Development of Dynamic Planning and Control Methodology (DPM): based on the user-defined dynamic modeling approach

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ABSTRACT | CPM-based scheduling methods have been most widely used in the planning and control of construction projects. However, their usefulness has been often questioned, particularly when a project is heavily constrained by either time or resources. This is mainly because those CPM-based methods lack the mechanism to effectively formulate construction plans and evaluate feedback effects on the construction performance. As an effort to address this issue, the Dynamic Planning and Control Methodology (DPM) has been developed by integrating the CPM-based network scheduling concept and the simulation approach. To be used as a standalone planning and control tool, DPM adopts *the user-defied dynamic modeling approach*, which allows construction planners to define contents of pre-structured models by setting the values of model parameters. Having the ability to simulate the dynamic state of construction with the required flexibility, DPM aims to help prepare a robust construction plan against uncertainties. Particularly, DPM focuses on construction feedbacks in dealing with indirect and unanticipated events that might occur during construction. As examined in a case study with bridge construction projects, the use of DPM would help ensure that construction projects could be delivered in time without driving up costs by enhancing planning and control capabilities.

KEYWORDS | user-defined dynamic modeling, simulation, project management, dynamic modeling, system dynamics

1 Introduction

Since CPM (Critical Path Method) introduced network scheduling in the early 1950's, many CPM-based network scheduling methods have been developed. PERT (Program Evaluation and Review Technique, 1958) was developed to supplement CPM by incorporating probabilities into the duration of project activities. PDM (Precedence Diagramming Method, 1964) diversified precedence relationships between activities. In addition, GERT (Graphical Evaluation and Review Technique, 1966) made it possible to model 'what-if' conditions by incorporating probabilistic branching and loop structures into network scheduling. These CPM-based scheduling methods have been most widely used in the planning and control of construction projects.

However, their usefulness has been often questioned, particularly when a project is heavily constrained by

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either time or resources. Since CPM-based scheduling methods assume that the attributes of project activities such as duration and production rate are known at the beginning of a project and do not change during the project execution, they are not adequate for representing the actual project process [Martinez and Ioannou, 1997]. This results in frequent updates to reflect the actual performance into scheduling. As a result, CPM-based scheduling methods lack the mechanism to effectively formulate and evaluate construction plans, which is required to deal with a high degree of complexities involved in today's construction projects.

Researchers on simulation-based construction management [Halpin, 1977; Paulson, 1983; Bernold, 1989; Martinez, 1996] have argued that this incapability of CPM-based scheduling methods can be overcome by adopting a simulation approach, which can describe and capture the dynamic state of construction, and provide an analytic tool to evaluate construction plans with a diagnostic capability. Their research results have demonstrated that simulating construction plans prior to physical execution can substantially enhance the effectiveness of planning [Martinez and Ioannou, 1997]. However, despite its potential advantages simulation-based methods have not been widely used in practice yet. This is because they are not as flexible and easy to use as CPM-based methods, limiting their simulation capability to a specific construction process instead of a whole construction project. The unpopularity of simulation-based methods is also attributed to the lack of consideration on human factors such as workers' fatigue and schedule pressure on productivity, which is crucial to ensuring reality in the representation of construction processes.

As an effort to address this challenging issue, we present *the Dynamic Planning and Control Methodology* (DPM), which has been developed to help prepare a robust construction plan, focusing on construction feedbacks in dealing with indirect and unanticipated events during construction. To be a standalone planning and control tool with the ability to simulate the dynamic state of construction, DPM rigorously integrates the CPM-based network scheduling concept and the simulation approach. To achieve this research goal, we have elaborated the concept of *the user-defined dynamic modeling approach*, based on which network scheduling components are incorporated into system dynamics simulation models. Following a brief introduction of the research methodology, we discuss the implementation of DPM and its applicability with a case study in the subsequent sections.

2 Research Methodology: System Dynamics

System dynamics was developed to apply control theory to the analysis of industrial systems in the late 1950's [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 non-linear systems like construction. Construction projects are inherently complex and dynamic, involving multiple feedback processes and non-linear relationships [Sterman, 1992]. In this context, a system dynamic modeling approach is well suited to dealing with the dynamic complexity in construction projects, which has been proven by some researchers [Ng et al., 1998; Peña-Mora and Park, 2001].

System dynamics modeling generally proceeds in the following steps [Kwak, 1995]: First, based on a modeler's understanding on the system, conceptual model structures are described in the form of a causal loop diagram to show the dynamics of variables involved in the system. In a causal loop diagram, variables are connected by arrows that denote the causal influences between variables [Sterman, 2000]. Figure 1-a represents causal relationships between construction progress and schedule

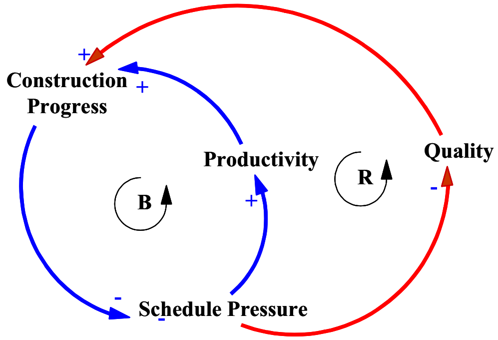


Figure 1-a. Causal Loop Diagram Notation

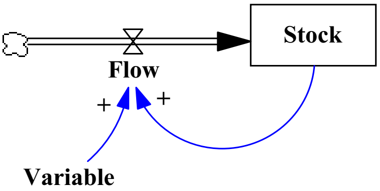


Figure 1-b. Stock and Flow Structure

pressure. Appropriate schedule pressure can increase productivity, which can facilitate the construction progress. At the same time, higher schedule pressure can also slow down the construction progress by lowering work quality. As a result, increased or decreased construction progress affects schedule pressure again, forming feedback loops.

Having a causal loop constructed, variables in the model structures come to have quantitative attributes with equations implemented based on the relationships built in the causal loop diagram. This step also includes the identification of stock and flow structures (see Figure 1-b), 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 control quantities flowing into and out of stocks. For example assume the stock and flow structures in Figure 1-c. 'Rebar in Inventory' represents a stock, in which rebar is accumulated as

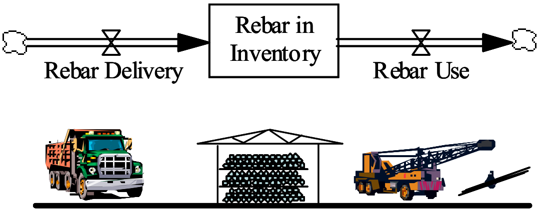


Figure 1-c. Example of Stock and Flow Structure

it is delivered through the flow of 'Rebar Delivery' and from which stored rebar is taken out as it is used through the flow of 'Rebar Use'. Once this model formation step 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.

