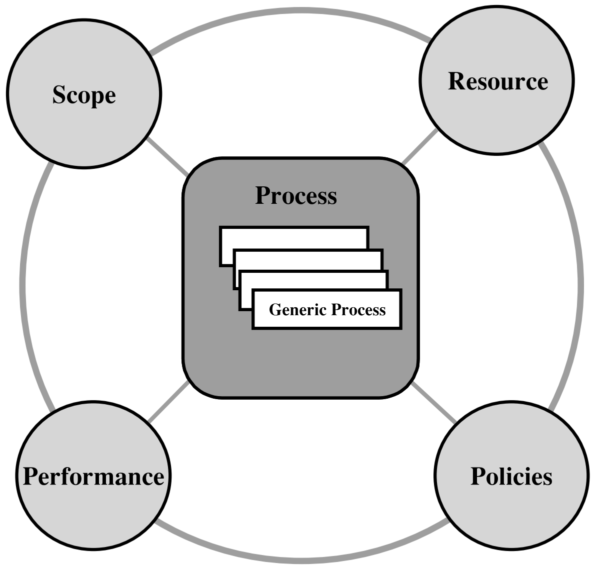
bigger impact on the construction performance than the change option. By adopting the change option, it is possible to avoid rework on problematic tasks that may require more resources. However, as discussed earlier, changed tasks can also become a change source that may cause other subsequent changes, which might have more impact on the construction performance than rework option under certain conditions.

For example, if a change option is adopted in Cases I and II in Figure 2 the concrete layer will become thicker than the planned thickness as a result of pouring more concrete. This may trigger subsequent changes in succeeding tasks, e.g., reducing the size of ventilation ducts. In addition, in Case IV in Figure 2, it may be possible to proceed with the superstructure without correcting the position of the piles. However, this change option may necessitate the change of the column position and unplanned cantilever construction in order to keep the original floor layout. Consequently, a decision on the change option needs to be carefully made based on a good understanding of how changes evolve to non-value-adding iterations, which can create unanticipated and indirect side effects of the decision.

Dynamic construction project model

A dynamic construction project model has been developed with effective change management and construction policy-making, both at the strategic level and at the operational level, taken into consideration. As shown in Figure 3, the project model consists of a process model structure and four supporting

Fig. 3. Schema of dynamic construction project model



model structures for project scope, resource acquisition and allocation, project performance, and construction policies.

The process structure portion, as the most important part of the model, captures dynamic feedback processes involved in construction, allowing the simulation of a flexible number of construction activities. Other supporting model structures assist in analyzing the tradeoff of managerial change and rework on a given problem, and in examining the effectiveness of construction planning and control. Following discussions on the scope of the model, this section describes the generic process model structure, which constitutes the skeleton of the dynamic project model. Other model structures and equations can be found at http://star.mit.edu/moonseo/DCM SDR/OtherModelStructure.

Model boundary

The model boundary chart in Table 1 summarizes the model scope by classifying key variables into "endogenous", "exogenous" and "excluded". Some important considerations in determining the model boundary include the following. To have the flexibility of traditional network scheduling tools, the scheduling logics of those tools are incorporated into the model. For example, the model treats the typical precedence relationships in traditional tools (start-to-start, start-to-finish, finish-to-start, and finish-to-finish) as external concurrence, and an exogenous model variable, "precedence relationship", is used to represent those relationships. Meanwhile, work dependencies within an activity such as a physical constraint (e.g., structural work on the second floor

Table 1. Model boundary chart

	Endogenous	Exogenous	Excluded
Policy	Managerial change ratio Quality management thoroughness Upstream change accommodation rate Workforce adjustment rate	Average managerial change ratio Average quality management thoroughness Willingness to adopt overtime Willingness to control head count	
Performance	Actual productivity Perceived productivity Actual work quality Schedule pressure fatigue Actual progress Perceived progress Project progress	Reliability External sensitivity Internal sensitivity Average productivity	Safety Cash flow Accident rate Seasonal factor Experience dilution
Scope	Adjusted activity duration Target activity duration	Activity scope Activity duration	
Process	Request for information rate Fraction of RFI Fraction of total RFI Work available Reprocess address rate Work release rate Initial work introduce rate Reprocess Request to upstream rate	Average quality management time Average RFI reply time Average hidden change Reprocess time in upstream Average time to adjust workforce Internal concurrence Precedence relationship	Minimum work to undiscovered change
Resource	Potential work rate from resource work rate	Initial staffing	Potential work rate from equipment Budget constraints

can start only after the completion of the first-floor work) are represented by an exogenous variable, "internal concurrence".

In addition, focusing on the control aspect of project management, the model allows the value of some endogenous variables (e.g., "managerial change ratio" and "quality management thoroughness") to be updated by model users during simulation. Lastly, as a result of considering unique features of construction, some of the variables that are often used in other project management models are excluded from the model scope. For example, "undiscovered change", which can be defined as an unintended change that has not been inspected (often referred to as "undiscovered rework or error" in other project models), is not considered in the model. This is because the quality management cycle in construction is relatively short, for which the impact of undiscovered changes is not substantial.

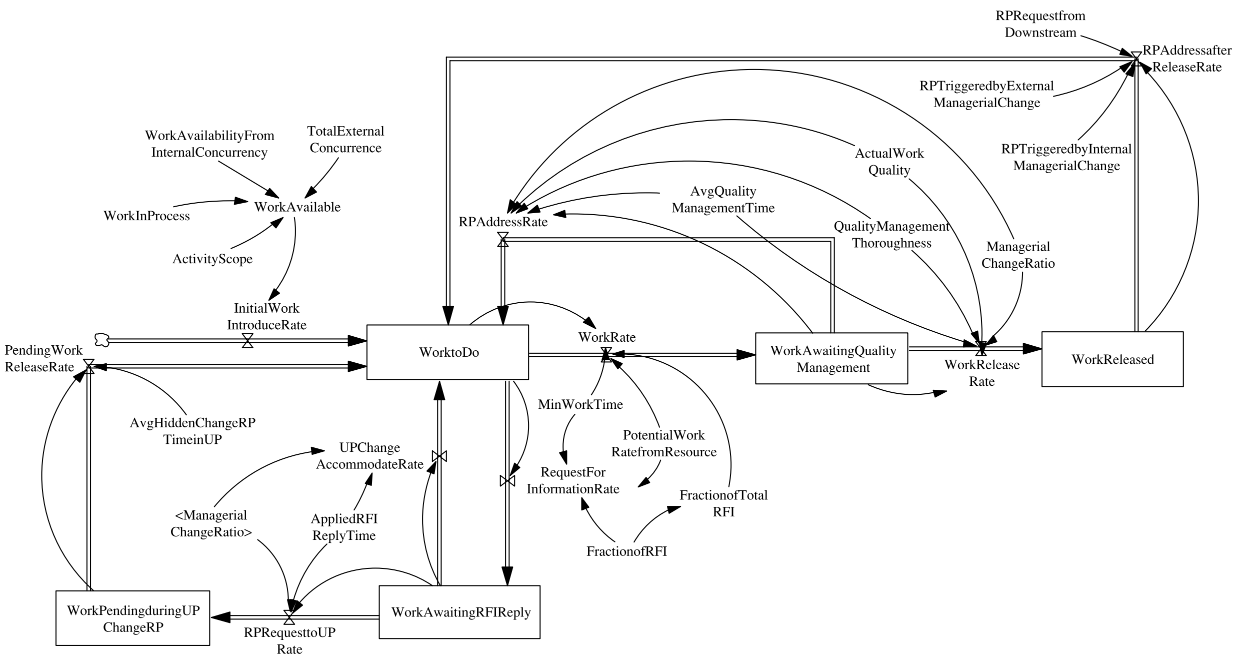


Fig. 4. Generic process model structure

Description of generic process model structure

The generic process model structure in Figure 4 consists of generic parameters and structures, common to construction projects, with the ability to customize for a specific project and to describe project activities. During the model simulation, this generic model structure is repeated to represent an arbitrary number of construction activities. In Figure 4, workflow during construction is represented as tasks flowing into and through five main stocks, which are named *WorktoDo*, *WorkAwaitingRFIReply*, *WorkAwaitingQualityManagement*, *WorkPendingduringUpchangeRP* and *WorkReleased*.

