Dynamic Planning and Control for Large-Scale Infrastructure Projects: Route 3N as a Case Study

by

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ABSTRACT

Construction processes inherently involve complex interactions among variables including, but not limited to, physical attributes, logistics, resource availability, budget restrictions, and management techniques. Labor productivity, a key variable in the profitability of a project, is influenced by complex and competing factors such as skill level, fatigue, motivation, and schedule pressure. Contractors continue to struggle with a fragmented industry where competitive pricing and labor productivity are defining factor in their competitive advantage. Competitive pricing for materials is readily achievable for major contractors. Increased and reliable labor productivity is essential for a contractor's competitive advantage. The current management tools for the industry are inflexible when planning and controlling work on a fast-track project where information is knowingly incomplete, both in final design and construction means and methods. Actual events and conditions are more challenging than anticipated, which demands pulling together resources more rapidly to execute with precision and ensure the project is still delivered on-time and within the budget. Dynamic Planning and Control Methodology (DPM) is intended to make a marked difference in the success of the project. DPM is a demonstrated research objective, which can lead to this competitive advantage. This thesis will outline the prior research efforts, the relative position of DPM in the existing research environment, the fundamentals of DPM, and the challenges and results of its implementation on an active large-scale infrastructure project.

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God Bless.

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EXECUTIVE SUMMARY

Dynamic planning and control methodology (DPM) integrates the principles of System Dynamics modeling techniques with Robust Design as well as Axiomatic Design, Dependency Structure Matrix, Theory of Constraints, Concurrent Engineering, CPM, PDM, PERT, GERT, and SLAM to analyze and quantify the effect of numerous dynamic interactions within product development, manufacturing, and construction processes [Peña-Mora and Park, 2001].

The current management tools for the construction industry are inflexible when planning and controlling work on a fast-track project where information is knowingly incomplete, both in final design and construction means and methods. This uncertainty may turn out to be benign in the overall execution of the project, but where actual conditions are more challenging than anticipated, this requires the team to pull together its resources more rapidly and execute with precision to ensure the project is still delivered on-time and within the budget. This is where DPM is intended to make a marked difference in the success of the project.

Today, expectations for marked improvement and delivering a product faster and better continue to drive markets, the construction industry is no exception. Those in the industry providing design, construction and consulting services that embrace the tools that can make them more cost-effective and efficient have much to gain in this large, world-wide industry. Utilization of DPM will be a distinguished competitive advantage.

This research is focused on the application of DPM on fast-track project being delivered under a Design-Build-Operate (DBO) contract with a fixed budget of $385 million. The Route 3 North Transportation Improvement Project is expected to span 42 months and entails widening a major transportation artery between Boston and the State of New Hampshire from four lanes to six lanes plus widen or relocate the existing bridges to accommodate eight lanes, should future traffic demand necessitate further roadway reconstruction.

Chapter 1 describes the research background including motivations, objectives and expected benefits from the use of DPM. In Chapter 2, the dynamics of construction processes are highlighted. Then, Chapter 3 presents the evolution of prior research efforts in related applications. Chapter 4 introduces the component methodologies utilized by DPM from prior research efforts and industry standards. Chapter 5 presents the fundamental concepts of DPM including the system architecture of DPM and the generic system dynamics models for the construction process, which distinguish DPM from other research approaches. Chapter 6 lays out the case study and the results generated from the implementation of DPM. Chapter 7 highlights the current efforts by the research team to transition this research into commercial application. Finally, Chapter 8 discusses where further research and development efforts could be directed.

CHAPTER 1

RESEARCH BACKGROUND

Planning consists of determining all items of work or activities necessary for completion of a contract, their interrelationships, and order of performance. *Scheduling* involves the translation of the plan into a timetable by assignment of time estimates or durations for the accomplishment of each activity [Bhandari, 1977]. *Controlling* is the process of making events conform to schedules by coordinating the action of all parts of the organization according to the plan established for attaining the objective [Moder et al., 1983].

Construction processes inherently involve complex interactions among variables including but not limited to physical attributes, logistics, resource availability, budget restrictions, and management techniques. During project execution, these variables control and are controlled by the other closely related variables which change as the system moves through time. Imbalanced interactions among the variables can cause inefficiencies and uncertainties in the project execution [Paulson and Koo, 1987], which can deteriorate planned construction sequences and increase total project costs. Moreover, as construction projects continue to increase in size, the planning and control of the projects become more difficult as a result of increased complexity and uncertainty; the larger and more complex the project, the more difficult it is for the project manager to coordinate all the resources to reach the common goal. In addition, today's business environment in the construction industry is getting more competitive, making "time-to-market" together with cost reductions an important program management objective. As a result, the industry seeks a more efficient planning and control method to supplement, enhance or replace the traditional methods.

As outlined by Peer (1977), there exist four distinct categories of schedule activities in planning construction sequences:

1. Preparatory activities that are not an integrated part of the main production process on site. Some of these have to be completed before production on site can be started, and the rest must be completed in accordance with on-site progress. This includes all approval and planning procedures and supplies.
2. Main repetitive activities that form continuous production lines to be performed by specialized crews throughout the project in a fixed technological sequence, e.g., masonry and formwork.
3. Interlinked activities that can be a single activity or a continuous production line, but only its earliest start and latest finish are connected with two of the main production lines. This connection defines a maximum allowed time interval for performing these types of activities. As long as it is not being exceeded, their duration have no influence on the total construction time.
4. External activities that are not integrated into the main production process but are part of the project.

1.1 OBJECTIVES OF THE RESEARCH

The research aimed to implement Dynamic Planning and Control Methodology (DPM) on an active large-scale infrastructure project. DPM's simulation-based dynamic approach to planning and control was specifically called out in the winning bidder's contract proposal submittal and utilized during the project initiation phase.

Using the DPM model developed [Peña-Mora and Park, 2001], this research will be the implementation of the model on an active project to calibrate the current assumptions and functions. Notwithstanding the previous research, the implementation of this model will necessitate reevaluation of the feedback loops and addition of new dynamic elements, as well as the elimination of elements currently within the model. Implementation will be performed in two phases: application of model variables with parameters and calibration. Initially, project-specific information will be assembled within the model. This phase includes interviewing key project personnel such as the bid estimator, project manager, project scheduler, general superintendent, lead design engineer, and lead procurement engineer to input early assumptions, estimates, and risk assessments. During the calibration phase, status update meetings with the management team will be essential to accurately update the model, adjust for impacts and changes which occurred during the past period, and revise the 'to-go' plan as necessary. This research will be executed in coordination with the project team, but will avoid interference with their daily operations.

Model implementation will require quantification of dynamic variables, identification of correlations among the variables, and accurate projections of potential dynamic environments. Specifically, the distinction between physical progress and process durations from non-productive or risk-associated factors will more accurately allocate the given time to meet the project completion date. Where efficiencies and potential risks are revealed, these observations could benefit the team's approach to project completion.

During the interview process with project participants, the research team will capture subjective information by eliciting qualitative estimates of the degree of influence common occurrences present. It is believed that qualitative estimates are practical since the impact of uncertainties is easier to express in linguistic terms [Chang, 1987]. While there are no institutional restrictions on the degrees of influence, this research will simplify the degrees to five levels: high, medium, average, low, and no influence.

This research will also highlight the realities and challenges of implementing this methodology into the construction industry. In particular, the research will document the events leading from the development of the methodology, to the disclosure of the technology, to filing a provisional patent on the technology and an outlook for future successes. This segment of the research will highlight the transition of the methodology from academic research to practical application and market penetration into the construction industry.

1.2 BENEFITS OF THE RESEARCH

The dynamic planning and control methodology (DPM) provides a robust plan to absorb both potential and unforeseen impacts to the project cost and/or project schedule [Peña-Mora and Park, 2001]. Applied during the initial planning process and exercised during project execution, DPM facilitates on-time project delivery within an established budget for large-scale infrastructure projects by enhancing planning, monitoring and control capabilities. DPM is not intended to foresee the future or assure with absolute certainty the outcome of events, but rather establish an executable plan flexible enough to absorb the impact of uncertainties and complexities that are inevitably forthcoming.

DPM is intended to improve upon the current management tools used to plan efficient operations, track and maintain planned productivity, and manage schedule and cost impacts. DPM offers a significant advancement in planning and controlling processes and work activities that are subject to multiple and unanticipated changes. During the planning process, DPM identifies opportunities to plan work activities and optimize work sequences subject to limited and variable resources. During project execution, the action plan remains dynamic and offers flexibility in the execution of the contract. When change events do occur during execution their effect on the overall system can be better managed and the appropriate contingency plan may be implemented. Importantly, DPM offers management the tool it needs for quick decision-making and rapid response to changed conditions in the most cost-efficient and productive means available. Lastly, the actual performance experienced will be retained which will provide the means for continuous improvement, thereby closing the feedback loop.

With the adoption of DPM, the management team will have a tool adaptable to changing circumstances that includes past resource experiences, which is continuously updated with current and relevant experiences. DPM can be integrated with a firm's existing estimating and costing system thereby expanding the knowledge base for future applications.

1.3 DPM IMPLEMENTATION CHALLENGES

The main thesis objective addresses the challenges of implementing this dynamic management tool to an active construction project, more specifically the Route 3 North Transportation Improvement Project north of Boston, Massachusetts. This thesis will share the techniques selected and utilized to extract model variables and inputs, the utilization of the data collected within the model simulation, and the significance of the model outputs for continuous project planning and control.

Each project manager plans the project execution based on personal past experiences, organizational ability, intuition, and common sense. A corporate identity is developed and sustained by the aggregate performance of each project manager whose personal technique may or may not be similar to those of fellow co-workers. A project's success will be heavily influenced by the chosen managerial technique and its adaptability to continuously changing conditions.

As stated by Bhandari (1977), to keep proper tabs and stay on top of managerial issues, one must have:

1. The ability to get quick and reliable answers to computational and statistical questions, including those of forecasting with rapidly changing inputs.
2. The ability to recover or retrieve information, often in new combinations or contents, that has already been produced but is now filed away.
3. The ability to amass and interpret the greatest number of relevant facts and relationships upon which to base administrative decisions.

4. The ability to foresee the consequences of current or impending decisions and policies on future behavior of the system so devised.

The management of construction processes is particularly complex given the combination of both fixed and dynamic resources, inherent time delays for procurement, and "ramp-up" that are typically variable and often unpredictable, as well as limitations from human characteristics including cognitive and temperamental.

In contrast to the manufacturing industry, there currently exists little opportunity for scalability in the construction industry since most projects are "one of a kind" products – each project has its own site and distinct layout with customized logistical processes. As a result, there is only a narrow basis for a fundamental approach to production control and effective use of information technology. Adding to the complexity of construction management is the multitude of project participants - there are lead designers and their specialty engineers (e.g. structural engineer, HVAC engineer) and there are lead constructors and their specialty contractors (e.g. vendors, suppliers, installers) for the various functional elements of the project such as the structural steel, masonry, painting, and landscaping to name a few. With an increase in the number of project participants comes an undisputed increase in the amount of information being circulated. These and other factors contribute to the extreme fragmentation of the construction industry, which has plagued purposeful integration and process improvements [Brandon et. al., 1998].

1.4 DPM IMPLEMENTATION BENEFITS

Notwithstanding the challenges stated above there is ample room for vast process improvements in the industry. While other construction industry research objectives are focused on process improvements through enhanced process and product visualization and enhanced means of communication, this research addresses enhancements to process execution utilizing knowledge-based expert systems to leverage corporate knowledge.

The advantage of DPM is the dynamic planning and control methodology that provides a robust plan to absorb both potential and unforeseen impacts. The practical benefit of DPM is enhanced when adopted in combination with the five fundamental principles of "Rules of Engagement" [Helmes et al., 1999]. These five fundamental principles are:

1. *Reasonableness of the approach.* The schedule that both parties commit to must represent a logical plan for completing the work. This includes reasonable durations for activities, reasonable logic ties, and reasonable allocations of resources. Without a reasonable approach, decisions may be fundamentally flawed and conflicts between parties become more likely.
2. *Good faith.* Both sides must proceed in a spirit of trust and fair play. Each party must assume that the other will execute its responsibilities in accordance with contract obligations and the objectives of the project, and hold themselves to the same standard. This spirit helps prevent disputes and keeps the focus on the completion of the project.
3. *Sense of urgency.* Both parties must commit to executing their respective functions with all due speed. With appropriate prioritization and coordination, the work can proceed according to the plan laid out. Neither party should delay just because extra time appears to be available or because sufficient resources are not at hand, provided these resources were foreseeable at the outset of the project.
4. *Discipline.* Both owner and contractor must exercise discipline in maintaining and statusing the schedule on a regular basis. This includes evaluating changes and their impact on the current schedule, consistent with the amount of change occurring. The parties must also make decisions in the timeliest fashion possible. The fact that certain decisions cannot yet be made should not serve as an excuse to avoid decisions about how to proceed until those decisions are made. Delayed decision making threatens project completion.
5. *Communication.* Because no project proceeds completely according to the initial plan, both parties need a commitment to regular communication about project conditions, problems, and solutions. This communication

must be open, non-adversarial, and cooperative in spirit, consistent with each party's understanding of the contract.