3 Implementation of DPM

As conceptualized in Figure 2, DPM aims to be a standalone simulation-based tool that is flexible and applicable enough for the planning and control of construction projects by integrating the simulation approach and the CPM-based network scheduling. In this section, we discuss the implementation of DPM with descriptions on *the user-defined dynamic modeling approach*, the system dynamics models that constitute DPM, and the functionality of DPM.

3.1 User-Defined Dynamic Modeling Approach

The concept of *the user-defined dynamic modeling approach* has been elaborated as a vehicle to integrate the traditional network scheduling and the simulation approach. With this modeling approach, DPM has generic parameters and structures, common to almost all construction projects, with the ability to customize for a specific project and to describe specific project activities. As a result, project managers can define contents of pre-structured DPM models by setting the values of model parameters.

The success of *the user-defined dynamic modeling*

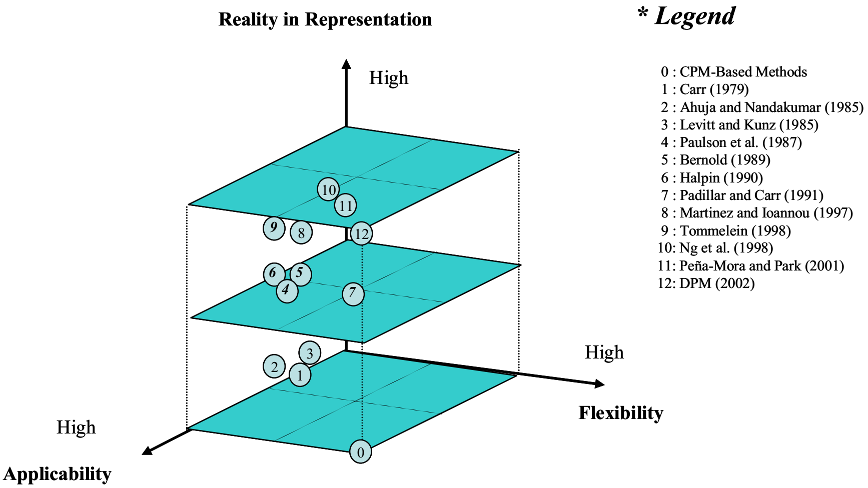


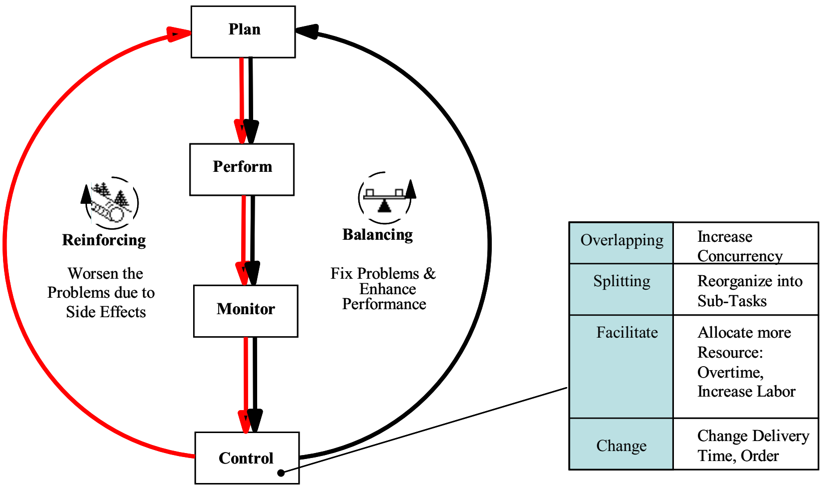
Figure 2. Target Functionality of DPM (Dimensionless)

approach depends on how well pre-structured models can represent construction processes and dynamics involved in a given project and how reliable the simulation output of the models is. Focusing on these issues, the following subsections discuss how the concept of *the user-defined dynamic modeling approach* has been incorporated into DPM.

Capturing Construction Dynamics

The user-defined dynamic modeling approach focuses on feedback processes involved in construction. Those feedback processes contribute to the generation of indirect and/or unanticipated events during the project execution and make the construction process dynamic and unstable, which is hard to capture with the traditional planning tools.

Suppose that construction processes consist of a set of steps conceptualized in Figure 3. When a certain control action is taken to reduce variations from the planned performance, the action can fix problems and enhance the construction performance but at the same time it can worsen the performance in another



Overlapping	Increase Concurrency
Splitting	Reorganize into Sub-Tasks
Facilitate	Allocate more Resource: Overtime, Increase Labor
Change	Change Delivery Time, Order

Figure 3. Feedback Processes during Construction

area due to side effects of the action. For example, when a construction project is behind schedule, one possible action to meet the original schedule is to change the equipment used on a particular activity. By replacing the current equipment with high performance equipment, it is possible to facilitate the construction process. However, it may take some time for the workers to get familiar with the operation of the new equipment or coordinating with other subsequent processes may become more difficult. As a result of low productivity and increased coordination problems, it is also possible that changing equipment can further delay the construction schedule.

Although many other factors can exist, *the user-defined dynamic modeling approach* recognizes construction changes, work dependencies among activities, construction characteristics, and human responses to work environment and policies as the major factors that trigger construction feedbacks and dynamics. As a result, this modeling approach assists DPM in simulating construction processes more realistically before the actual resource commitment. Detailed descriptions on this issue can be found in Park [2001].

Reducing the System Sensitivity

A key asset of *the user-defined dynamic modeling approach* is that before controlling an activity, it reduces the sensitivity to variations the activity may experience. This feature, together with the ability to formulate and evaluate construction plans ahead of time, helps dampen the effect of hard-to-control variations, while keeping control efforts minimized. In DPM, this is implemented by adopting *reliability buffering* [Park, 2001].