Available tasks at a given time are introduced into the stock of *WorktoDo* through the *InitialWorkIntroduceRate*. The introduced tasks are completed through the *WorkRate*, unless changes in prerequisite upstream work are found. The completed tasks, then, accumulate in the stock of *WorkAwaitingQualityManagement*, where they are waiting to be monitored and inspected. Depending on work quality, some completed tasks are either returned to the stock of *WorktoDo* through *RPAddressRate* or released to the downstream work through *WorkReleaseRate*. It is also possible for released tasks to return to the stock of *WorktoDo* again through *RPAddressAfterReleaseRate*. In addition, in case upstream problematic work is found during the pre-checking period, corresponding tasks flow from and to *WorktoDo* through

RequestForInformationRate, *UpChangeAccommodateRate*, *RPRequesttoUpRate* and *PendingWorkReleaseRate*. Detailed descriptions of task flows among these main stocks are as follows.

PRE-CHECKING DURING CONSTRUCTION When upstream changes are found during the base work, downstream workers normally provide a "request for information" (RFI) to upstream workers or project managers. If, by means of RFIs, the changes turn out to have occurred in the upstream by mistake (unintended changes) and a managerial decision is made in the downstream to correct the changes in the location of the change generation (in the upstream), corresponding downstream tasks are delayed until the upstream changes are reprocessed. For example, assume that before the floor tile work is started, it is found that the floor slab was constructed thicker than its specification as a result of inaccurate concrete pouring in the upstream. As a result, if the tile work proceeds with the current concrete slab unchanged, the facility may not have the required ceiling height. In this case, the project manager may ask the upstream concrete crew to correct the slab thickness by chipping the excess concrete. In the model structure, this process is represented as the iteration of *WorkAwaitingRFIReply-WorkPendingduetoUPChangeRP-WorktoDo* (L1). Downstream tasks corresponding to upstream changes are moved into *WorkAwaitingRFIreply*, and then into *WorkPendingduetoUpChangeRP*, where they wait for the upstream changes to be reprocessed. When the upstream changes are reprocessed, pending downstream tasks are returned into the stock of *WorktoDo* for the base work.

However, the iteration of L1 does not take place in the following cases. First, when upstream changes have been released to the downstream by managerial decisions (managerial changes), they are supposed to be accommodated by changing associated downstream tasks. Continuing with the floor tile work example, it is possible to find the inaccurate concrete construction just after pouring concrete in the upstream. However, after comparing the impact of each option (managerial change or rework) on the construction performance, the project manager may decide to change the specification of downstream tasks such as the thickness of mortar or the method of waterproofing instead of ordering rework on the concrete slab. In this case, since a change option has been intentionally adopted during the upstream work, corresponding downstream tasks are supposed to be changed after the management decision is confirmed through RFIs. Second, such a decision on change option (accommodating upstream changes by modifying downstream tasks) can be also made during the downstream work. Going back to the floor tile work example, it is possible to find the inaccurate concrete construction and to adopt a change option during the tile work (during the downstream work). In the model structure, both cases are represented as associated tasks in *WorkAwaitingRFIreply* being returned to *WorktoDo* through *UPChangeAccommodateRate* (L2).

The iteration loops of L1 and L2 have non-trivial impacts on the construction performance. In particular, when construction is performed concurrently, the impact of those loops becomes greater. Design and construction overlapping causes construction work to proceed with incomplete design drawings. Consequently, there can be numerous RFIs during construction, which can disrupt the construction sequences. Even among design activities many non-value-adding iterations that can be represented by L1 or L2 occur as a result of insufficient volume and poor information on tasks. In fact, it is observed in the research case project, Route 3 North Project, that non-value-adding iterations very often occurred during the design work, which significantly delayed the whole construction processes.

Quality management   Completed construction tasks are internally monitored and/or inspected by the owner's representatives. Depending on the result of such quality management, completed tasks are either released to the downstream or reprocessed. The following task flows in the model structure represent the quality management process in construction. Tasks accumulated in *WorkAwaitingQualityManagement* are periodically monitored and inspected. In principle, tasks achieving the target quality level and intended functions are approved and moved to *WorkReleased* (L3), while others are disapproved and moved to the stock of *WorktoDo* (L4). This process is governed by work quality, quality management thoroughness, and willingness to adopt managerial changes.

Work quality (*ActualWorkQuality*) is a function of the reliability of an activity, upstream quality impact, perceived schedule pressure and workers' fatigue. An unreliable activity generates more changes than a reliable activity. Low quality of the upstream work can also lower work quality, depending on the activity's sensitivity to upstream changes. More precisely, upstream hidden changes that have not been discovered during downstream pre-checking impact work quality. Lasting schedule pressure also can lower work quality, since workers often attempt to achieve the target schedule by cutting corners. Lastly, when overtime continues after a certain threshold, workers can become fatigued, which possibly lowers work quality as well.

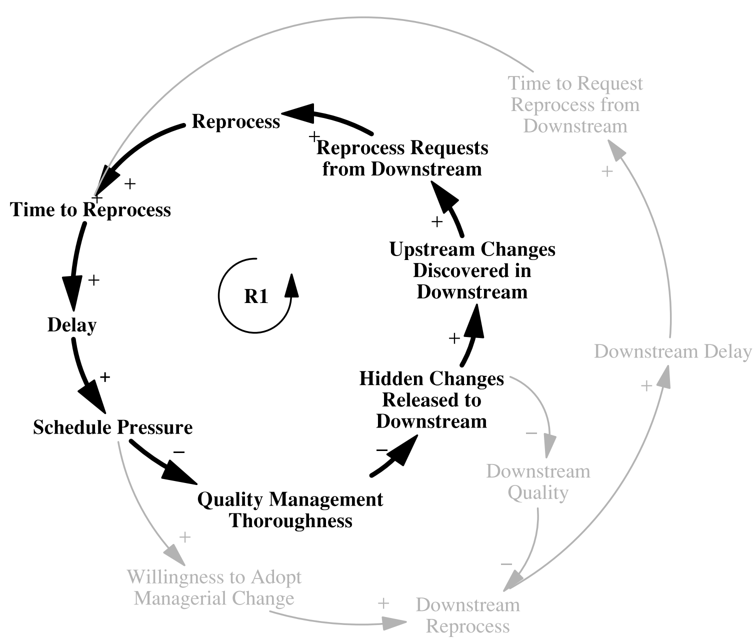
During quality management, it is possible to release changes to the downstream by failing to notice them. This process is governed by *QualityManagementThoroughness* in the model. If the downstream worker also fails to notice the hidden changes, they can cause deterioration in the downstream work quality. Meanwhile, when schedule pressure lasts during construction, quality management thoroughness tends to become lower, which can trigger the reinforcing feedback processes denoted as R1 in Figure 5(a) and R2 in Figure 5(b).

As conceptualized in Figure 5(a), high schedule pressure can make quality management efforts less thorough, which results in more hidden changes released to the downstream work. During the downstream pre-checking process, hidden changes released from the upstream work can be discovered. Once they are found, depending on managerial decisions, downstream workers request the upstream worker to correct the hidden changes. Thus, more hidden changes cause more correction requests from the downstream, which increases the amount of work to be reprocessed and its reprocessing time in the upstream. Increased reprocessing time then further delays the construction process, which leads to higher schedule pressure.