It is unreasonable to expect no impacts or changes once a project commences. More realistically, the initial plan is challenged from the start and continuously through the project duration. For the schedule to serve as an effective tool it must represent a reasonable and current plan to accomplish the work while sustaining sufficient flexibility to address potential execution challenges. As the project proceeds, unexpected progress, delays, and technical conditions challenge the plan and adjustments are required to keep the schedule accurate. If appropriate, the current plan requires logic network modifications to properly represent how the work is actually being performed and how the work remaining is expected to be performed. If the project schedule does not reflect past project performance, it may misrepresent the contemporaneous to-go completion plan [Helmes et al., 1999].

When planning for a potential schedule impact often the estimated duration is unknown and the parties are reluctant to assign a specific duration to the changed event. Notwithstanding cost disputes, it is important to input a schedule fragnet utilizing the best information available when the issue arises to reflect changed or extra work conditions. Just as the original baseline schedule was estimated from the information available and known at the time, this approach must be following in the determination of the change impacts. The change impact must be mutually approached with reasonableness of expectation and prudence. Inserting the schedule fragnet and evaluating the revised schedule, management has the necessary information to decide what actions need to follow as a result of the change. Timely decision-making following the changed event is absolutely crucial; delayed decisions compound the impact of the initial event [Helmes et al., 1999].

CHAPTER 2

CONSTRUCTION PROCESS DYNAMICS

Construction is inherently dynamic and involves multiple feedback processes, which produce self-correcting or self-reinforcing side effects of decisions [Sterman, 1992]. These feedback processes can become more dynamic and complex under time and resource constraints.

This chapter will discuss the common process dynamics such as variable productivity rates, the effect of worker fatigue and process feedback effects. In addition, this chapter will introduce the concept of a system dynamics modeling environment and its ability to capture and process dynamic relationships and present them through graphical means.

2.1 PRODUCTIVITY ISSUES

As discussed in the Modification Impact Evaluation Guide (July 1979) developed by the U.S. Army Corps of Engineers (USACE), two major impacts upon labor costs are reduced productivity and pay scale increases. The latter is a factor when changes delay progress such that work that would have otherwise been completed during a planned construction phase and is required to be performed at a time when higher wages are in effect. Reduced productivity takes many forms, but implies a loss from some established normal or anticipated level of productivity.

Although construction does not lend itself to definitive measurements of labor productivity, there are methods a contractor can use to quantify anticipated labor costs when preparing a bid. The most common technique draws heavily on data derived from the contractor's past experiences, including any indicated trends, present labor pay rates, and anticipated labor rate increases during the life of the project [USACE, 1979].

That portion of the Contract Price devoted to labor costs indicates the contractor's anticipated level of labor productivity. Whether or not the anticipated profit is realized is dependent on the contractor's ability to maintain the planned labor productivity. With effective management and a little bit of luck, the contractor may achieve labor productivity that exceeds its expectations. Alternatively, labor inefficiencies may be realized due to many uncontrollable factors. Labor productivity is optimal when there is good "job rhythm" [USACE, 1979].

Productivity disruption occurs when workers are prematurely moved from one assigned task to another. Regardless of the competency of the workers involved, some loss in productivity is inevitable during a period of orientation to the new assignment. This loss is repeated if workers are later returned to their original job assignment. Learning curves that graph the relationship between production rate and the repeated performance of the same task have been developed for various industrial tasks. The basic principle of all learning curve studies is that efficiency increases as an individual or team repeats an operation over and over; assembly lines are excellent demonstrations of this principle. However, although construction work involves the repetition of similar or related tasks, these tasks are seldom identical. Skilled construction workers are trained to perform a wide variety of tasks related to their specific trade. Therefore, in construction, it is more appropriate to consider the time required to become oriented to the task rather than acquiring the skill necessary to perform it. One of the attributes of the construction worker is the ability to perform the duties of this trade in a variety of environments. How long it will take the worker to adjust to a new task and environment depends on how closely related the task is to his experience or how typical it is to the work usually performed by his craft. The time required for a worker (or crew) to reach full productivity in a new assignment is not constant. It will vary with skill, experience, and the difference between the old and new task. For example, an ironworker is moved from placing reinforcing bars to the structural steel erection crew. The ironworker is qualified by past training to work on structural steel, but the vast majority of his experience has been with rebars, and the two tasks are significantly different. As a second example, the same ironworker is moved from placing reinforcing bars for Building A to the same work in Building B, which is similar but not identical to Building A. In this second example, the loss of productivity would be significantly less. In the pricing of the original bid, the contractor should have factored its own loss of productivity when moving from one task to another under its planned project execution [USACE, 1979].

The optimum crew size is the minimum number of workers required to perform the task within the allocated time frame. Optimum crew size for a project or activity represents a balance between an acceptable rate of progress and the maximum return from the labor dollars invested. Increasing the crew size above optimum can usually produce a higher rate of progress, but at a higher unit cost. As more workers are added to the optimum crew, each new worker will increase crew productivity less than the previously added worker. Carried to the extreme, adding more workers will contribute nothing to overall crew productivity [USACE, 1979].

Working more hours per day or more days per week than the standard 8-hours, five-days a week (Monday through Friday) introduces premium pay rates and efficiency losses. Workers tend to pace themselves for longer shifts and more days per week. Longer shifts will produce some gain in production, but at a higher unit cost than at a normal hour of work. With overtime work, some of the labor costs produce no return because of inefficiencies. Occasionally, the contractor must offer overtime work to attract sufficient manpower. In this case, this additional cost must be borne by the contractor [USACE, 1979].

The responsibility for motivating the work force and providing a psychological environment conducive to optimum productivity rests with the contractor. Morale does exert an influence on productivity, but so many factors interact on morale that their individual effects defy quantification [USACE, 1979]. Normally, pricing of changed work does not include loss of worker morale. The degree to which this may affect productivity, and consequently the cost of performing the work, would normally be very minor when compared to the other causes of productivity loss. A contractor would probably find that it would cost more to maintain the records necessary to document productivity losses from lowered morale than justified by the amount he might recover. Moreover, the level of morale is a factor in determining the effectiveness of the contractor in its labor relation responsibilities [USACE, 1979].

In the Modification Impact Evaluation Guide, the USACE presents its derivation of productivity losses, which are often relied upon and utilized for pricing of changed work. While these productivity losses are supported by relevant research conducted by the USACE, challenging these notions and assumptions are justified.

2.2 DESIGN-DRIVEN AND CONSTRUCTION-DRIVEN FEEDBACKS

Construction is inherently dynamic and involves multiple feedback processes that produce self-correcting or self-reinforcing side effects of decisions (Sterman, 1992). Under a fast-track environment these dynamics are further exaggerated and more complex. For this reason, fast-tracking construction usually involves more diversified and dynamic feedback processes than does sequential construction [Peña-Mora and Park, 2001].

Overlapping design and construction activities has the potential to yield improved project performance in comparison to a sequential project process. However, this compression and overlapping approach introduces concurrencies that may prove detrimental to the project performance if not properly managed. Where the goal of the overlapping approach is to shorten the project duration and reduce project costs, poor management of this approach may actually yield a delayed project at an increased cost.

With more uncertainty in the design process, the necessity for assumptions to be made may be increased [Tighe, 1991]. For example, oversizing of foundations may occur to accommodate a wider variety of equipment loading forces. Air handling units might be oversized to accommodate a wider variety of systems requirements. These oversizing initiatives, while intending to 'cover all the bases' may yield unnecessary costs to the project. Furthermore, as the final design is not established at the start of the construction phase, further design changes will likely impact the construction phase. Design changes that lead to construction changes may lead to schedule delays and cost overruns. The frequency and magnitude of design changes will play a significant role in the overall project success.

In planning a fast-track project, the schedule is likely to have little project float to utilize; impacts from design changes to the construction will likely compress a construction schedule. Figure 1 and 2 illustrate the complexity and interrelationship between design and construction activities; Figure 1 highlights with bold lines typical design-driven feedback loops, while Figure 2 highlights typical construction-driven feedback loops.

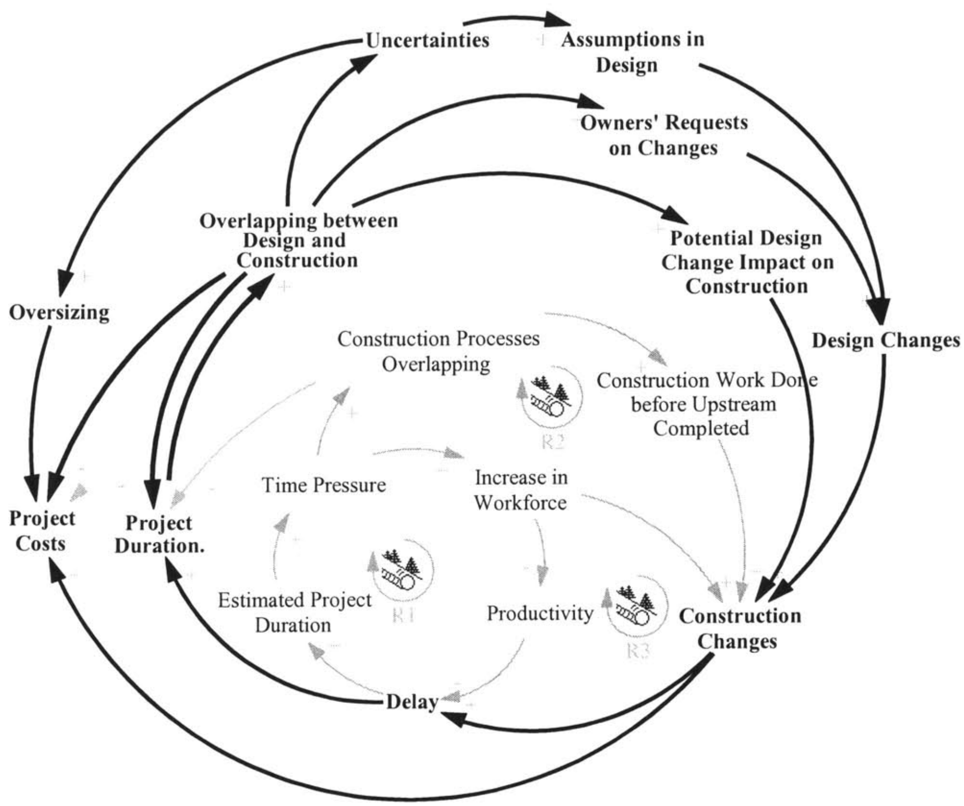


Figure 1: Design-Driven Feedback Loops in Fast-Tracking [adapted from Park (2001)]

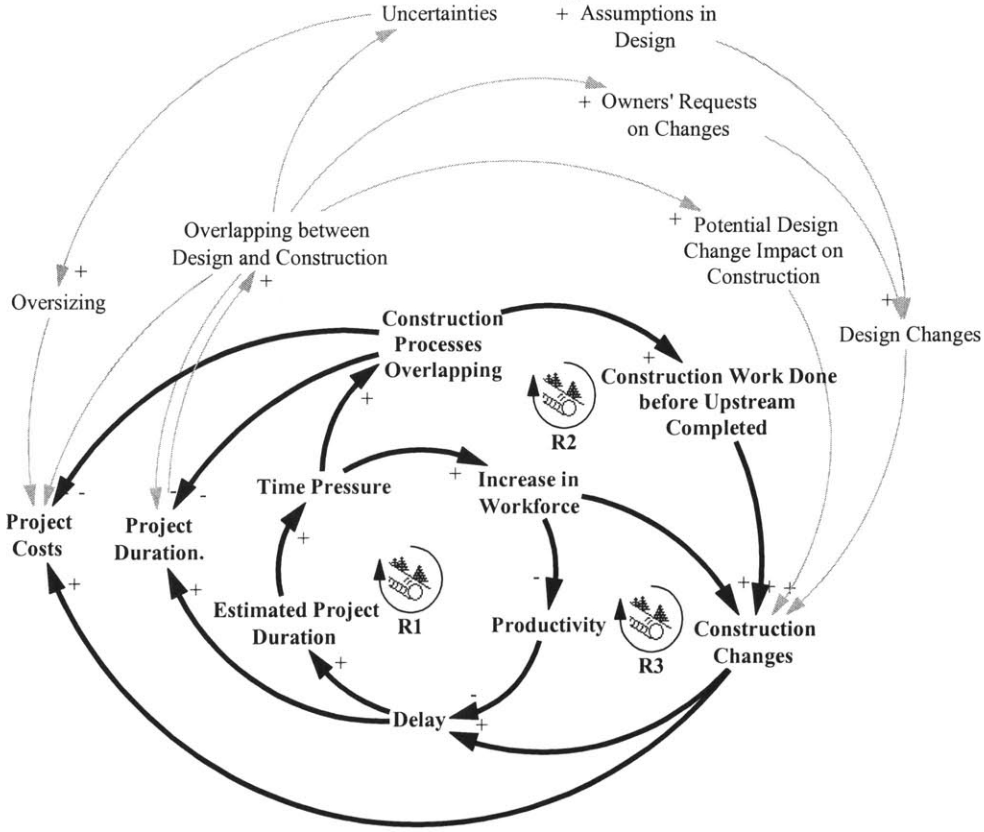


Figure 2: Construction-Driven Feedback Loops in Fast-Tracking [adapted from Park (2001)]