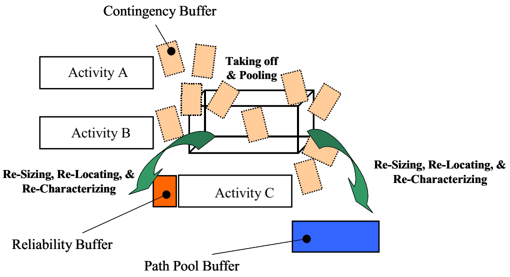


Figure 4. Reliability Buffering Steps

In contrast to the traditional contingency buffer, *the reliability buffer* aims to systematically protect the whole project schedule performance by pooling, re-locating, re-sizing, and re-characterizing the contingency buffers, if any exits. As depicted in Figure 4, *reliability buffering* starts with taking off any contingency buffer that is fed explicitly or implicitly in individual activities. Taking off contingency buffers from individual activities can make the activities benefit from appropriate schedule pressure, overcoming 'the last-minute syndrome'. In addition, *the reliability buffer* is fed in the front of the successor activity in precedence relationships and is characterized as a time to find problems or finish up work in the predecessor and ramp up resources on the successor activity. By putting buffer at the beginning of activities instead of at the end of activities, *the reliability buffer* can deal with the issue of ill-defined tasks that may require time for definition. This makes it possible to focus on activities having problems before they activate a domino effect, as it might happen with the traditional contingency buffer. In addition, *reliability buffering* provides a systematic way in sizing a buffer based on the simulation result of the construction process.

Smart System

Another fundamental concept to implement *the user-defined dynamic modeling approach* is *smart system* using software agent technology. Normally, the past experience on a construction project tends not to be utilized in the traditional planning and management. In contrast, *smart system* attempts to convert the past experience to knowledge. This knowledge-based approach makes DPM smarter and more accurate, as construction proceeds. At the beginning of construction, DPM would be established with many

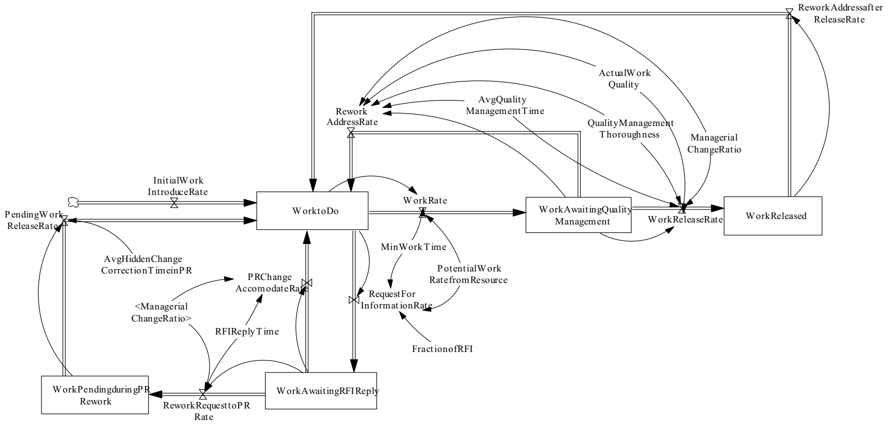


Figure 5. Construction Process Model Structure

assumed variables, but as construction advances, actual performance will replace the initial input values for a more realistic projection of the construction performance.

3.2 System Dynamics Model Development

The user-defined dynamic modeling approach has been materialized into DPM using system dynamics models; a process model and four supporting models for project scope, resource acquisition and allocation, project performance, and construction policies. In this section, we describe the process model structure, focusing on feedback processes involved in construction processes.

The process model presented in Figure 5 replicates the generic construction process. In the model structure, workflow during construction is represented as tasks flowing into and through five main stocks, which are named *WorktoDo, WorkAwaitingRFIReply, WorkAwaitingQualityManagement, WorkPendingduringPRRework* 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 defects in the prerequisite predecessor work are found. The completed tasks, then, accumulate in the stock, *WorkAwaitingQualityManagement* where they are waiting to be monitored or inspected. Depending on work quality, some completed tasks are either returned to the stock of *WorktoDo* through *ReworkAddressRate* or released to the successor work through *WorkReleaseRate*. In addition, it is also possible for released tasks to return to the stock of *WorktoDo* again through *ReworkAddressafterReleaseRate*. In case predecessor problematic work is found during the pre-checking period, corresponding tasks flow from and to *WorkToDo* through *RequestForInformationRate, PRChangeAccomodateRate, ReworkRequesttoPRRate* and *PendingWorkReleaseRate*. More detailed discussions on these processes are as follows.

When predecessor defects are found during construction, workers in the successor activity normally ‘request for information’ (RFI) to workers in the predecessor activity or project managers. If by means of RFIs, the predecessor defects turn out to have made by mistake and a managerial decision is made to correct the defects in the location of the defect generation, corresponding successor tasks are delayed until the predecessor defects are corrected. For example, assume that before starting the floor tile work, it is found that the floor slab was constructed

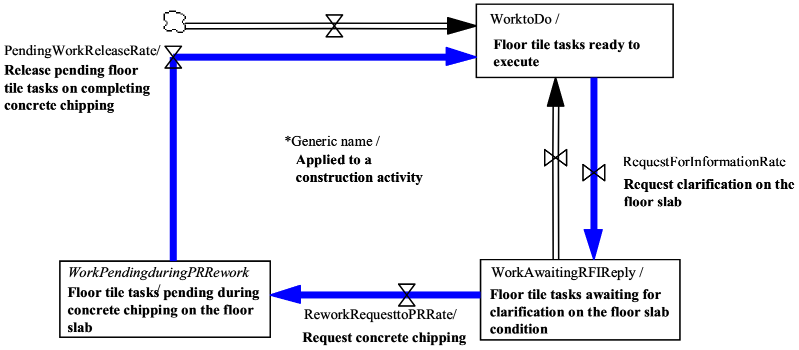


Figure 6-a. L1 Iteration Process

thicker than its specification due to inaccurate concrete pouring in the floor pouring activity. 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 concrete crew to correct the slab thickness by chipping the excess concrete. Figure 6-a conceptualizes this iteration process (L1).

However, the iteration of L1 does not take place in the following cases. First, when predecessor defects have been released to the successor by managerial decisions, they are supposed to be accommodated by changing associated successor tasks. Continuing with the floor tiling work example, it is possible to find the inaccurate concrete construction just after pouring concrete in the floor pouring activity. However, after comparing the economic impact of each option (change or rework) on the construction performance, the project manager may decide to change the specification of floor tiling activity tasks such as the thickness of mortar or the method of waterproofing instead of ordering rework on the slab. In this case, corresponding successor tasks are supposed to be changed after the management decision is confirmed through the answer to RFIs. Secondly, it is also possible for predecessor defects to be accommodated by a change decision during the successor work. Both cases are represented in Figure 6-b (L2).