In addition, the reinforcing loop in Figure 5(b) shows that increased hidden changes resulting from lowered quality management thoroughness can impact the construction process along a different impact path. If not discovered during the downstream pre-checking process, increased hidden changes have a bigger impact on the downstream work quality, creating more reprocess iterations in the downstream work. Then, increased reprocess iterations delay the downstream work process and lengthen time intervals in requesting upstream change corrections. Consequently, this feedback process, which is triggered by lowering quality management thoroughness, also impacts the construction schedule performance.

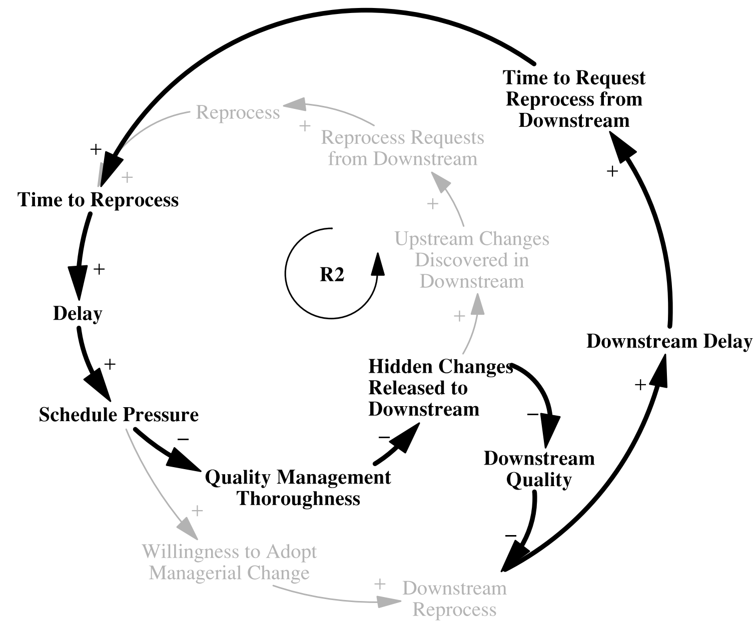
It is also possible for some of discovered changes to be released to the downstream work by a managerial decision (*ManagerialChangeRatio*). The more construction is delayed, the more often the change option tends to be

Fig. 5. Feedback Processes in Quality Management: (a) R1; (b) R2; (c) R3

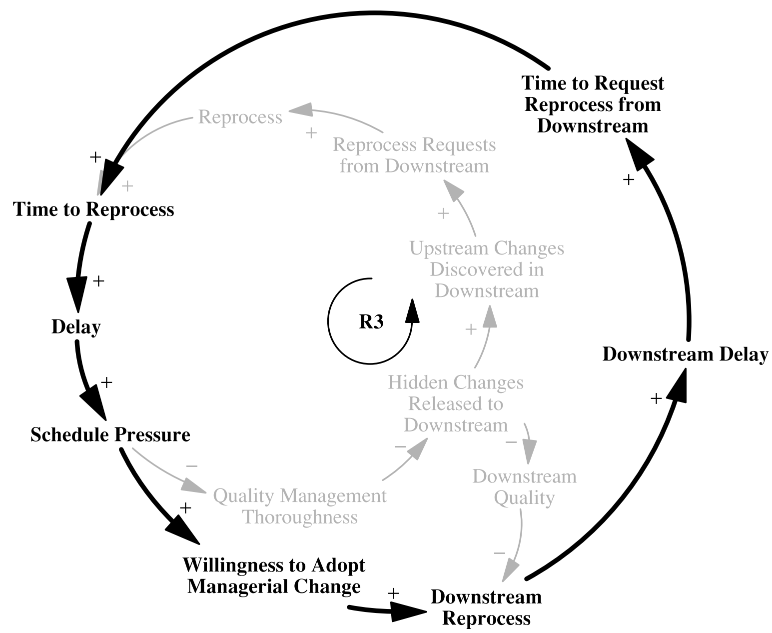


(a)

Fig. 5. (*Continued*)



(b)



(c)

adopted. As conceptualized in Figure 5(c), increased willingness to adopt managerial changes under high schedule pressure triggers more reprocess iterations in the downstream work, which delays the downstream work process. Downstream delays, then, impact the schedule performance of the upstream work through the feedback processes shown in Figure 5(b).

Reprocess iterations of work released Tasks already released to the downstream can be also reprocessed in the upstream. In the model structure, this is represented as tasks flowing from *WorkReleased* to *WorktoDo* through *RPAddressAfterReleaseRate* (L5). There are three variables that constitute *RPAddressAfterReleaseRate*. That is, *RPRequestfromDownstream*, *RPTriggeredbyInternalManagerialChange*, and *RPTriggeredbyExternalManagerialChange*.

RPRequestfromDownstream is initiated by hidden upstream changes. Once upstream hidden changes are found during the downstream work and it is decided to correct them in the upstream work, they are returned to the upstream work. While discovered changes are being reprocessed in the upstream activity, the downstream activity is delayed. In addition, *RPTriggeredbyInternalManagerialChange* represents the impact of managerial changes on preceding tasks within the same activity, which is determined by the amount of managerial changes generated either before or after work execution. The impact is also related to an activity's sensitivity to internally made changes and the fraction of work released so far. This is because, the more sensitive an activity is and the more work an activity has done thus far, the more impact managerial changes can have. Finally, *RPTriggeredbyExternalManagerialChange* determines the impact of external managerial changes. Any managerial changes made in activities having precedence relationships or reprocess iteration relationships can be potential impact sources. In addition, an activity's sensitivity to those changes and the fraction of work released so far are also related to determining the impact of externally made managerial changes.

The model description can be summarized by saying that the generic process model structure in Figure 4 focuses on the feedback processes triggered by construction changes, which are made either intentionally or by mistake. Those feedbacks commonly occur in the construction process and they have non-trivial impacts on the performance of construction projects. Further discussions of the generic process model can be found at http://star.mit.edu/moonseo/DCM SDR/GenericProcessModel.

Analysis of change impact

Using the generic process model structure, this section analyzes the different impact patterns of construction changes according to change characteristics, and to discovery status and time. For clarity, managerial changes and unintended changes are analyzed separately.

Managerial change

In the upstream process model in Figure 6, tasks flowing through *UPChangeAccommodateRate* are all managerial changes, which result from a managerial decision during the pre-checking process, and *WorkReleaseRate* contains managerial changes. Once they are released to *WorkReleased*, managerial changes can impact other tasks that are already in *WorkReleased* because of their characteristics discussed above. As a result, impacted tasks in *WorkReleased* are moved to *WorktoDo* through *ReprocessRequestonWorkReleasedRate*. The number of tasks moved is directly related to the impact magnitude of managerial changes made.