CHAPTER 3

EVOLUTION OF THE CURRENT WORK

To date, research efforts on the simulation-based planning and control have been made to overcome problems that cannot be addressed in network-based planning methods. The research results have demonstrated a key advantage of simulation approach is its ability to identify potential conflicts before physical execution, substantially enhancing the effectiveness of planning and control [Martinez and Ioannou, 1997]. However, despite its potential advantages over network-based methods, only few of the existing simulation tools have proven their applicability to real construction processes. In this chapter, the previous researches on the simulation-based planning and control are reviewed together with their application examples. Then, Dynamic Planning and Control Methodology (DPM) is introduced as an alternative to network-based methods and compared to the previous research efforts.

3.1 HISTORY OF SCHEDULING SOFTWARE DEVELOPMENT

Prior to 1957 bar charts and S-curves were the primary planning and scheduling tools available for use by project management personnel. These tools were capable of comparing work over time through graphical means. At this time, planning and scheduling was considered more as an art than a science[1]. However, this changed dramatically in 1958 as two independent research efforts developed network-based scheduling techniques. The Dupont Company and Univac undertook the first research effort jointly; it resulted in the development of the CPM scheduling technique. The initial research was focused toward developing a time-cost trade-offs optimization algorithm and resulted in the network theory, which remains basically unchanged today. The U.S. Navy and its advisors for the Polaris submarine program undertook the second research effort; it resulted in the development of PERT scheduling technique.

While these two network techniques were developed independently and without the knowledge of the other effort, their results were surprisingly similar. The primary difference is that CPM is deterministic while PERT is probabilistic in its approach to time durations of schedule activities. When these techniques were unveiled in 1959, the hardware developed at the time was proprietary and data was batch loaded into mainframe computers. CPM and PERT were only conceptually developed and applied to a few test projects.

Throughout the 1960's, implementation of network-based planning and scheduling software was ever increasing. Dupont and the chemical industry continued to develop and utilize the CPM technique while several federal agencies, including U.S. Army Corps of Engineers (USACE), Veterans' Administration (VA), General Services Administration (GSA), and National Aeronautics and Space Administration (NASA), began to specify network-based techniques on their projects. There was considerable competition among the advocates of CPM and PERT during this time period, but by 1965 these terms were generally interchangeable. For the most part, the chemical and construction industries were proponents of the CPM technique while R&D, defense, and aerospace were typically applying the PERT technique.

A key development that helped launch the proliferation of network-based programs was the introduction of the IBM 360 computer in 1967. The IBM 360 computer revolutionized the

[1] By Webster's dictionary definition, an art is "the conscience use of skill and creative imagination" while science is "something that may be studied or learned like systematized knowledge" [www.m-w.com, 2000].

mainframe computer market by standardizing computer architecture. This development encouraged software to be written, which could be used on various computer models. Standardized computer architecture ultimately lead to the development of the commercial software packages and computer "time-sharing." The second and related event was the "unbundling" of software packages. Thus, the IBM 360 and the "unbundling" of IBM software packages provided greater accessibility to computers for network-based software.

During the early 1970's, CPM techniques were applied to a widening variety of diverse projects. The introduction of the construction management concept, especially on public sector projects, contributed heavily to the broadening use of CPM techniques. Embodied in the construction management concept was the use of fast-tracking (overlapping of design and construction activities) and multiple prime contract in lieu of one general construction contractor. Coordination of the intricate interrelationships resulting from fast-tracking and multiple prime contract requirements resulted in expanded usage of CPM techniques.

A second major factor in the expanding use of CPM techniques was the introduction of commercially available CPM software computer packages. Early vendors of CPM software systems included McAuto, Premis, and Project/2 for use on mainframe computers. However, since the project personnel were dependent on the computer specialist to run the data through a batch method, this method was cumbersome and inefficient. In addition, given the high capital cost of the mainframe computers, "time-sharing" was prevalent which contributed to the delay in obtaining contemporaneous feedback.

In addition to untimely response, there existed several other factors, which contributed to the inefficiencies of the techniques at this time. The mainframe computer reports were voluminous and difficult to interpret by the project personnel. Computer software programmers typically lacked construction industry experience and therefore failed to provide practical features in the software programs. To address the second issue, user groups were formed to provide relevant feedback to the software vendors. This effort was successful for continued improvement, upgrade, and user acceptability.

In 1974, Engineering News-Record (ENR) reported a survey of CPM use by a sample of the large construction companies. This survey reported that:

1. Not all large construction companies were using network methods
2. The primary use of CPM is project planning rather than control
3. Only a small percentage of user firms felt that they were very successful in achieving the numerous benefits attributed to the use of these procedures

Major concerns reported by top management of the sampled firms included "construction personnel not really using it" and "requires excessive work to implement" related to the difficulties of interfacing with the computer. CPM was not universally accepted and users were encountering significant implementation challenges during this time period.

With the introduction of Vax and Prime mini computers, there was a breakthrough in the use of CPM techniques. First the cost of these computers was only a fraction of the large main frame computers. Consequently, computers could be purchased that were totally dedicated to the planning and scheduling function. Secondly, these computers could reside at the construction site rather than at a remote location. This enhanced the ability to access the computer directly. In 1977, Artemis introduced the first project management software system for the mini computer. Other enhancement developments included the introduction of plotters and database capabilities. Electronic data processing applications were rapidly advancing.

Enhancements to CPM software included the ability to create graphical presentations of the schedule data, time-scaled network diagrams, and bar charts directly from the software program. Informed users were integrating CPM scheduling techniques with schedule hierarchy, punchlists, procurement tracking systems, cost reporting procedures, quantity-tracking curves, and other project management tools. Appropriately, CPM was recognized as one of many available management tools.

The introduction of microcomputers in the 1980's revolutionized the usability and acceptance of the CPM technique. These microcomputers provided the computing power of earlier main frames at a fraction of their costs. Hardware and software costs were drastically reduced such that personnel training costs became much more significant than the hardware and software costs. Importantly, microcomputers were "user friendly." Additionally, microcomputers were used as "stand alone" computers or as terminals in a computer network, which allowed the sharing of information between the jobsite and home office. Flexible software proliferated and enhanced graphic plotting capabilities quickly followed.

Table 1 identifies the then current hardware and software applications for several time periods, beginning with pre-1960. This matrix helps to follow the evolution of network-based planning and scheduling programs.

Table 1: Evolution of CPM Planning and Scheduling Programs

	Pre-1960	**1960-1965**	**1965-1970**
Hardware (HW)	IBM 1620 IBM 1401	IBM 1130 (1965) GE 225 Miniaturization of Tubes	IBM 360 (1967) Time Sharing
Software Programs	CPM/PERT R&D and Testing No Commercial Market since HW not Std.	Precedence Diagramming Resource Planning Early Commercial Availability HW Vendors give away Packages	Development of In-House Systems Enhancements Unbundling of Software
Processing Mode	Batch	Batch	Large Batch Time-Share Service Bureaus
Applications	Test Projects	Process Defense	Defense Aerospace School/Hospital Infrastructure

	1970-1975	1975-1980	1980-1985
Hardware (HW)	IBM 360 Time Sharing Early Minis (PDP 8, PDP 11)	Minis (Vax, Prime) Plotters	Micros (IBM-XT, IBM-AT)
Software Programs	Introduction of Commercial Project Management Software (Due to IBM 360 Development)	Commercial Packages replace Customized Packages	Large Selection of Commercially Available Packages Inexpensive
Processing Mode	Large Batch Tabular Reports Specialists User Groups	Informed Users Beginning Interactive Graphics	Interactive with English Commands
Applications	Diverse	Diverse	Diverse

	1985-1990	1990-1995	1995-2000
Hardware (HW)	Personal Computers	Personal Computers	Personal Computers
Software Programs	Large Selection of Commercially Available Packages Inexpensive	Large Selection of Commercially Available Packages Inexpensive	Large Selection of Commercially Available Packages Inexpensive
Processing Mode			
Applications	Diverse	Diverse	Diverse

3.2 SIMULATION APPROACHES

CYCLONE [Halpin, 1977] introduced a simulation technique into construction for the first time and INSIGHT [Paulson, 1983] has extended the modeling capabilities of CYCLONE together with interactive user interfaces [Peña-Mora and Park, 2001]. Both of them focus on the analysis of resource idleness resulting from the non-steadiness of construction processes and the minimization of its impact on the construction performance [Paulson et al., 1987]. Although both CYCLONE and INSIGHT allow flexible production rates for construction processes and constrain resources, they do not provide a capability to flexibly control the resource availability [Peña-Mora and Park, 2001].

Carr [1979] developed MUD to evaluate the effectiveness of a schedule network, focusing on correlations between activity durations and work conditions such as site condition, equipment efficiency, and weather condition [Peña-Mora and Park, 2001]. Using MUD as a component, Padilla and Carr [1991] developed DYNASTRAT, which allows dynamic resource allocation during the simulation of construction process [Peña-Mora and Park, 2001]. In evaluating uncertainties involved in construction, DYNASTRAT recognizes uncertainty as either favorable or adverse factors [Wang and Demsetz, 2000]. Meanwhile, factor-based simulation tools have been developed with the introduction of PRODUF [Ahuja and Nandakumar, 1985] and PLATFORM [Levitt and Kunz, 1985]. PRODUF can generate more objective distributions of activity durations, while it requires extensive historical data. By applying heuristic rules into simulation, PLATFORM reduces the amount of input data required for the simulation of activity durations. However, PLATFORM treats all associated factors as having the same effect on the construction performance [Wang and Demsetz, 2000], which leads to less reliable performance projection [Peña-Mora and Park, 2001].

These simulation-based planning methods have been further refined with STROBOSCOPE [Martinez, 1996]. STROBOSCOPE recognizes uncertainties involved in construction processes as a function of dynamic state of construction and describes activity duration and sequencing in terms of the dynamic information as the construction evolves [Martinez and Ioannou, 1997]. This modeling technique provides more flexibility and power in modeling the dynamic state of construction, making it possible to model the underlying process-level operations. In particular, one notable feature of STROBOSCOPE that can characterize and track individual resource units during simulation run provides more various options for simulating resource utilization processes. The effectiveness of this functional characteristic is well represented in the Tommelein [1998]'s pipe installation process model. To verify the usefulness of lean construction techniques in pipe installation, the model was structured to analyze the impact of coordination planning on resource management. With different input variables including production resources and duration, the model effectively simulated changes in pipe-spool buffer size, productivity of construction crew, and project duration [Tommelein, 1998]. In addition, STROBOSCOPE allows the expansion of its usage by providing the add-on function. An example is the STROBOSCOPE CPM add-on developed by Martinez and Ioannou [1997], which added probabilistic functions to the traditional CPM method. The applications of STROBOSCOPE, however, are still limited to a single construction process and to the simulation of physical unit flow in resource utilization [Peña-Mora and Park, 2001].

Figure 3 illustrates these simulation approach developments across a recent time horizon. Further explanation of each simulation approach is provided in the paragraphs that follow.