Once completed, construction tasks are internally monitored and/or inspected by the owner's representatives. Depending on the result of quality management, completed tasks are either released to the successor or reworked. The following task flows in the model structure represent the quality management

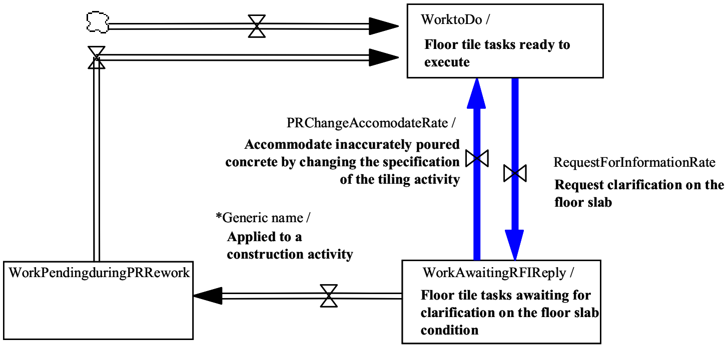


Figure 6-b. L2 Iteration Process

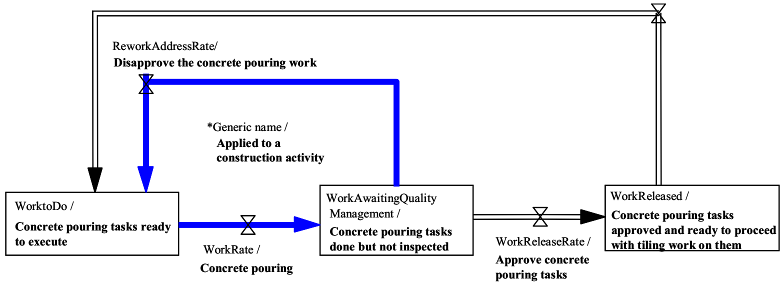


Figure 6-c. L3 Iteration Process

process in construction. Tasks accumulated in *WorkAwaitingQualityManagement* are periodically monitored and inspected. In principle, tasks satisfying the target quality level and having intended functions are approved and moved to *WorkReleased*, while defects are disapproved and pass into the stock of *WorktoDo* where they wait to be corrected. This process in associated with the floor tiling work example is conceptualized in Figure 6-c (L3). Meanwhile, the iteration of L3 is governed by *ActualReliability*, which is a function of the reliability of an activity, predecessor quality impact, and schedule pressure. An unreliable activity generates more defects than a reliable activity. In addition, the low quality of the predecessor work and lasting schedule pressure can also lower the reliability of an activity.

During quality management, it is possible to release changes to the successor by failing to notice them. In the model structure, the degree of overlooking defects is determined by *QualityManagementThoroughness,* which is normally low, when an activity work is complex or schedule pressure lasts throughout the activity work period. Overlooked defects (e.g., inaccurately poured concrete), which are defined as hidden defects, are released to the successor and can deteriorate the successor work quality, depending on the successor sensitivity to predecessor defects.

In summary, the feedback processes imbedded in the process model are common in the construction process, having nontrivial impact on the project performance. Thus, understanding their role and capturing their behaviors are critical to ensuring the reliability of a planning and control tool. By repeating the process model, DPM simulates a flexible number of construction activities, capturing the construction dynamics caused by those feedbacks. Further descriptions on the process model and other supporting models can be found in Park [2001].

3.3 Functionality of DPM

As a result of incorporating the concept of *the user-defined dynamic modeling approach* into system dynamics models, DPM has the planning and control functions conceptualized in Figure 7. Based on initial input data and control actions taken by DPM users, DPM creates a project plan, suggests project policies and simulates project performance profiles. As construction processes, the parameters in DPM can be calibrated for getting more reality and accuracy in projection of the project performance by comparing the simulated performance with the actual performance. All the simulation data and changes in the system are stored in its database for future utilization by an agent on the DPM system. Further descriptions on the DPM functionality are made below in terms of the incorporation of the existing scheduling methods and collaboration schemes.

Incorporating Existing Scheduling Methods

DPM incorporates the concept of strategic planning and concurrent engineering principles into its system as well as schedule networking concepts. The