By adopting the change option, it is possible to avoid the direct impact resulting from rework (R_{up} in Figure 6). However, as shown in Figure 6, a decision to adopt the change option in an activity can create subsequent non-value-adding iterations within the activity (C_{up}) and in the downstream activity (C_{dn}). Thus, managerial changes may have a bigger impact on the construction performance than rework, depending on the sensitivity of associated tasks to the managerial changes and on how much work has already been done at the change impact time. In Figure 6, the impact of the change option on

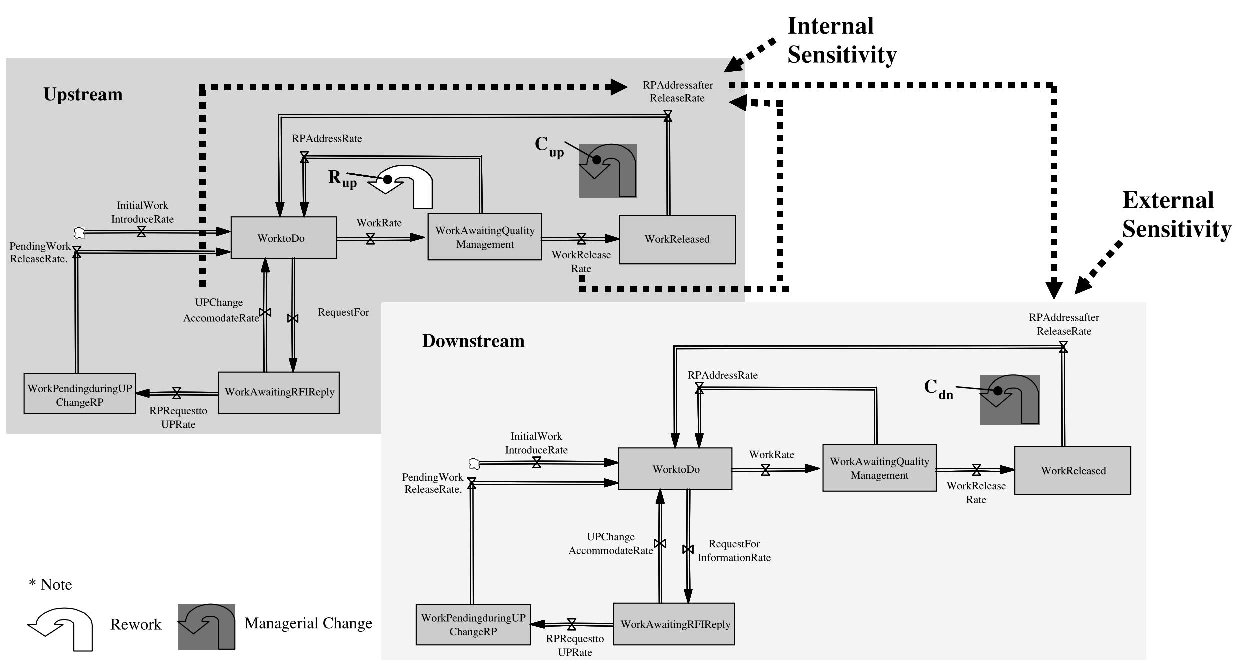


Fig. 6. The impact of managerial changes

the upstream activity (C_{up}) is in proportion to the sensitivity of the upstream work to internal changes ("internal sensitivity", which refers to the degree to which an activity is sensitive to changes made internally) and the progress of the upstream work. Meanwhile, the impact of change on the downstream activity (C_{dn}) can be measured as a function of the activity's sensitivities to the upstream work change (external sensitivity) and to the downstream work progress at the change impact time. In addition, depending on the characteristics of a construction system, managerial changes also have different intensity and magnitude (mostly according to production rate, work quality, and managerial tendency to adopt the change option).

Unintended change

Unintended changes have more complex impact patterns. Normally, the impact of unintended changes becomes greater, as discovery time lengthens and discovery location moves away from the location of change generation. In addition, when changes are made on the work, based on which other work has been already done, they can create a ripple effect impacting the other work as well. Table 2 analyzes the impact of unintended changes in terms of types, paths, and magnitude. For effective analysis, we assume that only the rework option is adopted at each managerial decision point.

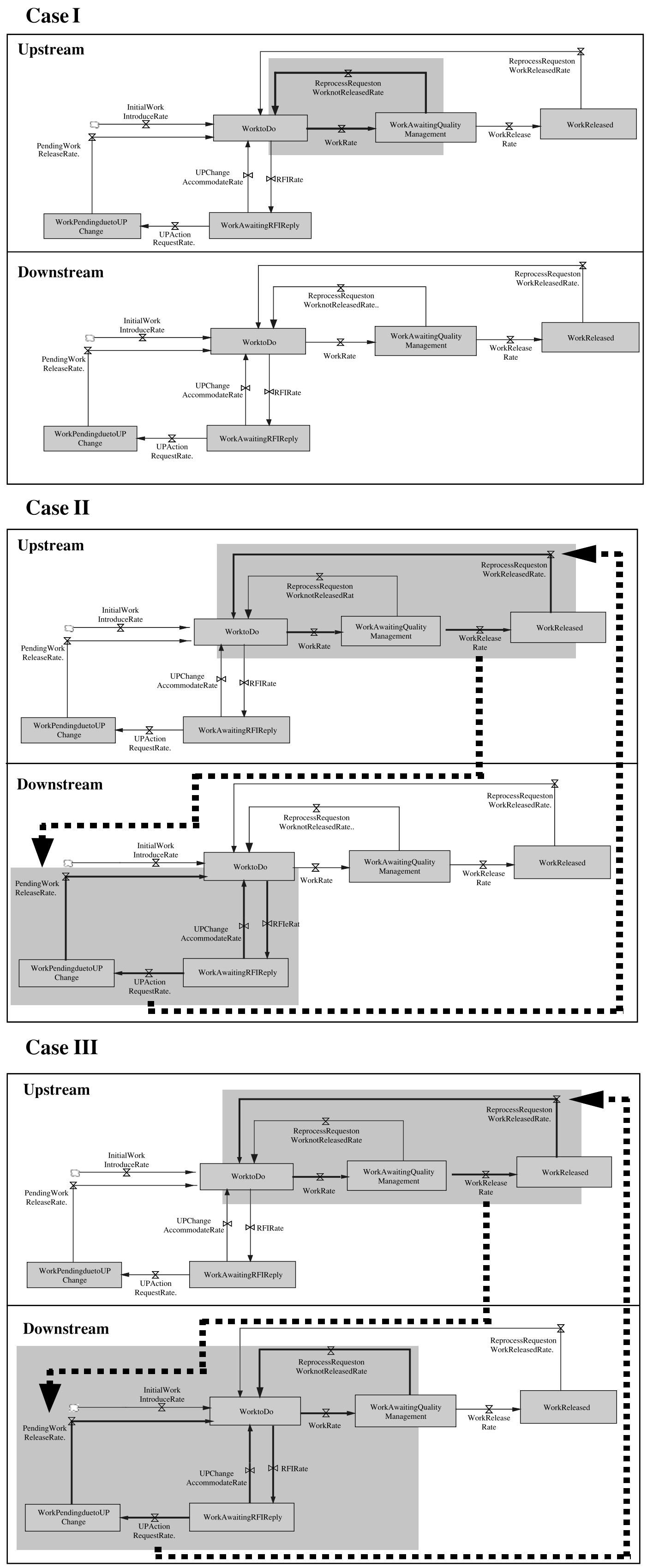
As summarized in Table 2, in Case I, where unintended changes are found during upstream quality management, the type of impact on the downstream work is a time delay and its magnitude is weak owing to a short impact path. Since problematic tasks are corrected before they are released to the downstream work, there is a time delay but no direct impact on the quality of the downstream work.

In Case II, upstream hidden changes are discovered during the downstream pre-checking process and the discovered changes are returned to the upstream work. Case II has the same impact type as Case I, but the impact magnitude is greater than that of Case I. This is because Case II has a longer impact path

Table 2. Impact of unintended changes

Cases	Source, discovery time & Location	Impact on downstream		
		Types	Path length	Magnitude
Case I	Upstream changes found after upstream work	Delay	Short	Weak
Case II	Upstream changes found before downstream work	Delay	Long	Medium, ripple effect in upstream
Case III	Upstream changes found after downstream work	Delay and quality impact	Very long	Strong, ripple effect in upstream and quality deterioration in downstream

Fig. 7. The impact of unintended changes



length, as depicted in Figure 7, and ripple effects are associated with the impact process. For example, suppose that it is found during steel member erection that some steel members do not fit others. In this case, the steel worker will inform the design team of the mismatch of those steel members and return the members to the steel manufacturer. Then, the design team has to re-size the steel members and the new specification for the steel members will be forwarded to the steel manufacturer. In addition, if the newly specified members do not fit other structural components that have physical connections with the corrected steel members, the design team may change the specification for the connected structural components as well. During this iteration period, workers and cranes that have been working on the site have to wait for new steel members to arrive.