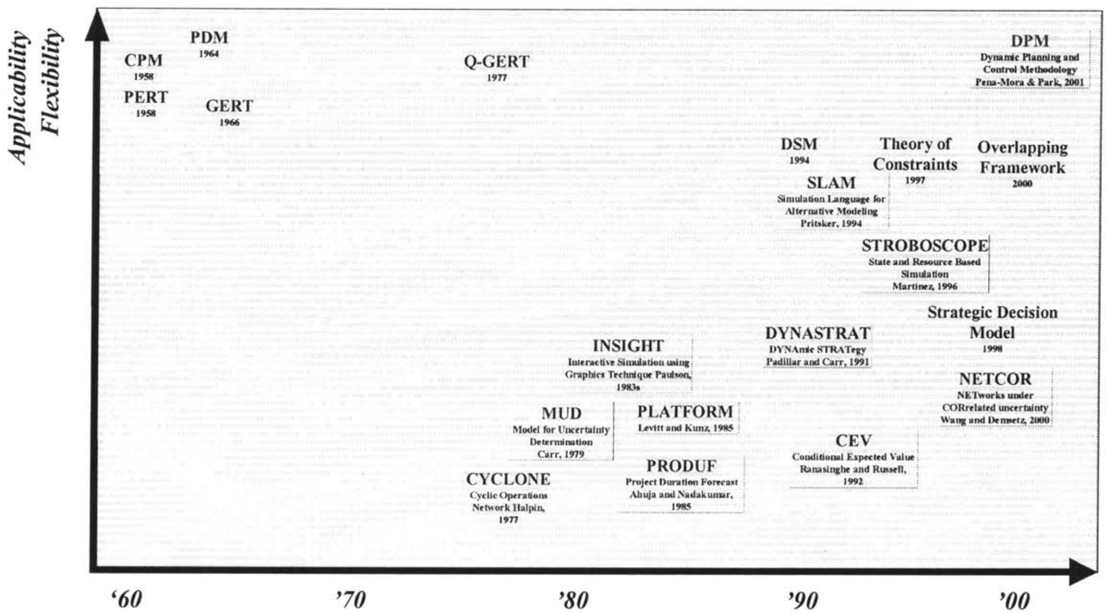


Figure 3: Development of Recent Simulation Approaches [adapted from Park (2001)]

3.2.1 CYCLONE

CYCLONE (Cyclic Operations Network) is based on classic network-based techniques for modeling and analyzing construction operations [Halpin, 1977]. It has the capacity to compare various construction methodologies and conduct a sensitivity analysis of a selected methodology to determine the optimal or best resource mix. This approach was developed to focus on resource utilization on readily identifiable process-oriented operations that were cyclical or repetitive. The method focuses on how an operation is accomplished and how the interplay of resources within a given technology leads to imbalances, which potentially impact productivity and unit cost. Its intent focuses on how, rather than when, a particular operation is to be accomplished by examining the basic components of the process under consideration and the interaction of these components in a dynamic situation. CYCLONE is a well-established, widely used and simple system that is easy to learn and effective for modeling many simple construction operations [Martinez, et. al, 1999].

3.2.2 INSIGHT

INSIGHT (Interactive Simulation using Graphics Techniques) is a newly developed simulation language [Paulson, 1983], which is an event-driven, network-based, discrete operations simulation program under development at Stanford University. INSIGHT is based on and an extension of CYCLONE, the work by Professor Halpin of Purdue University, by adding modeling capability.

3.2.3 STROBOSCOPE

STROBOSCOPE (State and ResOurce Based Simulation of Construction ProcEsses) is a newly developed simulation language [Martinez, 1996], which executes simulation-relevant algorithms. It can dynamically access the state of the simulation and properties of the resources involved in construction operations. It has an add-on, which allows the definition of CPM networks with stochastic durations and calculation of various statistics about the project and activities [Wang and Demsetz, 2000]. STROBOSCOPE is a programmable and extensible simulation system designed for modeling complex construction operations in detail and for the development of special-purpose simulation tools [Martinez, et. al, 1999]. It is particularly valuable where the construction processes are repetitive in terms of time (the same tasks performed over and over) and in terms of space (the same tasks performed in several places, for example on multiple levels of a high-rise building). Thus, the construction simulation is not only cyclical to represent temporal repetitions but also scaleable to represent spatial repetitions [Ioannou, et. al, 1996].

3.2.4 PROSIDYC

PROSIDYC (PROject Simulation Dragados Y Construcciones) is a system for simulating construction operations jointly developed by the Planning and Methods Unit of Dragados y Construcciones, Madrid, Spain and the Division of Construction Engineering & Management at Purdue University. PROSIDYC is a computer-based system for analyzing construction job-site production processes. It is used to improve productivity in the field by studying resource utilization and cycle times and identifying opportunities for production improvement. PROSIDYC uses the CYCLONE modeling format and uses a set of graphical modeling elements to develop a network model for the process of interest. The model identifies waiting or delay states as well as active productive states. The computer program allows the modeler to identify resources that are under-utilized and bottlenecks in the process.

3.2.5 NETCOR

NETCOR (NETworks under CORrelated uncertainty) is a factor-based model [Wang and Demsetz, 2000], which incorporates the effect of correlation in network schedules and provides factor sensitivity information to support schedule risk management. Based on qualitative estimates of sensitivity of each activity to each factor, uncertainty in an activity's duration distribution is attributed to factor conditions; uncertainty is considered to have both favorable and adverse effects that could increase or decrease activity durations. NETCOR utilizes a grandparent-parent-child structure that systematically breaks down the effects of uncertainty by factor and condition, to identify factors that have the greatest impact on a project.

3.2.6 MUD/DYNASTRAT

MUD (Model for Uncertainty Determination) is a simulation-based model [Carr, 1979], developed to evaluate a project network under uncertainty. MUD simulations recognize correlations between activity durations and external factors such as site conditions, crew efficiencies, equipment performance, and weather. MUD simulations are refined as a component of the DYNASTRAT (DYNAmic STRATegy) model, for dynamically allocating resources [Padilla and Carr, 1991]. In DYNASTRAT, an activity's duration is the product of work crew productivity, a weather correction factor (based on historical data), and duration-modifying factors (independent of calendar dates). Uncertainty is considered to have both favorable and adverse effects. MUD/DYNASTRAT assumes a positive correlation and adopts a factor-based approach. In addition, it requires extensive inputs or historical data [Wang and Demsetz, 2000].

3.2.7 PRODUF

PRODUF (Project Duration Forecast) is a factor-based model developed to generate more objective duration distributions of activities before performing conventional Monte Carlo simulation procedures [Ahuja and Nankakumar, 1985]. PRODUF captures positive correlation resulting from shared factors. For most factors, only the adverse effect of uncertainty is considered. PRODUF assumes a positive correlation and adopts a factor-based approach. In addition, it requires extensive inputs or historical data [Wang and Demsetz, 2000].

3.2.8 PLATFORM

PLATFORM is a rule-based model to update durations of incomplete activities, based on durations of completed activities [Levitt and Kunz, 1985]. In PLATFORM risk factors are assessed to schedule activities. A "knight" risk factor signifies that two or more shared activities experience actual durations shorter than planned durations. On the other hand, a "villain" risk factor signifies that two or more shared activities experience actual durations longer than planned. Reducing remaining durations of activities identified with "knights" and increasing durations of activities identified "villains" capture correlation. PLATFORM assumes a positive correlation and adopts a factor-based approach. In addition, it relies on the performance of completed activities and treats all factors as having the same effects [Wang and Demsetz, 2000].

3.2.9 CEV

CEV (Conditional Expected Value) elicits correlated coefficients through an interview process [Ranasinghe and Russell, 1992]. The conditional expected value is dominated by the elicitation process, and therefore requires quality inputs. Uncertainty is not factor-based, but nonetheless considers both favorable and adverse effects.

3.2.10 SLAM

SLAM is a Fortran-based computer simulation language for alternative modeling [Pritsker, 1995]. It is a process-oriented simulator and comes with an optional graphical user interface for constructing graphical models. A general purpose simulation language, it supports multiple modeling viewpoints in an integrated framework. Discrete events, continuous, and network modeling perspectives are supported in developing simulation models.

3.3 DIRECT-ELICITATION MODELS

Exact Simulation

To conduct an exact simulation analysis incorporating the effect of correlation, a proper assessment of the joint probability density function (PDF) for the correlated variables is needed

[Touran and Wiser, 1992]. The only joint PDF for which a well-organized theory of statistical inference currently exists is the multivariate normal distribution [Law and Kelton, 1991]. If variables are assumed to follow a normal distribution, then one only needs the multivariate normal distribution to generate correlated variables, given that the correlation coefficients among variables are known [Touran and Wiser, 1992]. Due to the difficulty of quantitatively assessing the correlation coefficient, qualitative estimates may be adopted [Touran, 1993].

Quantile Simulation

A facility in commercially available Monte Carlo-simulation software may be used to capture the effect of correlation when the correlation coefficient is known [Chau, 1995]. The sampling procedure increases the probability of sampling the same quantiles from two PDF's when the correlation coefficient is positive. Similarly, when the correlation coefficient is negative, there will be a higher probability of sampling the *n*th percentile and 100 – *n*th percentile from the two PDF's.

MSRN

In the MSRN (Modified Second Random Number) simulation-based model, the value of the correlation coefficient is again used to influence the selection of random numbers. For example, Van Tetterode [1971] modified the second random number by a proportion of the difference between the first and second random numbers.

Factored Simulation

A stochastic network model dealing with correlated durations was developed by Woolery and Crandall [1983]. In this model, activity duration consists of a time distribution for the activity duration under optimal conditions and a series of time distributions for various factors that may lengthen the activity duration. For a given activity, these factors are assumed to be independent. For example, delays as a result of labor or material shortage are independent of weather conditions. However, the effect of one factor on multiple activities may be assumed to be correlated, either perfectly or partially. The use of a base duration modified by a series of factor-related distributions is a logical way to evaluate the effect of uncertainty. However, since the base duration is considered optimal, uncertainty is only treated as an adverse effect. Factored Simulation assumes a positive correlation and adopts a factor-based approach [Wang and Demsetz, 2000].

3.4 DYNAMIC PLANNING AND CONTROL METHODOLOGY

In fact, significant advances in the simulation approach have been achieved through the past researches. However, only few of the current simulation-based methods have the flexibility and reliability necessary to be used as an alternative to network-based methods [Peña-Mora and Park, 2001]. For this reason, despite their potential advantages over network-based methods, they have not been yet widely accepted by the industry. For a simulation-based method to be accepted as an alternative to network-based methods, it needs to be as flexible and applicable as network-based methods are, as well as having capabilities to realize its potential advantages over network planning methods [Peña-Mora and Park, 2001].

Table 2 compares DPM's methods against traditional network-based methods. As opposed to the previous simulation approach, DPM adopts the user-defined modeling approach [Peña-Mora and Park, 2001]. The user-defined modeling approach makes it possible to significantly increase the applicability of simulation approach in project management, while keeping the required simulation capabilities. Following Table 2, Figure 4 graphically represents the advantages of DPM over network-based methods and the existing simulation techniques.

Table 2: Comparison of DPM with Network-based Methods [adapted from Park (2001)]

Description		Network-based Methods				DPM
		CPM (Deterministic)	PDM (Deterministic)	PERT (Probabilistic)	GERT (Probabilistic)	
Input		- Duration - Precedence Relationships (FS only)	- Duration - Precedence Relationships (FS, FF, SF, SS) - Lead/Lag	- Duration - Precedence Relationships - Duration Probability - Path Probability	- Duration - Precedence Relationships - Duration Probability - Path Probability - Probabilistic Branching	- Duration - Relationships (Internal & External Dependencies) - Construction Characteristics - Resource (Labor, Material, Equipment) - Other Influences Profiles (e.g., Changes, Cash Flow, Safety, Environment, Seasonal Effects)
Output		- Estimated Completion - Criticality - Float	- Estimated Completion - Criticality - Splitting - Float	- Probabilistic Estimate of Completion - Criticality - Path Probability - Float	- Probabilistic estimate of completion - Policy alternatives under "what-if" conditions	- Performance Curves (Time, Costs, Quality, Safety, Environment) - Criticality - Profile Probability - Policy alternatives under "what-if" conditions - Policy Guidelines (Labor Control, Overlapping Degree)
Relationship	Type	Linear				Linear & Non-linear
	External	Start & Finish of Activities				Entire Duration of Activities
	Internal	Not Considered				Considered in the form of internal constraints caused by physical constraints, resource availability, production rate, etc.
Resource Utilization		Resource Leveling and Allocation				Resource Availability and Utilization Rate considered
Progress		Fixed				Varied (depending on construction characteristics, productivity, schedule pressure, fatigue, etc.)
Problem Solving Capability		Mainly using criticality on time				Analyzing cost-benefits tradeoffs of policies and tracing the causes of simulation results (e.g., resource bottleneck, productivity decrease, financial constraints)