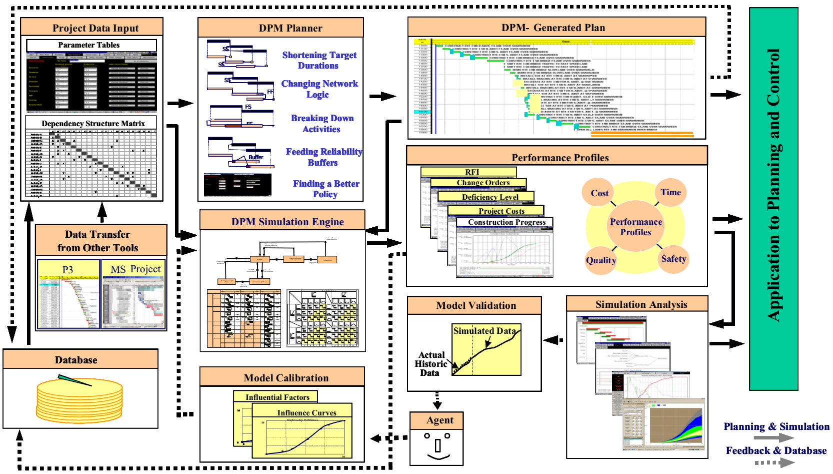


Figure 7. System Architecture of DPM

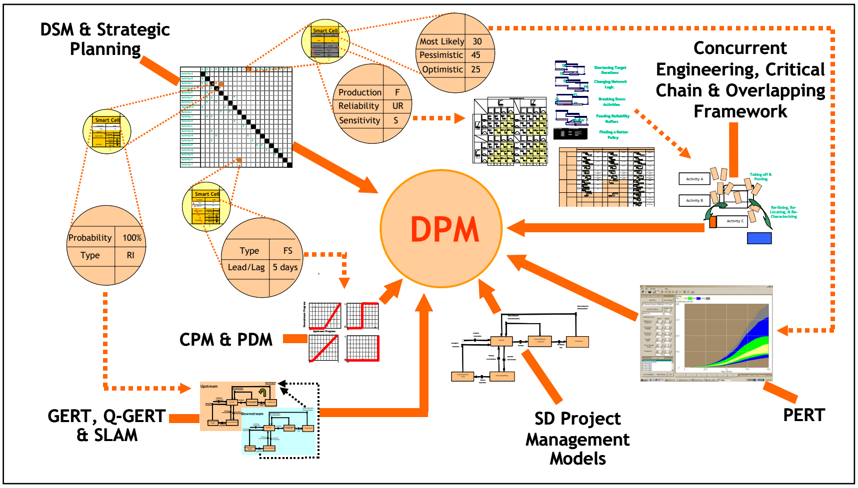
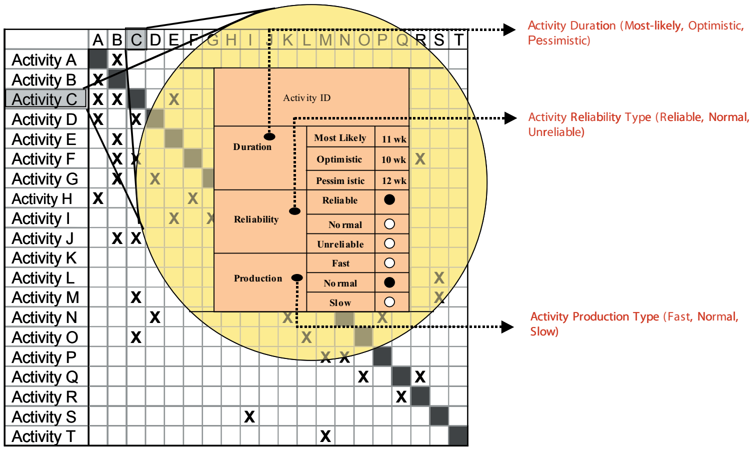


Figure 8. Integrating Methodologies

incorporated methods play their roles in the DPM system, as conceptualized in Figure 8.

Strategic Planning and DSM

DPM implements the concept of strategic planning by representing input data with DSM (Dependency Structure Matrix, Steward, 1965 and Eppinger et al., 1992) and developing *smart cells*. DSM representation and *smart cells* make it easier to recognize relationships between activities. In addition, they organize input data so that input data can be effectively utilized by other DPM functions. There are two kinds of *smart cells*. *Smart cells* for an activity (Figure 9-a) contain information on activity duration and activity characteristics such as production types and reliability. Meanwhile, those for relationship (Figure 9-b) have information on the relationship of the associated two

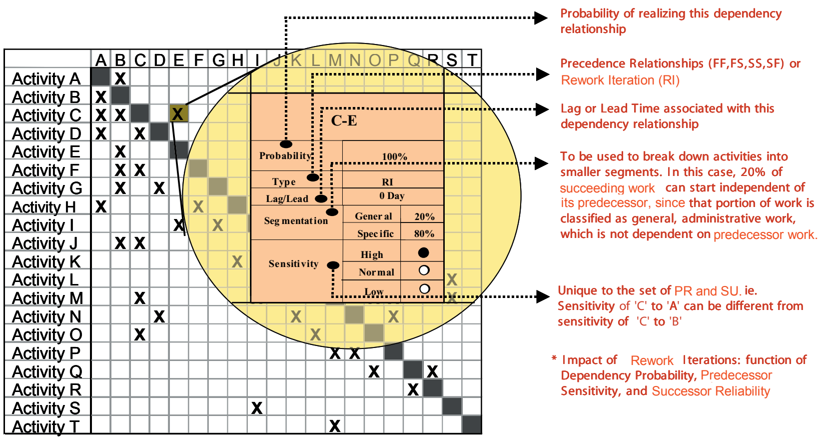


Activity Duration (Most-likely, Optimistic, Pessimistic)

Activity Reliability Type (Reliable, Normal, Unreliable)

Activity Production Type (Fast, Normal, Slow)

Figure 9-a. Smart Cell for Activity



Probability of realizing this dependency relationship

Precedence Relationships (FF,FS,SS,SF) or Rework Iteration (RI)

Lag or Lead Time associated with this dependency relationship

To be used to break down activities into smaller segments. In this case, 20% of succeeding work can start independent of its predecessor, since that portion of work is classified as general, administrative work, which is not dependent on predecessor work.

Unique to the set of PR and SU. ie. Sensitivity of 'C' to 'A' can be different from sensitivity of 'C' to 'B'

* Impact of Rework Iterations: function of Dependency Probability, Predecessor Sensitivity, and Successor Reliability

Figure 9-b. Smart Cell for Relationship

activities. Relationships represented by *smart cells* include rework iteration relationships (RI) as well as precedence relationships (FS, FF, SF, SS).

CPM & PDM

DPM implements the scheduling concept of CPM and PDM by controlling the successor work dependency on the predecessor work progress. Work dependencies represented in DPM constrain the construction process more realistically than the precedence relationships in CPM and PDM, as exampled in Figure 10. Graph A represents that successor work can be started only after 50% completion of the predecessor work and no more work dependency exists thereafter, which is similar to FS relationship in CPM and PDM. Meanwhile, Graph B describes the work dependency such that successor work can be progressed in proportion to the predecessor work progress even after 50% completion of predecessor work. Depending on the nature of construction work, this kind of work dependency can be more realistic. For example, consider the steel