In Case III, where upstream hidden changes are discovered after the corresponding downstream work has been done, the problems created in the upstream work impact the downstream work quality as well as delaying the process. The magnitude of the impact is also greater than in the other cases. This is because Case III has the longest impact path, as depicted in Figure 7. In addition, quality deterioration and ripple effects are associated with the impact processes involved in Case III. For example, suppose that after concrete has been poured into the forms for the foundation, it is found that the strength of the poured concrete is not enough to support the dead load of the building. In this case, the resources commissioned both in the foundation and in the design work are squandered and the foundation work is delayed during the demolition of the problematic concrete and re-calculation of the concrete strength.

In this section, we have analyzed the impact of managerial changes and unintended changes separately, assuming that only the rework option is adopted at each managerial decision point. In practice, however, to analyze the impact of a change we need to combine the impact paths of unintended changes and those of managerial changes. Once combined, they produce much more complicated impact patterns, which are hard to map out using mental models. For this reason, model-based policy making can be an effective approach to construction change management.

Application of the Dynamic Project Model

The developed dynamic project model is being applied to the construction of 27 bridges in order to help manage changes and prepare a robust construction plan. The construction is part of a $400 million Design/Build/Operate/Transfer project awarded to Modern Continental Companies, Inc. for roadway improvements along State Route 3 in Burlington, MA. The development process is expected to span 42 months with project completion achieved in February 2004. The project scope includes widening the 21 miles of the state roadway and the existing 15 underpass bridges, and renovating 12 overpass bridges. In this article, we present a case study of the Treble Cove Road Bridge Construction, one of bridge renovation projects.

Model set-up

The dynamic project model was set up to represent the case project using project data obtained from interviews with schedulers and engineers involved in the project. The actual project activities were aggregated up to 28 design and construction activities, and the construction activity characteristics summarized in Appendix I were used as input for the model parameters. In addition, the construction team's policy on labor control, general practice on change option, and expected quality management thoroughness were reflected as planning assumptions for the "base case" simulation.

Base-case model behaviors

For the base case, the model was simulated with the following managerial policies: 100 percent flexible labor control policy, with which the level of workforce is adjusted as much as required during construction, 50 percent average managerial change ratio, 90 percent average quality management thoroughness, and 0 percent buffering. The simulated actual duration of the base case was 559 working days. This is 168 days longer than the CPM (Critical Path Method)-generated duration of the base case. (In CPM, the duration of a project is determined only by the precedence relationship and the duration of project activities.) The simulation result indicates that the difference in the completion time is mainly due to a time delay caused by non-value-adding iterations among design and construction activities, which are not considered in the CPM analysis. Actually, the design development of the Treble Cove Road Bridge project has already shown significant delay as of Feb 1, 2001 and construction has not been yet started. This project was awarded to the contractor before the detailed scope of the project had been established. As a result, stage changes on the design work were frequently requested by the owner side during the sketch plan, final plan, and shop drawing submittal, which resulted in numerous design iterations. The base case simulates this challenge and shows how much non-value-adding iterations caused by changes can affect the project progress.

System behaviors and policy implications

In order to examine the effectiveness of different construction policies, simulations were done with the base case adapted with different scenarios for managerial decisions on change or rework, labor control, buffering, and some important time variables such as labor hiring time and RFI time. As a result of the simulations, the following policy implications were obtained.

Table 3. Effect of labor policies

Cases	Labor control policies	Completion time (days)	Labor hours (worker × hour)
1	100% flexible	559	1.305M
2	75% flexible	565	1.328M
3	50% flexible	573	1.369M
4	25% flexible	594	1.451M
5	100% overtime	583	1.381M
6	75% overtime	586	1.362M
7	50% overtime	589	1.345M
8	25% overtime	597	1.322M

First, a higher managerial change ratio (preferring the change option to the rework option) tended to reduce costs but lengthen the duration of this project. However, it is hard to generalize this result, since the tradeoff between change and rework is highly dependent on the construction system conditions at the time when a decision is made. This implies that effective change management requires an operational-level approach as well as well-prepared project policies such as labor-control policies, schedule buffering and delivery methods.

Second, in connection with labor control, flexible labor control (cases 1 to 4 in Table 3) was found to be more effective for the project in terms of schedule and cost reduction than overtime (cases 5 to 8 in Table 3). The main reason for this simulation result is that overtime applied for the case project lowered productivity and increased change rate, as workers' fatigue accumulated. In addition, as highlighted in Table 3, more flexible labor control led to more savings in time and cost. In fact, the effectiveness of labor control policies can vary depending on the nature of a project. However, many success stories of concurrent construction projects like our case-study project confirm the above policy implications, demonstrating that flexibility in labor control contributes to reducing the project duration and costs by assigning the workforce in a timely manner.

Third, buffering based on the characteristics of activities (see Appendix I) turned out to enhance most effectively the schedule and cost performance. To examine the role of buffering, the case project was simulated with various schedule buffering scenarios: no buffers; uniform buffers (the same buffering ratio is applied to all activities); and buffers based on the characteristics of activities (buffering ratios vary depending on the characteristics of associated activities). The simulated actual duration of the no-buffering case (case 1 in Table 4), which is applied to the base case, is 559 working days. Meanwhile, as indicated in Table 4, the buffering cases have shorter simulated actual durations (477, 463, 452, 451, and 445 days in cases 2, 3, 4, 5, and 6 respectively). In the buffering cases, applied buffers contributed to reducing the upstream change impact and non-value adding iterations. As a result, the

Table 4. Effect of buffering policies

Cases	Buffering (buffer size)	Completion time (days)	Deviation from Case 1	
			Days	%
1	None	559		
2	Uniform (25%)	477	−82	−14.6
3	Uniform (50%)	463	−96	−17.1
4	Uniform (75%)	452	−107	−19.1
5	Uniform (100%)	451	−108	−19.3
6	Subject to individual activity characteristics	445	−114	−20.3

Table 5. Effect of time delays

Cases	Time Delays		Completion time (days)	Labor hours (worker × hour)
	Time to increase workforce (days)	Time to reply to RFI*		
1	7	3	559	1.305M
2	14	3	577	1.309M
3	21	3	588	1.314M
4	3	3	548	1.300M
5	7	6	495	1.181M
6	7	9	478	1.147M
7	7	1.5	722	1.631M

* Time to reply to RFI is obtained by dividing the duration of the activity by the number of RFIs. For example, assuming that the activity A has 50 days duration and the divider is 5, time to reply to RFI will be 10 (50/5).

resource idle time and waste were reduced, which made it possible to more effectively utilize the given workforce. In particular, it was known that consideration of the characteristics of activities could increase the effectiveness of buffering (case 6 in Table 4).