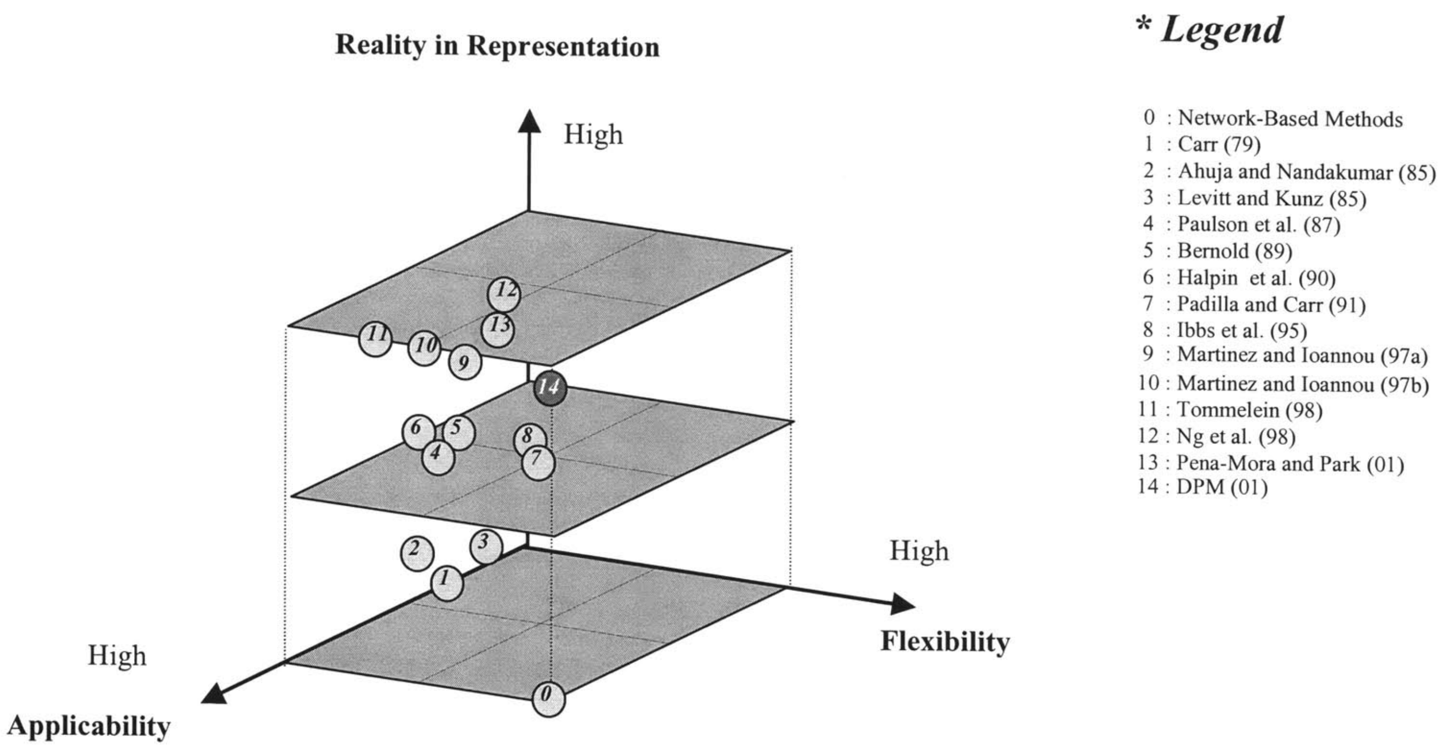


Figure 4: Comparison of Simulation Techniques (Dimensionless) [adapted from Park (2001)]

CHAPTER 4

METHODOLOGY COMPONENTS

This chapter will outline the base components that are incorporated into the DPM methodology. The proposed methodology integrates System Dynamics modeling techniques with Robust Design as well as Axiomatic Design, Dependency Structure Matrix, Theory of Constraints, Concurrent Engineering, PDM, CPM, PERT, GERT and SLAM to analyze and quantify the effect of the numerous dynamic interactions within construction processes. The following paragraphs provide a brief overview of these techniques.

4.1 SYSTEM DYNAMICS MODELING

A system dynamics modeling environment has a graphical user interface to allow a model developer to define a model through graphical inputs. The data and other information regarding the model are stored within a database structure that efficiently organizes the data. A second non-graphical editor is provided as a separate and distinct tool for editing the equations and other information representative of a model. This modeling environment allows the definition of a plurality of groups, with each group consisting of a data set representing a complete flow diagram and capable of being coupled to another group defining a portion of the model on the same layer of the model. Users have the ability to create customized user interfaces for their models without requiring programming experience. Users also have access to features that make it easy to create and save scenarios and models.

Sterman [1992] suggests that no mental model can adequately assess the impact of exogenous factors and allocate responsibility for delay and disruption. He further suggests that computer-modeling techniques are preferred to mental models for the following reasons:

- Computer models are explicit, and their assumptions are open for review
- Infallibly compute the logical consequences of the modeler's assumptions
- Ability to interrelate many factors simultaneously
- Can be simulated under controlled conditions, allowing analysis where the real world constrains its feasibility

System dynamics models are treated as formal models to replace mental models. A mental model is typically the understanding and intuition of the construction process derived from years of experience and observations in the field [Peña-Mora and Li, 1999]. However, the mental model is insufficient to analyze complex systems and in particular to analyze impacts and changes to this system. To this end, system dynamics modeling techniques will be instrumental in determining an effective overlapping strategy. More importantly, an effective overlapping strategy can be developed in a controlled environment.

The foremost utilization of the system dynamics model is to represent the interdependencies among the different project components. Such interdependencies often complicate the problem since a subtle change in one part of the system can trigger an effect on other parts of the system. This change can be severely detrimental to the overall system if it leads to delays to other tasks that find themselves dependent on the completion of the deferred activity. System dynamics is capable of tracing the interdependencies and in turn the causal impacts of changes [Peña-Mora and Li, 1999]. The system dynamics model enhances the user's understand when in a multi-loop environment the loop dominance can shift from one loop to another, for example, when the loop dominance shifts from balancing to reinforcing. Figure 5 illustrates a sample of variables that are involved in both balancing and reinforcing loops; the blue loop is a balancing loop, while the red loop is a reinforcing loop.

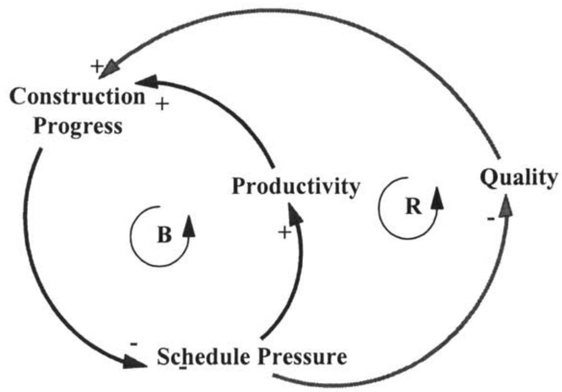


Figure 5: Balancing and Reinforcing Loops [adapted from Park (2001)]

4.2 ROBUST DESIGN

Robust Design is an engineering methodology for improving productivity during the early stages of design development to generate high-quality products quickly and at low cost. A fundamental principle is to improve product quality by minimizing the effect of the causes of variation without eliminating the causes. Through a process of parameter design, product performance is minimally sensitive to causes of variation. Its application to the dynamic planning methodology is to reduce the sensitivity of construction processes to hard-to-control variations.

4.3 AXIOMATIC DESIGN

Axiomatic Design was developed by Professor N. P. Suh at MIT to fulfill the need to unify and generalize available knowledge in the design field [Suh, 1990]. The concept of axiomatic design provides a systematic approach to gather and process design information (customer needs, functional requirements, design parameters, and process variables) to aid in product development and 'do things right the first time.' The basic assumption of axiomatic design is that there exists a fundamental set of principles that determine a good design practice. During the design process, the best product is selected from various alternatives, considering factors such as value added, cost, accuracy, delivery time, and consumer preference [Suh, 1990]. Axiomatic design enables project managers to evaluate the scenario advantages based on a series of relevant criterions.

The two design axioms below are the fundamental rules to implement the axiomatic design process, which are utilized by DPM.

Axiom #1: The Independence Axiom

Maintain the independence of functional requirements.

Axiom #2: The Information Axiom

Minimize the information content of the design.

One important function of axiomatic design is the ability to map out the interdependencies among various design and construction tasks. It is able to systematically make the inherent complexities explicit [Suh, 1990]. Axiomatic Design breaks a complex design process into manageable work packages that possess the ability to work independently from one another. This concept will be adapted to develop an effective and efficient construction planning process by evaluating various work methodologies. Its application will address the problems that arise from the fragmented approach to design and construction planning, and a non-homogeneous decision-making process within each organization [Peña-Mora and Li, 1999].

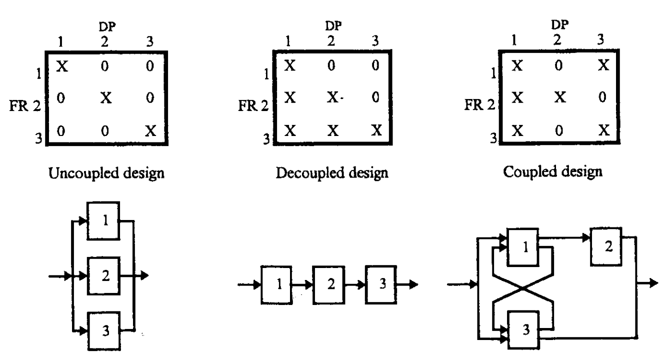


Figure 6: Examples of Dependency Matrices

Its application to the dynamic planning methodology is to rigorously define the objective of each planning step independently. Once the objective is clearly defined, an appropriate solution can be formulated to achieve the particular project objective [Peña-Mora and Li, 1999]. The two axioms are applied to ensure the objective is framed correctly in a solution-neutral environment, and the corresponding solution is the most effective for project implementation [Peña-Mora and Li, 1999].

4.4 DEPENDENCY STRUCTURE MATRIX

The Dependency Structure Matrix is a mathematical interpretation representing the interactions between two domains. The relationships among design parameters can be mapped for clarity and analysis. The elements of the design matrix are determined by taking the partial derivatives of design parameters. The overall effect of the dependency matrix can be calculated by summing the partial derivatives. This mapping process must satisfy Axiom #1 (The Independence Axiom). In an acceptable design, the mapping is such that each functional requirement can be satisfied without affecting other functional requirements [Albano, 1997].

The Independence Axiom defines three categories of dependence matrix [Suh, 1990], namely uncoupled design, decoupled design, and coupled design. The Information Axiom states that "among all designs that satisfy the functional independence (Axiom #1), the best design is the one with the least information content" [Suh, 1990].

The best possible design is the uncoupled design, where each functional requirement is satisfied independently by a corresponding design parameter. Hence, the design tasks can be performed in parallel and be completed within the shortest duration. The second-best design is the decoupled design. In this design configuration, the performance of each design task depends on the finalized information transfer from its upstream task. Therefore, the design must be carried out in series. Although a decoupled design requires a longer time frame than an uncoupled design, it is still possible to perform. The least desirable is the coupled design. In this scenario, the progress of two or more design tasks is mutually dependent. As a result, the information feedback is both crucial and difficult. Although the existence of a coupled design is highly undesirable, the attempt to completely eliminate all coupled relationships can be physically unrealistic and infeasible.

Dependency Structure Matrix is used to identify feedback and precedence activities to frame iterations through the entire design process flow. Its goal is to reduce a very large and complex schedule into comprehensible time periods. This synthesis enables project personnel to focus on short-term, intermediate goals.

4.5 THEORY OF CONSTRAINTS

Theory of Constraints (TOC) is a portfolio of management philosophies, management disciplines, and industry-specific 'best-practices' conceived and developed by Dr. Eliyahu M. Goldratt, usually applied to running and improving an organization. TOC acknowledges and manages the inter-dependencies within an organization, as well as between organizations, and their effect on flow through the entire supply chain.

The primary benefit of the TOC approach is its orientation toward the output of the entire system, rather than a compartmentalized look at components that may have little or no positive effect on overall performance. Constraints may be physical, such as a machine, person, or facility, or a policy that inadvertently discourages improved performance. A constraint is any factor that limits the system from achieving a set goal. Cost reduction is viewed as important, but not necessarily the most important part. It is viewed in its proper context as a part of a larger system and strategy to realize a company's goal of turning profits.

TOC consists of problem-solving and management/decision-making tools called the Thinking Process (TP) or a system-level approach to continuous improvement. Two basic constructs that underlie the TP is:

1. Causality: "If…Then…Because…"
2. Necessity: "In order to …I must…Because…"

TOC recognizes that the output of any system that consists of multiple steps, where the output of one step depends on the output of one or more previous steps will be limited or constrained by the least productive steps. In other words, the strength of the chain is dependent on the weakest link. Concentrated efforts to strengthen the weakest link will strengthen the overall system. According to TOC, this strengthening is achieved by following the Five Focusing Steps.