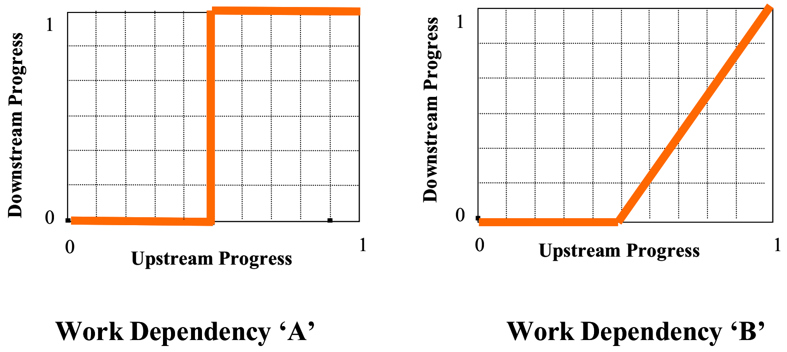


Figure 10. Examples of Work Dependency

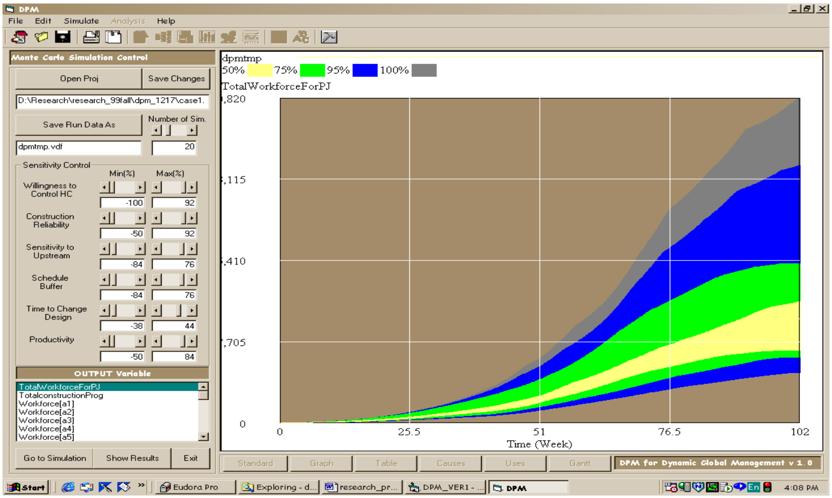
member erection activity and the concrete pouring activity for an office building construction project. Normally, concrete pouring can be started after steel member erection on one or two floors is done. However, the progress of concrete pouring is still dependent on that of steel member erection, even after the start of the concrete pouring activity.

PERT

PERT is taken into consideration in DPM by classifying activity durations into 'most-likely', 'pessimistic', and 'optimistic'. Once different types of durations are provided through a *smart cell*, DPM generates the spread of simulated actual project durations having confidence bounds based on a Monte Carlo simulation (see Figure 11).

GERT, Q-GERT and SLAM

For the implementation of the concepts from GERT, Q-GERT and SLAM, rework iterations caused by successor work defects are considered in DPM. Once the relationship type representing those iterations (RI) is indicated through *smart cells*, DPM creates rework iterations between predecessor work and successor



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dpmtmp.vdf

Number of Sim.: 20

	Min(%)	Max(%)
Willingness to Control HC	-100	92
Construction Reliability	-50	92
Sensitivity to Upstream	-84	76
Schedule Buffer	-84	76
Time to Change Design	-38	44
Productivity	-50	84

OUTPUT Variable:
TotalWorkforceForPJ
TotalconstructionProg
Workforce[a1]
Workforce[a2]
Workforce[a3]
Workforce[a4]
Workforce[a5]

Figure 11. Examples of PERT Simulation

work. The probability that governs the iteration processes can be also defined by users. For example, suppose that the activity C and the activity E in Figure 9-b represent engineering work and piling work respectively. Engineering work has a RI relationship with piling work, and the probability of realizing the relationship is 100%, which means that a certain amount of changes made during piling work would trigger the same amount of subsequent correction work in engineering work. Assuming that during the pile work steel piles continued sinking under the soil, as they could not reach a rock layer to support the piles, the engineering work for the problem area needs to be done again to find alternative ways.

Concurrent Engineering, Overlapping Framework and Critical Chain

The concepts and principles of concurrent engineering [Eppinger et al., 1992], Peña-Mora & Li's overlapping framework (2001) and Critical Chain [Goldratt, 1997] are incorporated into DPM. One of the major challenges facing concurrent engineering lies in an overlapping practice, for which Peña-Mora and Li (2001) developed an overlapping framework. In their framework, task production rate, predecessor production reliability, and successor task sensitivity are used to determine effective overlapping strategies in construction. In the same context, Goldratt (1997) introduced Critical Chain, in which it is emphasized to pull contingency buffers from individual tasks and aggregate them for a whole project and to resolve resource contentions. All of these methods are systematically integrated into DPM through *reliability buffering*, which was discussed earlier in this paper.

System Dynamics Project Management Models

The implications of the previous system dynamics models in project management [Richardson and Pugh, 1981; Abel-Humid, 1984, Reichelt, 1990; Cooper, 1994, Ford and Sterman, 1997; Lyneis et al., 2001] are imbedded in DPM. However, DPM distinguishes itself from the previous project models, since those previous models deal with project development under closed environment (e.g., product development or software development processes). As a result, they focus only on rework cycle that has a significant impact on the performance of a project having the same repeated processes under closed environment. In contrast, DPM focuses on change iteration cycles, which more frequently occur in construction than rework cycles, as well and attempts to capture construction dynamics.

Collaboration Schemes

Many different types of commercialized software are currently being used in the planning and control of modern construction projects. Even project functions working for the same project often use different types of tools. Furthermore, they tend to be geographically distributed and in different work conditions [Peña-Mora and Dwivedi, 2000]. For these reasons, DPM is designed to share project data with other existing tools and to support various kinds of computing devices, which is detailed below.

Project Data Sharing

As diagramed in the system architecture on Figure 7, data input can be made through DPM input windows or by transferring data from Primavera P3 or Microsoft Project into DPM. Once input data are simulated, the results are saved in the DPM database, which can be used for the calibration of the system dynamics models. DPM also provides a generic interface with various planning tools. As a result, it is possible for project management personnel to execute DPM own functions by simulating the system dynamics models and to do network scheduling work by calling P3 scheduling engine on the DPM platform.