Lastly, the simulations done with different time-variable scenarios demonstrated that shortening the required time for labor hiring and RFI reply contributes to enhancing the project schedule and cost performance. Particularly, RFI reply time greatly affected the project performance. As indicated in Table 5, shortening the RFI reply time by half could facilitate the project progress by 12 percent and reduce the project costs by 10 percent. In contrast, when the RFI reply time was doubled, duration and costs were increased by 29 percent and 24 percent respectively. These simulation results imply that for this case project, coordination among the project functions is crucial

Table 6. Simulation of policy recommendations

Cases	Flexibility in labor control	Buffering*[1]	Time delays: Time to increase workforce (days)	Time delays: Time to reply to RFI*[2]	Completion time (days)	Labor hours (worker × hour)	Output data
1	N/A	None	N/A		391	N/A	CPM*[3]
	100%		7	3	559	1.305M	Base
2	100%	Subject to individual activity characteristics	3	9	388	1.055M	RCMD

* Note
1. Buffer Size: Fraction of Taken-off Contingency Buffer.
2. See footnote to Table 5.
3. Based on CPM-related data only.

to the success of the project. In fact, the expected level of coordination among the owner, designer and constructor has not been met to date, since this case project was the first design/build contract for the members of the development team on the owner side. Consequently, the decision-making process in design and construction should be shortened and information flow among project functions should be streamlined to assist in reducing the decision-making time.

Recommendations

Findings obtained from the model simulations have their policy implications, narrowing down desirable sets of the project components. Having obtained the desirable project settings, we examined their effectiveness in a comprehensive manner, in order to provide policy recommendations. Table 6 summarizes the project settings with which the simulations have been done and compares the simulation results with the base case. In addition, Figure 8 shows graphical representations of the simulation results.

The simulation results demonstrated that applying the desirable project settings to the case project could significantly reduce non-value-adding change iterations and enhance the project schedule and cost performance (35 percent schedule reduction and 30 percent cost reduction compared to the base case). Of course, the simulation results have been obtained with the assumption that a significant time reduction in worker hiring and RFI reply has been achieved. In practice, it is not easy to achieve such an amount of time reduction, since there are many other factors that govern the processes. However, the important thing is that by utilizing the dynamic project

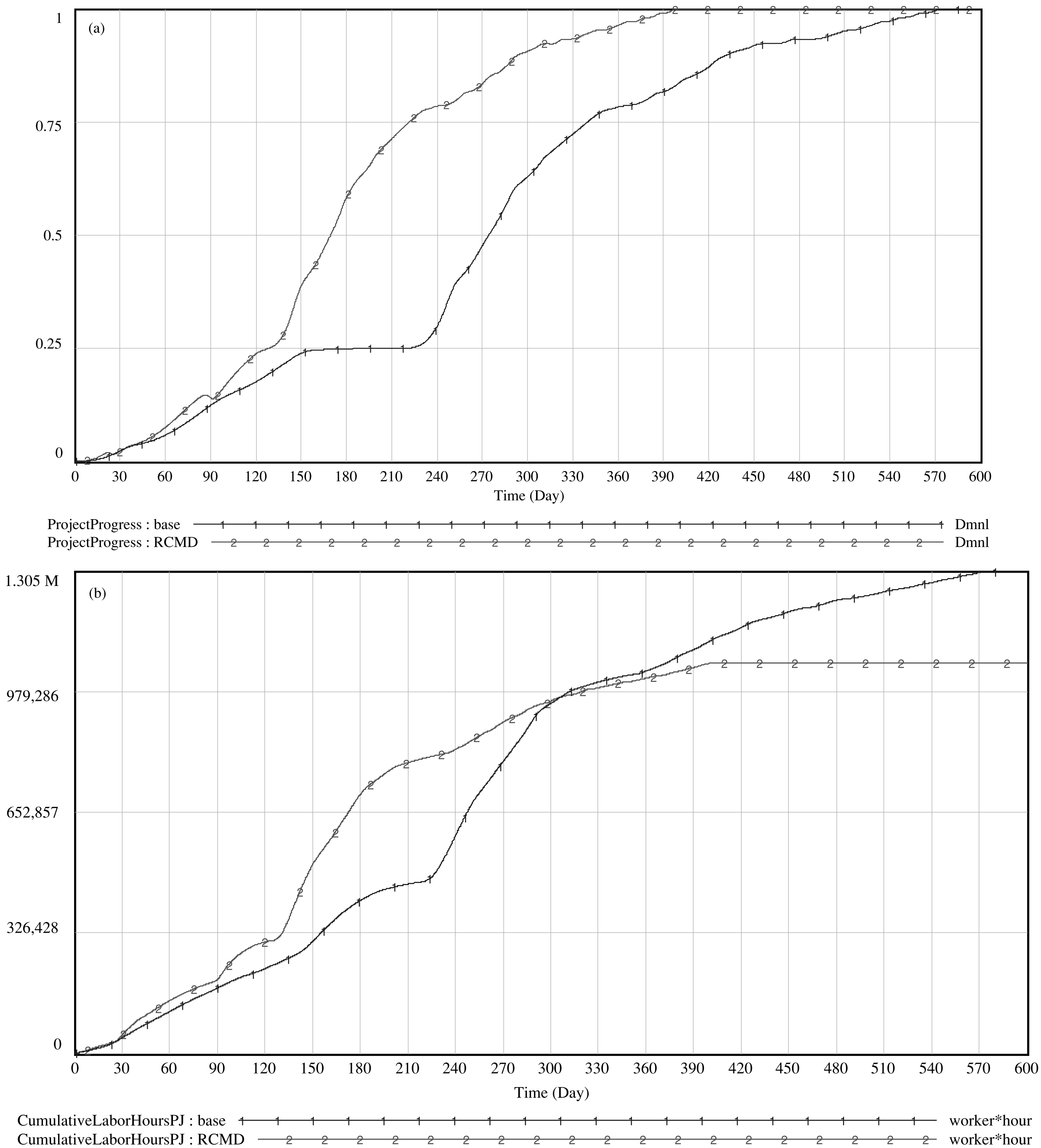


Fig. 8. Recommended policies vs base case (a) project progress; (b) cumulative work hours

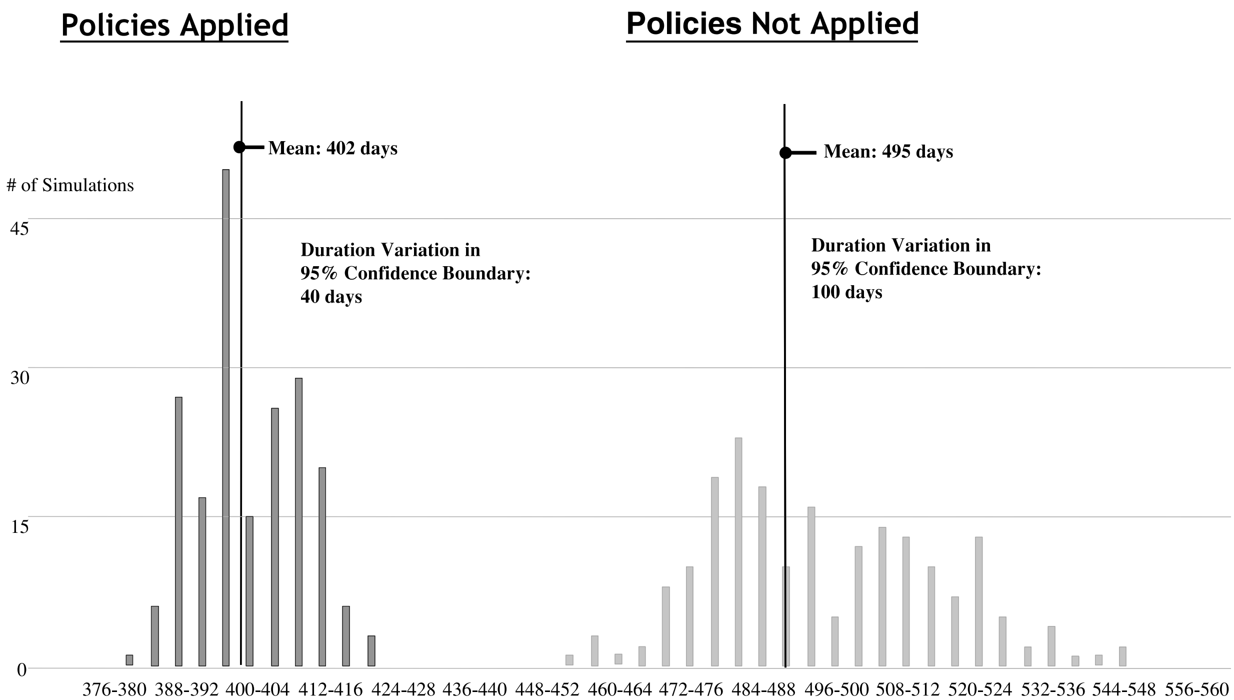


Fig. 9. Distribution of project completion times vs variations in work quality. RFI time reduction and 100% flexible labor control are applied to both cases. The reliability of project activities ranging from 0.75 to 1.25 is randomly generated with a 5% standard deviation

model-generated results, it is possible to find which activity will be the bottleneck of a project and where to focus during the project development. In fact, as discussed above, this case project experienced many design changes, which delayed the whole development process. Consequently, once the RFI reply time can be decreased by increasing the level of coordination among the project functions, it should be possible to avoid or significantly reduce the impact of those changes, as quantified by the project model simulations.