TOC challenges the user to define a goal and examine how the goal is served through actions and performance measures. Tools that aid in the identification and resolution of bottlenecks include: Goldratt's Five Focusing Steps (described below); Reality Trees; Evaporating Clouds; The Future Reality Tree; The Prerequisite Tree; The Transition Tree; The Socratic Method; and Drum-Buffer-Rope. These logical thinking processes provide a contextual basis from which to apply more commonly known quality tools, such as statistical process control, design of experiments, quality function deployment, and other structured problem-solving methods.

Goldratt's Five Focusing Steps are:

1. Identify the system's constraints – Determine what limits the system's performance.
2. Decide how to exploit the system's constraint – Modify or redesign the task or activity so work can be performed more effectively and efficiently.
3. Subordinate everything else to step 2 – Make elimination of the inefficiency of the existing constraint the top priority.
4. Elevate the system's constraint – Break the constraint by increasing its output capacity through the purchase of additional capacity or implementation of new information technology.

5. Once the constraint is broken, repeat step 1, but be aware of inertia to cause a new constraint – Go back and find the next weakest link which limits the system's performance.

TOC is applied to logically and systematically zero in on three essential process improvement issues of what to change, what to change to, and how to cause the change. In order to understand what to change, the current realities of the system must be understood. Once understood, a Current Reality Tree (CRT) can be developed to aid in communicating this revelation. The CRT reveals that most undesirable effects of the current system are the result of a few core problems. By addressing the root cause of the problem, its effect on the entire network can be modified.

To answer the question of what to change to, focusing efforts of resolving core problems could more effectively and efficiently eliminate multiple undesirable effects. Core problems are typically perpetrated by conflict between opposing requirements or prerequisites of the requirements. Through the use of Evaporating Clouds and Future Reality Tree, assumptions underlying the conflict are revealed to aid in finding simple yet meaningful solutions to the problems. Once the solution to the problem is selected, how to cause the change must be translated into an implementation plan that considers potential obstacles to the new process. A Prerequisite Tree (PRT) is useful for methodically planning the implementation effort. The PRT lists out the obstacles or concerns that could block achievement of the implementation plan.

Specific uses of the TP are the enhancement of vital management skills, such as: win-win conflict resolution; effective communication; team-building skills; delegation; and empowerment. By the application of TP to specific functional areas (Sales, Marketing, Logistics, Finance, Accounting, Engineering, and Project Management) Proven Solutions have been created.

4.6 CONCURRENT ENGINEERING

Concurrent Engineering was developed to address the necessary information transfer among a set of parallel activities, considering factors such as activity information certainty and sensitivity to errors [Peña-Mora and Li, 1999]. Concurrent Engineering specifically addresses the information flow for tasks where iterations, overlapping, and integration are expected. Once the goals of each schedule activity is defined and documented using the principles of axiomatic design, the concepts of concurrent engineering can be applied to analyze the validity and effectiveness of critical project activities. This analysis will then be used to develop a dynamic planning and control framework based on the task production rate, task reliability, and task sensitivity to upstream error.

4.6.1 Task Production Rate

Execution of work can possess a multitude of production types, from instantaneous to linear to any number of non-linear relationships. Two examples of non-linear production types are shown in Figure 7. An example of a fast production rate is a concrete placement activity; an example of a slow production rate is a carpet flooring activity.

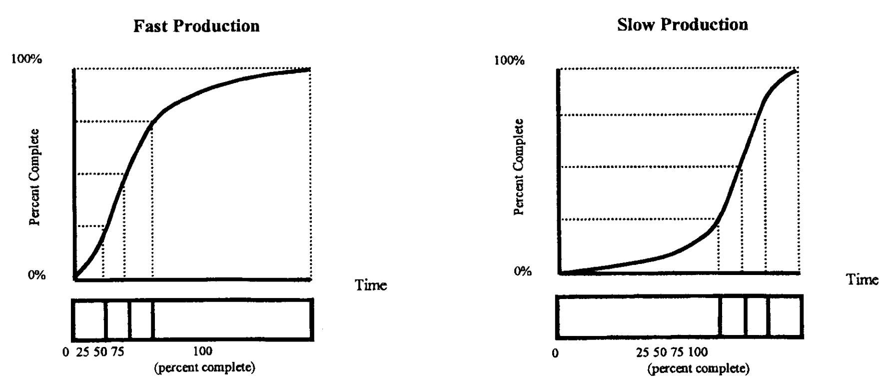


Figure 7: Examples of Production Types

These examples over-simplify the issue since more commonly, construction activities have variable production rates given the differences in multiple controlling factors such as availability of work, labor efficiencies, physical constraints, weather, and policies. Productivity may be achieved early in the task activity under a certain combination of controlling factors, while in other instances yield a very different productivity profile. This variability may exist within a single activity or be amplified when given multiple, seemingly repetitive activities.

4.6.2 Task Reliability

Besides the non-linearity of production rates, consideration must be given to the reliability of the work being performed. Task reliability is defined as the degree of confidence that the task will be done correctly and is insusceptible to errors or changes both within the overall system as well as from an external influence.

4.6.3 Task Sensitivity

Successor activities may or may not be affected by an error or change in its predecessor activities. Sensitivity is defined as how the task would be changed in light of errors or changes to upstream predecessor activities.

4.6.4 External Dependency

External or inter-phase dependency is the relationship across project phases or activities. In the traditional CPM-based methods, this relationship is illustrated by precedence logic relationships. These traditional methods establish relationships among multiple phases or activities based on the start and finish or related activities, permitting the use of lead and lags, but based on time units, rather than progress of work. In contrast, the inter-phase dependency permitted by DPM establishes the relationship across phases and activities based on work complete, which is more dynamic and is applicable throughout the activity duration. Two examples of external dependencies are illustrated in Figure 8.

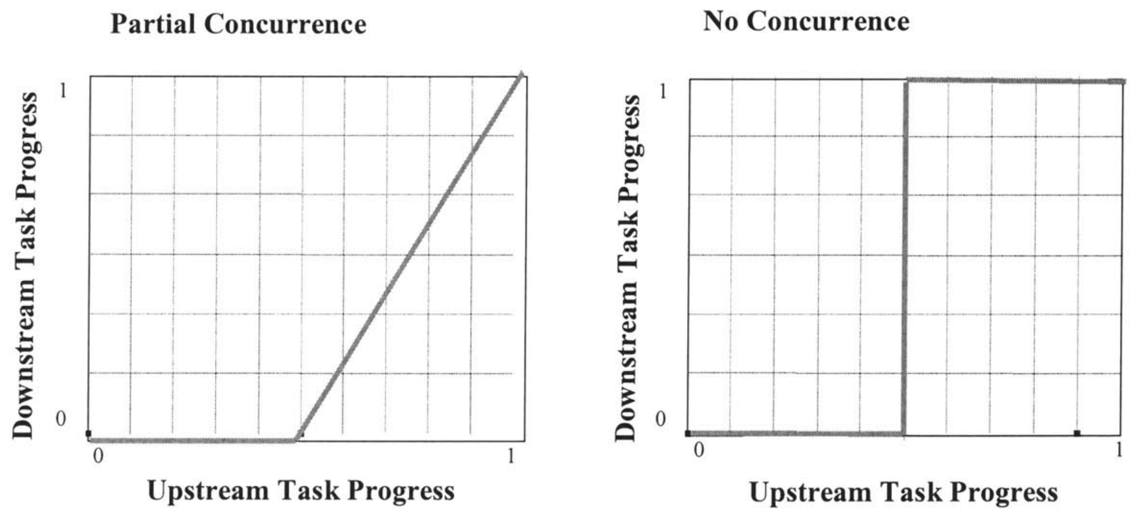


Figure 8: Examples of External Dependency [adapted from Ford and Sterman (1997)]

The graph on the left illustrates where when an upstream activity is 50% complete with its work, the downstream activity may proceed, but its work progress is proportional to the work being accomplished by the upstream activity. The graph on the right illustrates where when an upstream activity is 50% complete, the downstream activity may be start and be completed in its entirety, while the upstream activity continues to along its progress. Once the downstream activity is started, there is no further dependency on the upstream activity.

4.6.5 Internal Dependency

Traditional CPM-based methods do not permit consideration for internal dependencies within one phase or activity. However, project execution is often hampered by procedural or physical constraints within a single schedule activity. For example, inspection for work quality is necessary before a work activity such as erection of formwork is considered complete. This inspection activity repeatedly affects the formwork work package, and inspection for work quality procedural activities accompany the majority of construction work processes. Physical constraints are those that are fundamental to the erection of work, where beam erection must occur before the beams can be bolted in place. Here's another example of were an inspection activity inserts itself, the inspection of the field weld. Two examples of internal dependencies are illustrated in Figure 9.

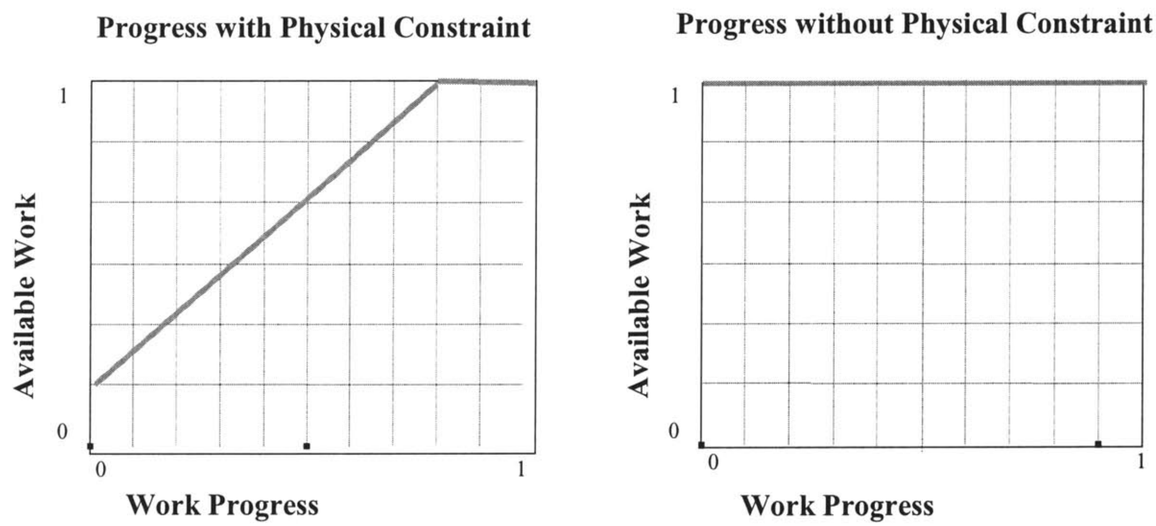


Figure 9: Examples of Internal Dependency [adapted from Ford and Sterman (1997)]

The graph on the left illustrates where physical constraints, such as progress of bolting beams is dependent on the quantity of beams erected. The graph on the right illustrates where when given available work, work can progress without physical constraints, provided there are enough resources for the work to progress.