Web-Based Collaboration

Due to the nature of construction, construction crews do not always get access to a desktop computer in

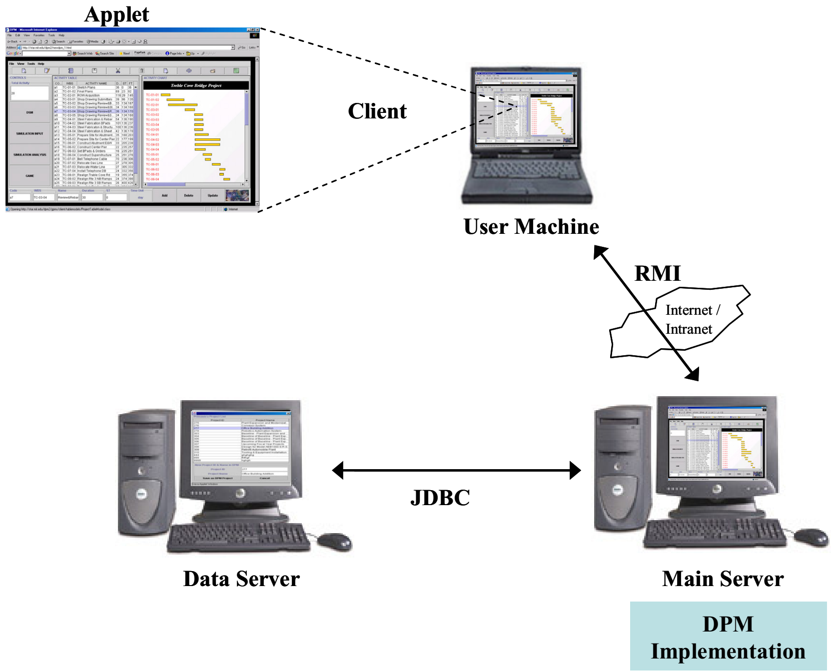


Figure 12. Collaboration Scheme

their site office, allowing only the use of wireless or portable devices. Therefore, effective monitoring and controlling require a system that can overcome the dependency of information on a desktop computer [Peña-Mora and Dwivedi, 2000]. To address this issue, the DPM system architecture supports various kinds of devices such as mobile phones, laptop computers, and palm pilots.

To materialize these collaboration schemes into DPM, three main tools, Java programming language, Vensim (system dynamics modeling software, Ventana Systems Inc.), RMI (Remote Method Invocation), and JDBC (Java Data Base Connectivity) have been used. As conceptualized in Figure 12, Java language makes DPM platform-independent. Vensim provides a simulation engine and analytical tools. To increase distributed computing capabilities, RMI allows Java objects running on the same or separate computers to communicate with one another via remote method calls. When a user starts working with DPM he/she enters the input parameters in an applet. Then, the applet requests simulations to the main server through RMI. Once simulations are done, DPM simulation results are saved in DPM database through JDBC. Combining these three main tools, DPM is able to be used collaboratively in heterogeneous environment.

4 Applications of DPM

The performance of DPM as a planning and control tool, and its applicability has been being examined with the construction of 27 bridges, which is a part of a $400 million Design/Build/Operate/Transfer project awarded to Modern Continental Companies, Inc. for roadway improvements along State Route 3 in MA. The project scope includes widening the 21-mile of the state roadway and the existing 15 underpass bridges, and renovating 12 overpass bridges. This paper presents the result of a case study with the Treble Cove Road Bridge construction, one of the overpass bridge renovations of the project, highlighting the applicability of DPM in the real world settings.

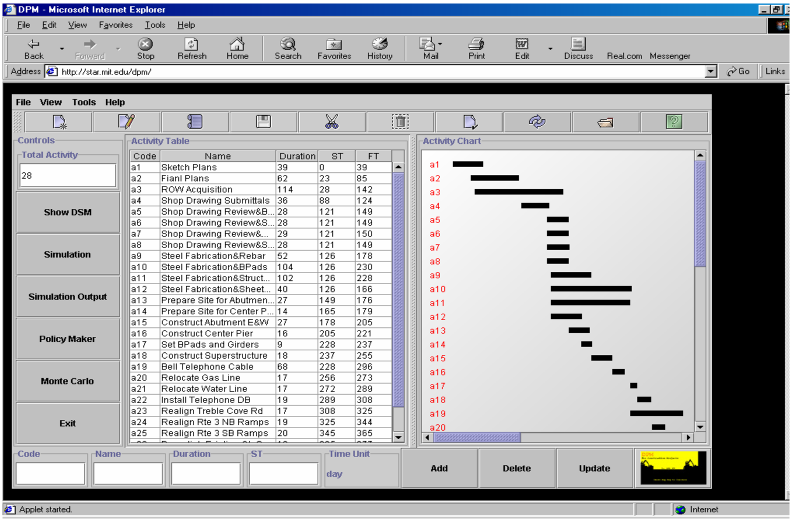
For the case study, we aggregated the original project activities to 28 design and construction activities in accordance with the DPM fundamentals. To get the necessary data, a series of interviews with schedulers and engineers involved in the project were made, through which the construction characteristics of the project activities were obtained. In the following subsections, first, we present the base case, in which the case project is simulated with 100% flexible headcount policy (level of manpower can be adjusted as much as required during construction) and no buffering policy (no contingency time is allowed for activities). Then, we discuss the results of simulations done adapting the base case with various scenarios to measure the effect of alternative construction policies. Finally, the most desirable set of construction policies for the case project are suggested based on the analysis of the DPM system behaviors.

4.1 Base Case Simulations

The simulated actual duration of the base case is 560 working days. This is 172 days longer than the CPM-based duration of the base case, which is 388 working days (see Figure 13-a and 13-b). 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 captured in the CPM-based tools. Actually, the design development of the Treble Cove Road Bridge construction 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, changes on the design work were frequently requested by the owner side during 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.

4.2 DPM System Behaviors and Policy Recommendations

To examine the effect of labor control policies, *reliability buffering*, and time components such as