In addition, the sensitivity studies where the recommended policies have been simulated under uncertain conditions imply that the dynamic project model-generated policies are robust against uncertainties. The simulation results presented in Figures 9 and 10 have been obtained by simulating the case project two hundred times.

The first sensitivity test was done to examine the policy's robustness to changes in work quality. During the simulation, a variation factor is randomly generated ranging from 75 to 125 percent, which is weighted to the initially given work quality of activities. As a result of multiple simulations, it turned

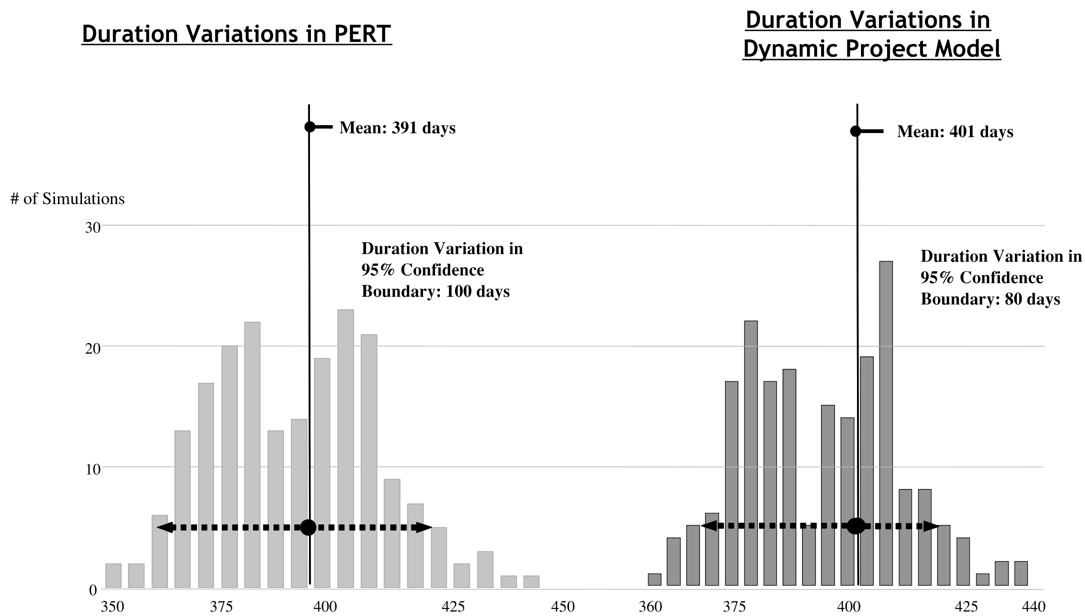


Fig. 10. Distribution of project completion times vs variations in input duration. RFI time reduction and 100% flexible labor control are applied to both cases. The variation factor for activity duration ranges from 0.75 to 1.25

out that the dynamic project model-generated policies could help reduce variations in the estimated project duration under uncertain work quality conditions. As shown in Figure 9, by applying the project policies, it was possible to reduce the variation of project duration within the 95 percent confidence boundary from 100 days to 40 days as well as enhancing the project schedule and cost performance.

In addition, the robustness of the dynamic project model-generated policies has also been tested by varying input durations, which is normal in PERT. When the case project had been simulated with a range of input durations, simulation results were compared to those calculated using PERT. This sensitivity test implies that the dynamic project model-generated policies could also help make the project completion less sensitive to variations in input durations by reducing the variation of project duration in the 95 percent confidence boundary from 100 days to 80 days. In addition, as shown in Figure 10, when the dynamic project model-generated policies are applied, the distribution of the project duration frequency becomes skewed to the left, which suggests that there is a higher possibility of achieving an early finish with the recommended policies than with PERT.

In conclusion, although the obtained simulation results can vary, depending on the project settings, they demonstrate well how the dynamic project model can contribute to enhancing project performance in a real-world setting by providing effective change-management plans and policy guidelines. Additionally, the simulation results also imply that model-based construction policies can be more effective when combined with other managerial efforts such as reducing the process time and increasing the level of coordination among project functions.

Conclusions

Although problems encountered during construction management are dynamic, they have been treated in a static manner (Lyneis *et al.* 2001). As a result, chronic schedule delays and cost overruns persist in construction projects. In this article, we have addressed this challenging issue by introducing the concept of dynamic change management to construction planning and control. Dynamic change management focuses on capturing feedback processes caused by construction changes and minimizing their impact. To realize this concept, we identified different characteristics and behavior patterns of construction change, and analyzed change impact on the construction performance according to change characteristics, and to discovery status and time. Then, we incorporated all our research findings into a cohesive dynamic project model. Although the research results discussed need to be further refined and developed, they demonstrate that the dynamic change management approach and the developed project model would help construction managers make a decision on change or rework during construction in a way that non-value-adding change iterations can be minimized. Some of the potential impacts of this research are as given in the following sub-sections.

Introduction of the change cycle

The rework cycle that has been extensively adopted for project management in other domains is not sufficient to adequately address problems encountered during construction. For this reason, we introduced the "change cycle" into the dynamic project model developed in this article. The change cycle can be also applied to other domains where a clear distinction between change and rework can be made and where effective change management is required for the success of a project. New concepts and model structures that have been introduced to the dynamic project model are summarized in Appendix II.

The SD model as a planning and control tool

Simulation capability has been seen as an opposite concept to applicability. In this context, the dynamic project model attempts to increase applicability,