4.6.6 Overlapping Frameworks

Eppinger [1997] classifies overlapping practices in terms of upstream evolution and downstream sensitivity, focusing on transferring information that is derived from design

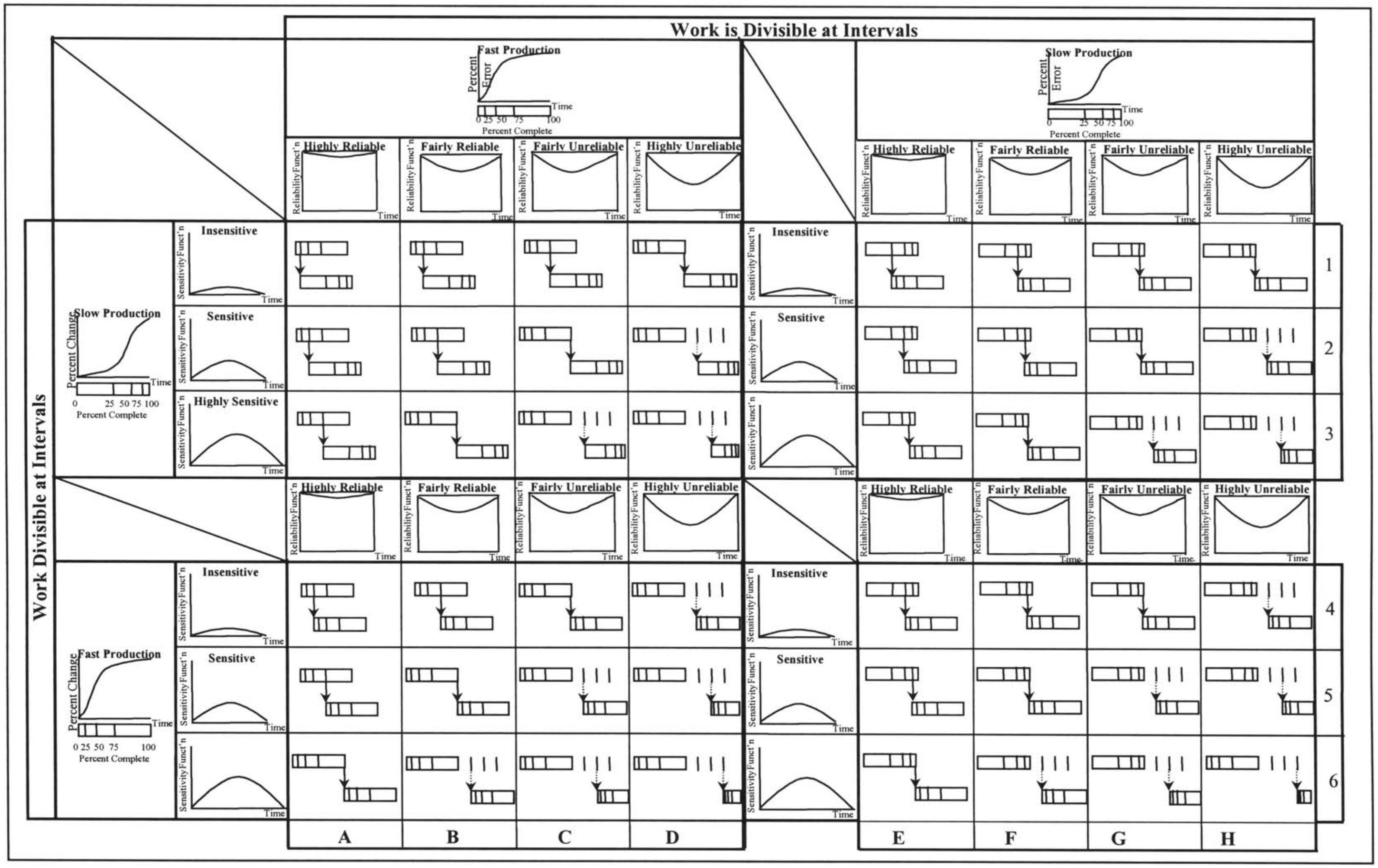


Figure 10: Overlapping Framework for Construction [adapted from Li (1999)]

parameters. Upstream evolution describes the ability of the upstream to provide finalized information with which a downstream task can proceed. Downstream sensitivity describes the sensitivity of the downstream to changes in an upstream task. By understanding evolution and sensitivity for sequential task pairs, an overlapping strategy can be chosen [Eppinger, 1997]. From Eppinger's perspective, poor overlapping does not create shorter project duration because earlier transfer of preliminary data brings subsequent changes followed by wasteful iteration.

Peña-Mora and Li [1999] applied this overlapping framework for effective management on fast-tracked construction projects. This research focused on the transfer of physical production units compared to Eppinger's framework, which deals with information transfer between overlapped activities. This research argued that task production rate, upstream production reliability, and downstream task sensitivity are activity characteristics used to determine effective overlapping strategies in construction. Figure 10 illustrates the overlapping framework adapted from Peña-Mora and Li.

4.7 I-J NODE METHOD

I-J Node Method defines work activities along arrows between nodes or events. Accomplishment of the work activity meets the event, which initiates the next work activity [Callahan et al., 1992]. One advantage of I-J method is that the first work element must be completed before its successor work element can begin. The scope of work breakdown can be very specific, which aids to clearly articulate the interim stages that kick-off or constrain the next stage of the schedule network.

Given a complex schedule network with many interdependent activities, the I-J method could require a vast quantity of nodes and arrows. The advantage of DPM over I-J method is that the interdependency is defined and retained in algorithms, rather than defined for each and every relationship between activities. This advantage substantially reduces the quantity of individual activity relationships.

4.8 CRITICAL PATH METHOD

Critical Path Method (CPM) plans the work sequence based on predetermined variables and activity durations. Schedule activities identified by CPM as critical path activities cannot be delayed; if they are delayed the project completion time will be lengthened. CPM also identifies activities with calculated slack time or float time, whereby the activity can be somewhat delayed without lengthening the project completion time [Meredith et al., 1995]. A significant failure of deterministic durations is that it neglects uncertainties and variability in production efficiencies within the schedule activities. Another key limitation of CPM is the inability to loop back to a previous activity. If an activity is performed multiple times, each repetitive event must be represented as its own activity.

DPM also utilizes the concept of critical path, but expands the perspective of criticality to a 'critical band' of activities. The 'critical band' of activities is more in tune with the realities of project management. In addition, the backward loops in DPM reduce the number of schedule activities.

4.9 PRECEDENCE DIAGRAMMING METHOD

Precedence Diagramming Method (PDM) is distinguished by the use of boxes that capture activity information including by not limiting to activity duration, activity description, lead/lag relationships to predecessor and successor activities, and calculated float values. Arrows connecting the boxes define the logical relationship among the activities [Callahan et al., 1992]. This differs from the I-J method where the arrows between nodes define the activity.

In the I-J method, the predecessor activity is required to finish before its successor activity can begin, or restricted to finish-to-start relationships. In PDM, four logical relationships are possible: finish-to-start, start-to-start, finish-to-finish, and start-to-finish. This variability allows more schedule flexibility and overlapping of work among related activities [Callahan et al., 1992]. This schedule flexibility commonly allows fewer schedule activities than in an I-J network.

One problem with the use of PDM is that it can be unclear what part of the predecessor activity is related to the successor activity [Callahan et al., 1992]. It can also be unclear what event or portion of the activity progress kicks off or constrains the follow-on activity. Activity lead/lag is a singular number without sufficient definition of the scope of work it represents. Without this clarity, the intent of the relationship could be misunderstood by those other than the author or could be forgotten by the author.

DPM is similar to PDM in that it utilizes the schedule activity information "in the boxes." In DPM, these boxes are characterized as "smart cells." The advantage of DPM over PDM is that the intent of the schedule activity relationships throughout the network is defined, retained, and easily recalled by DPM users. An additional advantage of DPM over PDM is that the inter-dependence within and between the activities is maintained through defined algorithms; work elements that require to be completed concurrently and dependent on each other for successful completion are clearly identified and articulated in the schedule network.

4.10 PROGRAM EVALUATION AND REVIEW TECHNIQUE

Program Evaluation and Review Technique (PERT) incorporates probabilities into the schedule activity durations. Pessimistic, most-likely and optimistic durations are determined and evaluated to calculate values of expected time, mean, standard deviation and variance for the schedule activity. There are two fundamental aspects of PERT: beta distribution of schedule durations and the central limit theorem. The central limit theorem purports that project duration tends to be normally distributed and that activity durations are independent.

Disadvantages of PERT include time-consuming schedule iterations, validity of the beta distribution of activity durations, validity of the central limit theorem for activity durations, identification of a single critical path based on the largest variance, and the inability to include alternative critical path probabilities in the original model.

Schedule activity duration variability is incorporated into DPM. The advantage that DPM offers over PERT is variability beyond schedule activity durations.

4.11 GRAPHICAL EVALUATION AND REVIEW TECHNIQUE

Actual site conditions heavily influence the execution of a construction project. Graphical Evaluation and Review Technique (GERT) is particularly useful to accommodate the different scenarios that may be encountered. GERT combines signal flow graph theory, probabilistic networks, PERT/CPM, and decision trees in a single framework [Meredith et al., 1995]. GERT models 'what-if' scheduling scenarios by incorporating probabilistic branching and loop structures. Through a graphical interface, GERT portrays alternate network paths and dependencies. Estimated probabilities are assigned to alternative paths based on user judgment and experience. Probabilistic branching allows one of several successor activities to be realized, while allowing flexibility in alternative outcomes. In GERT, looping back to earlier events is possible and acceptable. In addition, GERT incorporates activity duration variability and multiple terminate nodes. Incorporating all of these factors, the GERT network diagram yields a range of estimated completion dates.

GERT is typically applied to anticipate the uncertainties in the project schedule so that an appropriate amount of contingencies can be assigned to activities for these unforeseen conditions. If the scheduler does not consider uncertainties, the project schedule may be overly aggressive or optimistic. However, explicitly accounting for each and every uncertainty is unnecessary and unrealistic, yielding an overly conservative project schedule. GERT is useful in defining the appropriate amount of contingency based in the probability of occurrence.

A strong correlation exists between the GERT network diagramming and the concept of concurrent engineering. The activity characteristics used to define the overlapping framework in concurrent engineering can be converted to become the probabilities used in the GERT diagram. Consequently, the implications of the overlapping framework on the resulting project schedule can be represented numerically in the GERT network diagram [Peña-Mora and Li, 1999].

The distinction between GERT and DPM is the use of activity buffers from a pool of schedule buffers. This schedule buffer pool differs from the conventional calculation of project float. Where project float is calculated based on deterministic durations, the schedule buffer pool is the aggregate of available schedule float. In addition, activity buffers are distinguished from free float since this float is specified for the particular schedule activity, for use exclusive of its particular schedule activity.

4.12 QUEUE-GRAPHICAL EVALUATION AND REVIEW TECHNIQUE

Queue-Graphical Evaluation and Review Technique (Q-GERT) introduces queues to the GERT methodology. Its advantages over GERT include ability to manage multiple projects and multiple teams, decrease time duration of repeated activities, decrease probability of repeating activities, and offers alteration of planned activities.

Again, DPM has an advantage over Q-GERT through its use of activity buffers from a pool of schedule buffers.

CHAPTER 5

FUNDAMENTALS OF DPM

This chapter will highlight the fundamental aspects of DPM. The advantage of DPM is the ability to absorb unforeseen changes and minimize cost overruns and project delays. The system is dynamic through its interaction with feedback loops, where a change in one variable affects other variables over time, which in turn affects the original variable, and so forth.

All of the prior research efforts in network-based and simulation-based approaches have contributed to enhancing planning and control capabilities to some extents. However, despite the increased capabilities and advanced commercial software packages, the network-based scheduling methods still lack the mechanism to efficiently formulate and evaluate construction plans under uncertainties and constraints, which are required to deal with a high degree of complexities involved in today's construction projects [Peña-Mora and Park, 2001]. Since the network-based methods assume that the attributes of activities such as duration and production rate are known at the beginning of construction and do not change during construction, they cannot represent actual construction processes realistically, which results in frequent updates to reflect the actual performance into scheduling [Martinez and Ioannou, 1997]. Regarding this, many researchers [Halpin, 1973; Paulson, 1983; Bernold, 1989; Martinez, 1996] argue that problems the network-based scheduling methods have can be overcome by adopting the simulation approach, which can describe and capture the dynamic state of construction, and provide an analytic tool to evaluate construction plans and find possible problems with a diagnostic capability. Also, their research results including CYCLONE [Halpin, 1977], INSIGHT [Paulson, 1983], and STROBOSCOPE [Martinez, 1996] have demonstrated that the simulation approach can be more effective in dealing with the dynamic state of construction processes than the network-based methods and that its ability to simulate construction plans prior to physical execution can substantially enhance the effectiveness of planning [Martinez and Ioannou, 1997].

Due to its advantageous features, the simulation-based scheduling method has currently emerged as an alternative to the network-based method [Peña-Mora and Park, 2001]. However, despite its potential advantages over the network-based method, very few of the existing simulation tools have overcome their practical limitations and have proven their applicability to real construction processes. Their application is still limited to a specific construction process due to the lack of flexibility in modeling and only those who have a lot of modeling experience and knowledge can use them. In addition, excluding human factors from modeling makes simulation results less realistic since many dynamic feedbacks inherent within the construction processes are closely related to human factors e.g. the effect of workers' fatigue and schedule pressure on productivity. All of these things necessitate the development of a more flexible and applicable simulation-based tool for the planning and control of construction projects [Peña-Mora and Park, 2001].

5.1 DEFINITIONS

Production Type: The pattern of an activity work progress. In the case of *Fast Production,* productivity is initially high but decreases as construction progresses due to increased work complexity. In contrast, the productivity of *Slow Production* is initially low but increases as construction progresses due to learning effect.

Reliability: The degree of work quality and robustness against uncertainties. A *Reliable* activity produces less changes, while an *Unreliable* activity generates more changes.