Address: http://star.mit.edu/dpm/

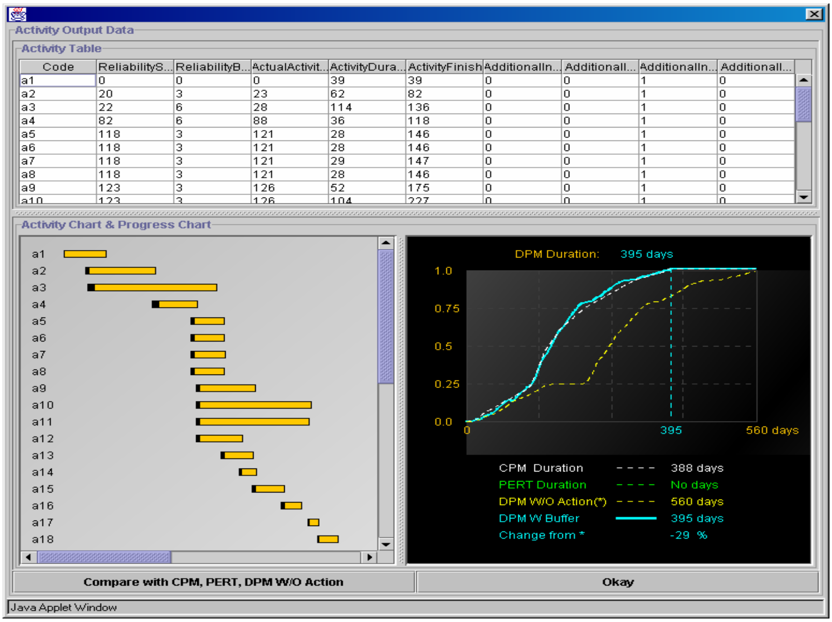
Total Activity: 28

Code	Name	Duration	ST	FT
a1	Sketch Plans	39	0	39
a2	Fianl Plans	62	23	85
a3	ROW Acquisition	114	28	142
a4	Shop Drawing Submittals	36	88	124
a5	Shop Drawing Review&B...	28	121	149
a6	Shop Drawing Review&S...	28	121	149
a7	Shop Drawing Review&...	29	121	150
a8	Shop Drawing Review&S...	28	121	149
a9	Steel Fabrication&Rebar	52	126	178
a10	Steel Fabrication&BPads	104	126	230
a11	Steel Fabrication&Struct...	102	126	228
a12	Steel Fabrication&Sheet...	40	126	166
a13	Prepare Site for Abutmen...	27	149	176
a14	Prepare Site for Center P...	14	165	179
a15	Construct Abutment E&W	27	178	205
a16	Construct Center Pier	16	205	221
a17	Set BPads and Girders	9	228	237
a18	Construct Superstructure	18	237	255
a19	Bell Telephone Cable	68	228	296
a20	Relocate Gas Line	17	256	273
a21	Relocate Water Line	17	272	289
a22	Install Telephone DB	19	289	308
a23	Realign Treble Cove Rd	17	308	325
a24	Realign Rte 3 NB Ramps	19	325	344
a25	Realign Rte 3 SB Ramps	20	345	365

Time Unit: day

Applet started.

Figure 13-a. DPM-Generated Activity Performance (I)



Code	ReliabilityS...	ReliabilityB...	ActualActivit...	ActivityDura...	ActivityFinish	AdditionalIn...	Additionall...	AdditionalIn...	Additionall...
a1	0	0	0	39	39	0	0	1	0
a2	20	3	23	62	82	0	0	1	0
a3	22	6	28	114	136	0	0	1	0
a4	82	6	88	36	118	0	0	1	0
a5	118	3	121	28	146	0	0	1	0
a6	118	3	121	28	146	0	0	1	0
a7	118	3	121	29	147	0	0	1	0
a8	118	3	121	28	146	0	0	1	0
a9	123	3	126	52	175	0	0	1	0
a10	123	3	126	104	227	0	0	1	0

Figure 13-b. DPM-Generated Activity Performance (II)

labor hiring and RFI reply time, simulations have been done by adapting the base case with different construction scenarios. The model simulation results provided valuable policy implications, making it possible to narrow down desirable sets of the project components. 100% flexible labor control policy was found to be most efficient in terms of schedule reduction. It was also observed that applying *reliability buffering* based on the characteristics of construction activities, and reducing workforce control time and RFI reply time contributed to shortening the project duration.

As indicated in Table 1, applying the desirable project settings to the case project would significantly enhance the project schedule and cost performance (29% schedule reduction and 23% cost down compared to the base case). This simulation result has been obtained, assuming that a significant time reduction in worker hiring and RFI reply was achieved, which is not easy in practice due to many other factors that govern the process. However, the important thing is that by utilizing DPM-generated results, it is possible to find which activity will be the bottleneck of a project and where to focus during the project design and construction.

5 Conclusions

This paper presented the Dynamic Planning and Control Methodology (DPM) as an effort to address some of challenging issues that have persisted in the planning and control of construction projects. All of the concepts and logics of DPM have been derived from closer observations of construction processes and practices thus far, and they have been elaborated, taking consideration into the functional requirements to realize *the user-defined dynamic modeling approach*. These fundamental concepts and logics have been materialized by incorporating *reliability buffering* contents and concurrent engineering principles into system dynamics models as well as schedule networking concepts of CPM, PDM, PERT,

Table 1. Simulation of Policy Recommendations

Cases	Flexibility in labor Control	Reliability Buffering*	Time Delays		Completion Time (Days)	Labor Hours (worker*hour)	Output Data
			Time to Increase Workforce (days)	Time to Reply RFI*			
1	N/A	None	N/A		388	N/A	CPM*
	100%		7	3	560	1.305M	base
2	100%	Subject to Individual Activity Characteristics	3	9	395	1.055M	RCMD

* Note 1. Buffer Size: Fraction of Taken-off Contingency Buffer (20% of Activity Original Duration)
2. Divider of activity original duration to get the average time to reply RFI.
3. Based on CPM-related data only

GERT, and SLAM. Then, the performance of DPM as a planning and control tool and its applicability in real world settings was examined with an application example. The potential impact of this research can be summarized as follows:

- Increase the planning and control capability: Problems encountered during construction are fundamentally dynamic. However, they have been treated statically with a partial view on a project [Lyneis et al., 2001]. As a result, chronic managerial problems persist in carrying out construction projects and schedule is continuously updated with a time delay in a monotonic way. In this context, DPM would help prepare a more robust construction plan against uncertainties and provide policy guidelines.
- Enhance learning in project management: Learning has rarely accumulated across construction projects. This is, in part, because construction is process-based work that is performed on an unfixed place by a temporary alliance among multiple organizations [Slaughter, 1998]. However, it is also true that the lack of learning in construction is attributed to the lack of learning mechanism in the traditional CPM-based planning tools. Equipped with *smart system*, DPM allows the model structures to be tuned up based on information obtained from the actual project performance, which would make it possible to embed one's knowledge and learning from a project into the planning and control system.
- Increase the applicability of simulation approach to project management, while keeping the required simulation capability: The simulation capability tends to be seen as an opposite concept to applicability. Partly due to this recognition, the previous research efforts to increase the applicability of the simulation approach have mainly focused on the development of user-friendly graphic representations of simulation components. In contrast, DPM would increase applicability, while keeping required reality in representation by realizing *the user-defined modeling approach*. The collaboration schemes incorporated into DPM also increases the applicability of simulation approach by assisting in dealing with geographically distributed projects.

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