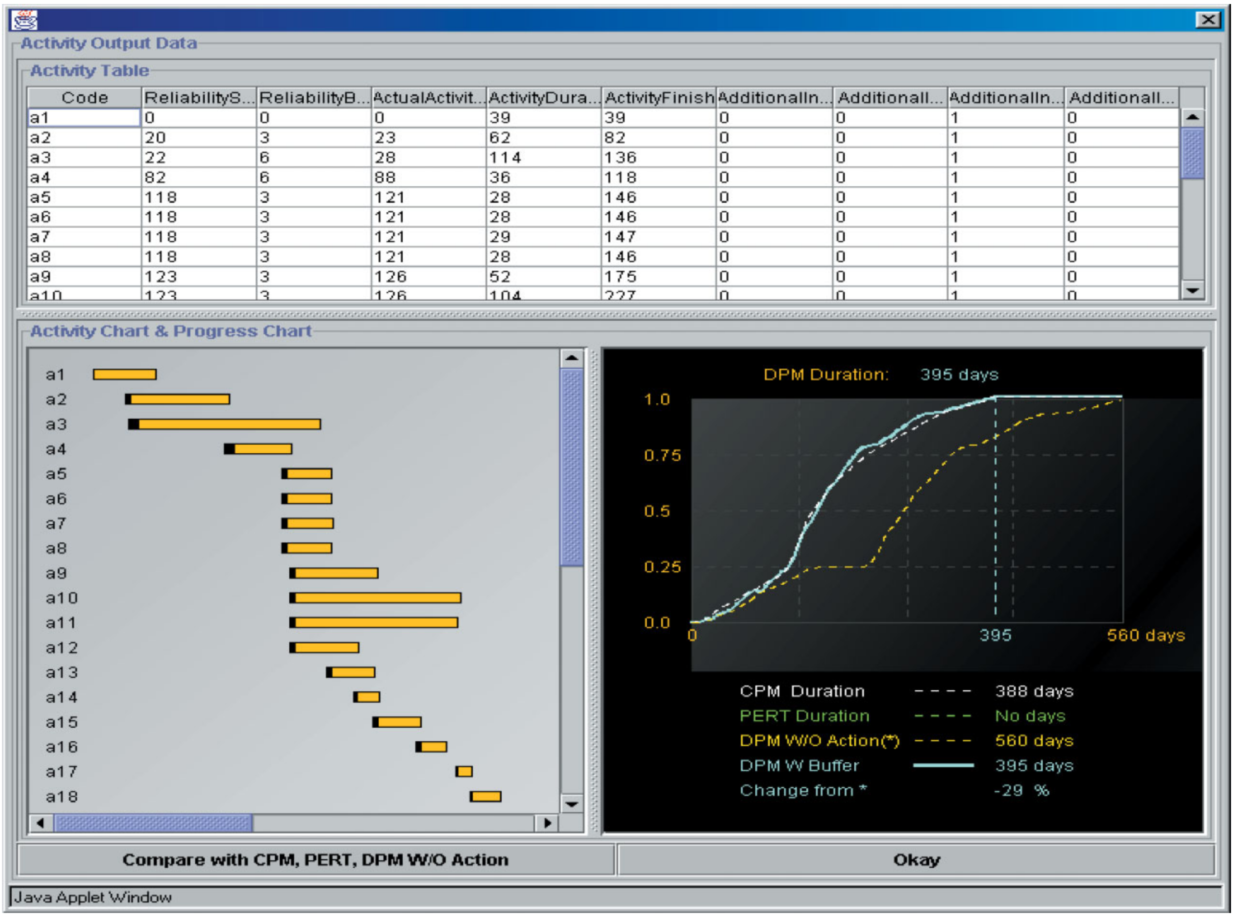


Fig. 11. The dynamic project model as a planning and control tool

while keeping the required reality in representation. To do this, the dynamic project model identifies the most influential construction dynamics and characteristics, which are converted into the generic parameters and structures in system dynamics models. In addition, by incorporating the fundamental concepts and principles of network-based tools such as CPM, PDM, and PERT into the system dynamics models, the dynamic project model has the flexibility and functionality of the traditional planning tools as well as having the required simulation capability (see Figure 11). Lastly, the dynamic project model focuses on the control aspect of management at the operational level as well as project planning, by allowing endogenous model variables to be updated by model users during simulation.

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Appendix I. Input data for the Treble Cove Project

Activity code	Activity name	Duration (days)	Driving precedence relation	Production	Reliability	Sensitivity	Effective buffering ratio
1	Sketch Plans	33		S	HU	IS	0
2	Final Plans	66	1ss20	S	HU	S	1
3	ROW Acquisition	130	2ss3	S	R	IS	0.25
4	Shop Drawing Submittals	35	2	F	R	S	1
5	Shop Drawing Review/BPads	30	4	S	U	IS	0.5
6	Shop Drawing Review/Struct Steel	30	4	S	U	IS	0.5
7	Shop Drawing Review/Rebar	30	4	S	U	IS	1
8	Shop Drawing Review/SOE Plans	30	4	S	U	IS	1
9	Steel Fabrication/Rebar	60	7ss5	S	N	S	0.75
10	Steel Fabrication/BPads	120	5ss5	S	N	S	0.75
11	Steel Fabrication/Strutural Steel	120	6ss5	S	N	S	0.75
12	Steel Fabrication/Sheet & Brace	45	8ss5	S	N	S	0.75
13	Prepare Site for Abutment E/W	33	8	F	R	IS	0.25
14	Prepare Site for Center Pier	13	12	S	R	IS	0
15	Construct Abutment E/W	30	13fs2	S	N	S	0.5
16	Construct Center Pier	15	15	S	N	IS	0
17	Set BPads and Girders	5	10	S	N	IS	0.5
18	Construct Superstructure	20	17	S	N	IS	0
19	Bell Telephone Cable	80	17ss0	S	U	IS	0.75
20	Relocate Gas Line	15	18	S	U	S	0.5
21	Relocate Water Line	15	20	S	U	S	1
22	Install Telephone DB	15	21	S	U	S	1
23	Realign Treble Cove Rd	10	22	S	R	S	1
24	Realign Rte 3 NB Ramps	20	23	F	R	S	1
25	Realign Rte 3 SB Ramps	20	24	F	R	S	0.75
26	Demolish Existing Ctr Span	10	25	S	R	IS	0.75
27	Demolish Existing EAbut	10	26	S	R	IS	0
28	Demolish Existing WAbut	10	27	S	R	IS	0

Notes
1. Default precedence relationship: FS0.
2. General convention for precedence relationship: preceding activity type lead/lag.
3. Production type: F (Fast), S (Slow).
4. Reliability: R (Reliable), N (Normal), U (Unreliable), HU (Highly Unreliable).
5. Sensitivity: S (Sensitive), N (Normal), IS (Insensitive).
6. Effective buffering ratio: The buffering ratio of individual activities that can create the best schedule for the case project.

Appendix II. Comparison with previous project management models

Modeling issues		Evolved from		Rationale for model changes
Model sector	Issues	Reference models	Changes	
Process	Overall	Richardson and Pugh (1981) Abdel-Hamid (1984) Cooper (1994) Ford and Sterman (1997) Lyneis (1999)	*Augment/Newly introduce*	
			Change cycles	Distinguishing from rework
			RFI Iterations during pre-checking	Representing change order process
			Locating change/Rework source	Implementing use-defined modeling
			Having multiple ext. dependencies	Implementing use-defined modeling
			Progress-based monitoring and quality management	Having more reality in representing construction process
			Remove	
			Coordination loop	Coordination between activities is rare in construction Usually, RFI is answered by Project Manager
			Rework preparation loop	Practically difficult to trace different work efforts In particular, ineffective when activities are aggregated
			Task releasing policy	Not appropriate in construction
			Remove	
	Undiscovered errors		Stock for undiscovered errors	Construction and design have a relatively short quality management cycle Construction is a physical manifestation
	Interaction among phases	Reichelt (1990) Homer *et al.* (1993)	*Augment/Newly introduce*	
			Iterations triggered by downstream	Representing feedback caused by downstream
Scope	Work availability	Homer *et al.* (1993) Ford and Steman (1997)	*Augment/Newly introduce*	
			Integrating with precedence relationships	More effectively representing work dependencies involved in construction
	Design changes	Cooper (1980) Reichelt (1990)	*Remove*	
			Adding design change to activity scope	Not distinguishing design from construction for DPM to be a planning and control tool for general use
Performance	Productivity quality	Homer *et al.* (1993) Cooper (1994) Hines (1999) Lyneis (1999)	*Augment/Newly introduce*	
			Progress-based productivity determined by a function of learning and complexity	Different productivity patterns involved in construction, which are changing throughout the construction period
			Remove	
			Experience and quality dilution Gaining OTJ experience	Not significant compared to progress-based productivity and quality
Resource		Lyneis (1999)	*Remove*	
			Budget constraints in labor control	Tentatively out of model scope