Sensitivity: The degree of how much an activity is sensitive to changes made internally (*Internal*

Sensitivity) or externally (*External Sensitivity*). A *Sensitive* activity is more vulnerable to changes than an *Insensitive* activity.

Changes: changes refer to work state, processes, or methods that deviate from the original plan or specification

Unintended Changes: Changes resulting from work quality, work conditions or scope changes, which can cause managerial changes, rework, or hidden changes, depending on managers' willingness to adopt the change option and quality management thoroughness.

Managerial changes: Changes made by a managerial decision to avoid the direct impact of rework

Hidden Changes: Unintended changes that have been inspected and monitored but not found. Hidden changes are released to the downstream work together with work done correctly.

Quality Management: Actions taken to improve quality through monitoring or to control quality through inspection, including quality assurance by contractors and quality control by owners' representatives

Quality Management Thoroughness: Thoroughness in doing quality management. In the model structures, it refers to the fraction of discovered changes in total changes that have occurred, while (1- *Quality Management Thoroughness*) represents the fraction of hidden changes in total changes that have occurred.

5.2 CONSTRUCTION CHANGES, INTENTIONAL AND UNINTENTIONAL

Changes comprise the single major source of delays and cost overruns for projects of any kind [Lee et al., 1997]. A key asset of DPM is the reduction of sensitivity of activities to variations they may experience from their related predecessors and successors. This feature, together with the ability to formulate and evaluate construction plans ahead of time, helps

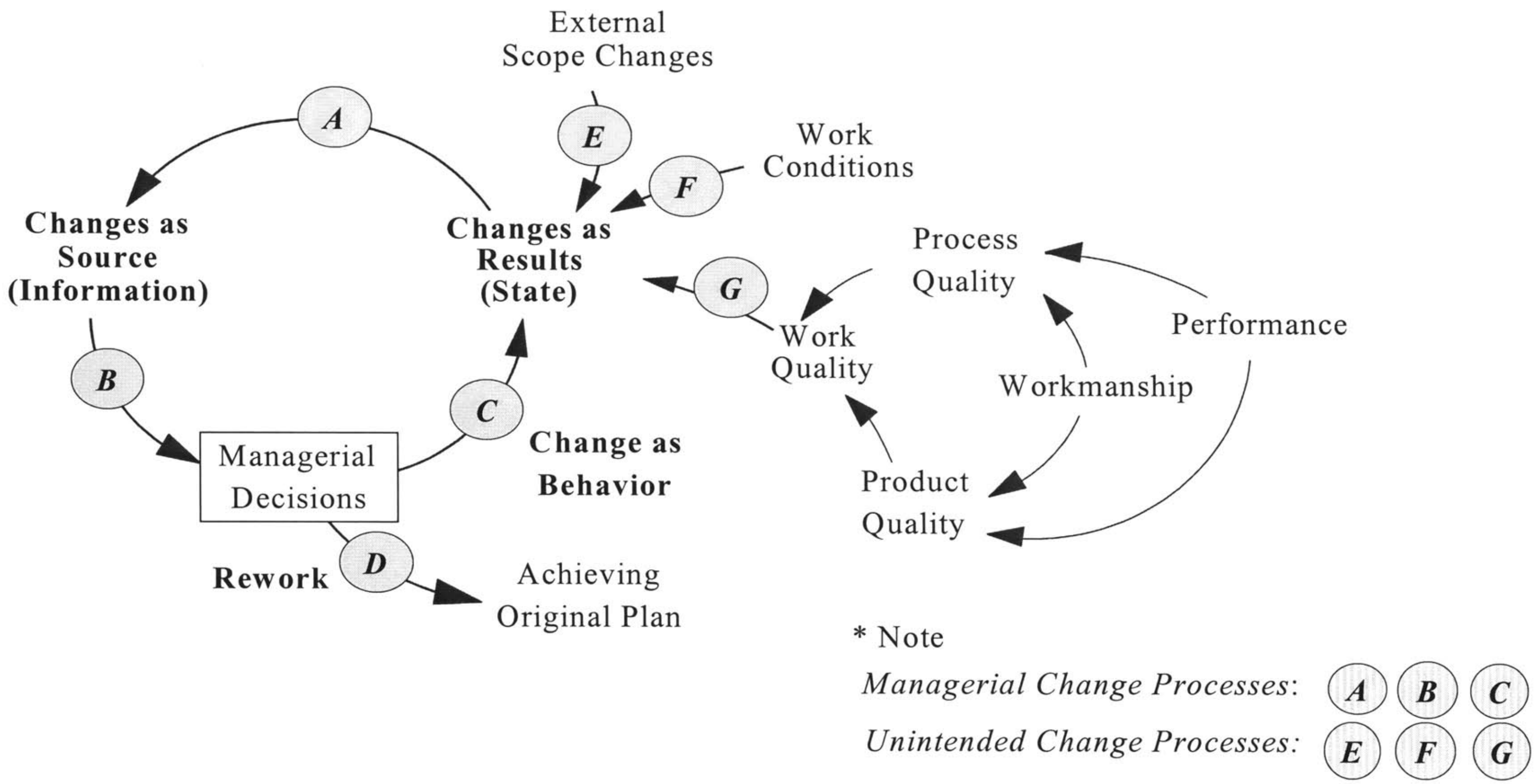


Figure 11: Categories of Changes [adapted from Park (2001)]

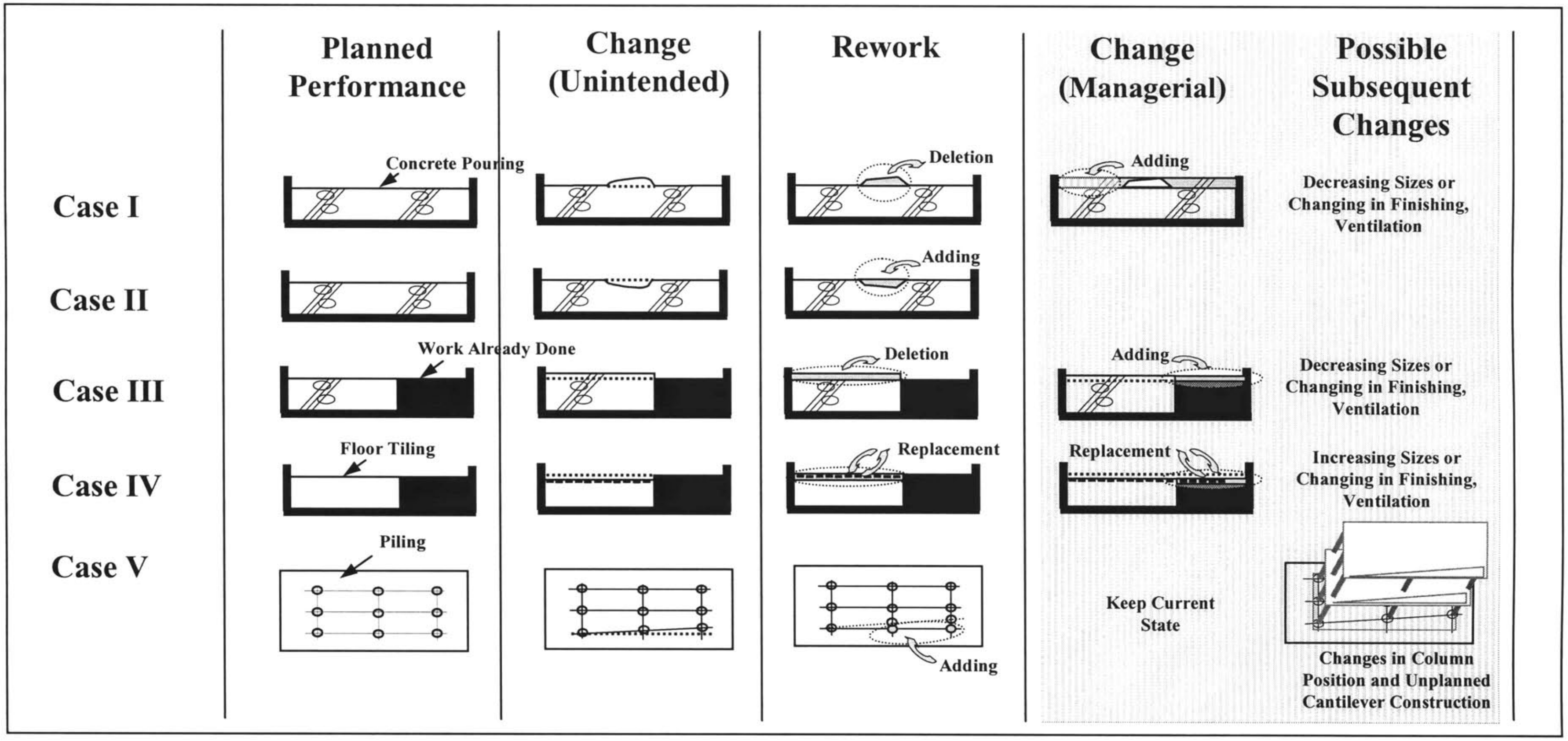


Figure 12: Working Examples of Changes [adapted from Park (2001)]

dampen the effect of hard-to-control variations, while keeping control efforts to a minimum. This will be especially beneficial for large-scale projects, which involve a high degree of uncertainties. Consequently, the successful development of DPM would help ensure that large-scale infrastructure projects can be delivered on-time within the established budget by enhancing the planning and control capabilities of project management. It would also help increase the applicability of the simulation-based scheduling to construction projects by providing a reliable and flexible simulation methodology. There are two general categories of changes, intentional and unintentional illustrated in Figure 11. Figure 12 provides working examples from the construction process to illustrate intentional and unintentional changes.

5.3 GENERIC MODEL STRUCTURE

DPM constraints neither the type of construction project nor the type of project delivery method. Developed with generic parameters, DPM characterizes a specific construction project and its associated level of project management at either higher-level milestone management or lower-level process management. Figure 13 illustrates the generic model structure.

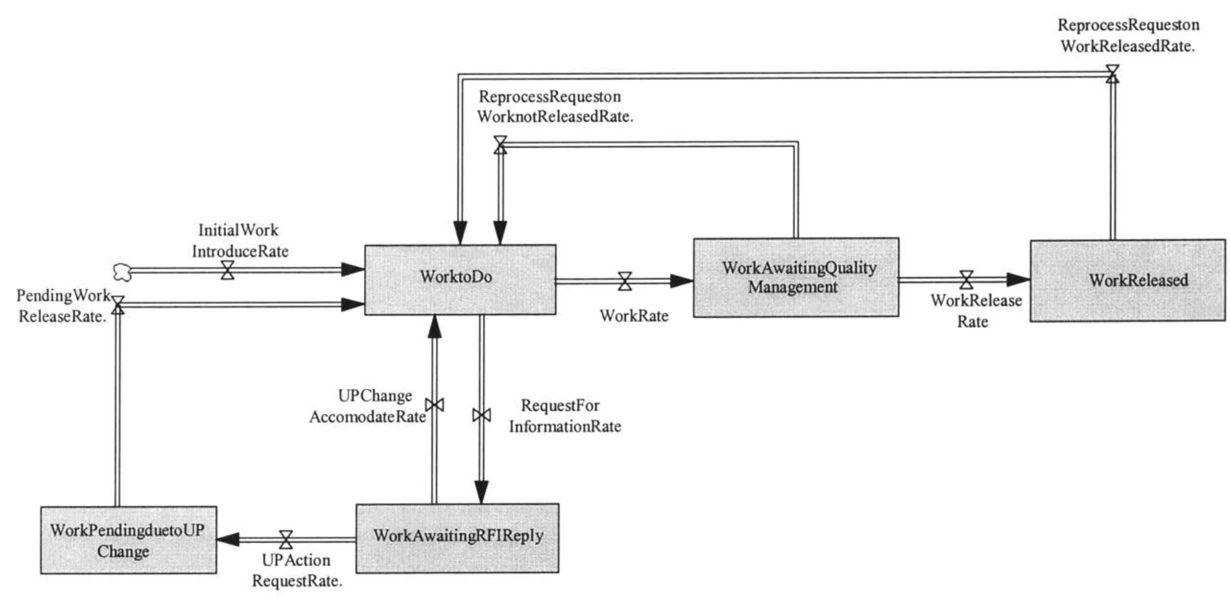


Figure 13: Generic Model Structure [adapted from Park (2001)]

5.4 RELATIVE POSITION OF DPM

DPM is distinguished from other planning methods by its ability to represent reality and deal with dynamic complexities. In addition, DPM is distinguished as a user-defined simulation from a modeler-defined simulation, which permits additional flexibility and customization to make the tool more applicable to serve the needs of the user. Figure 14 illustrates where DPM is positioned relative to CPM-based tools and modeler-defined simulations.

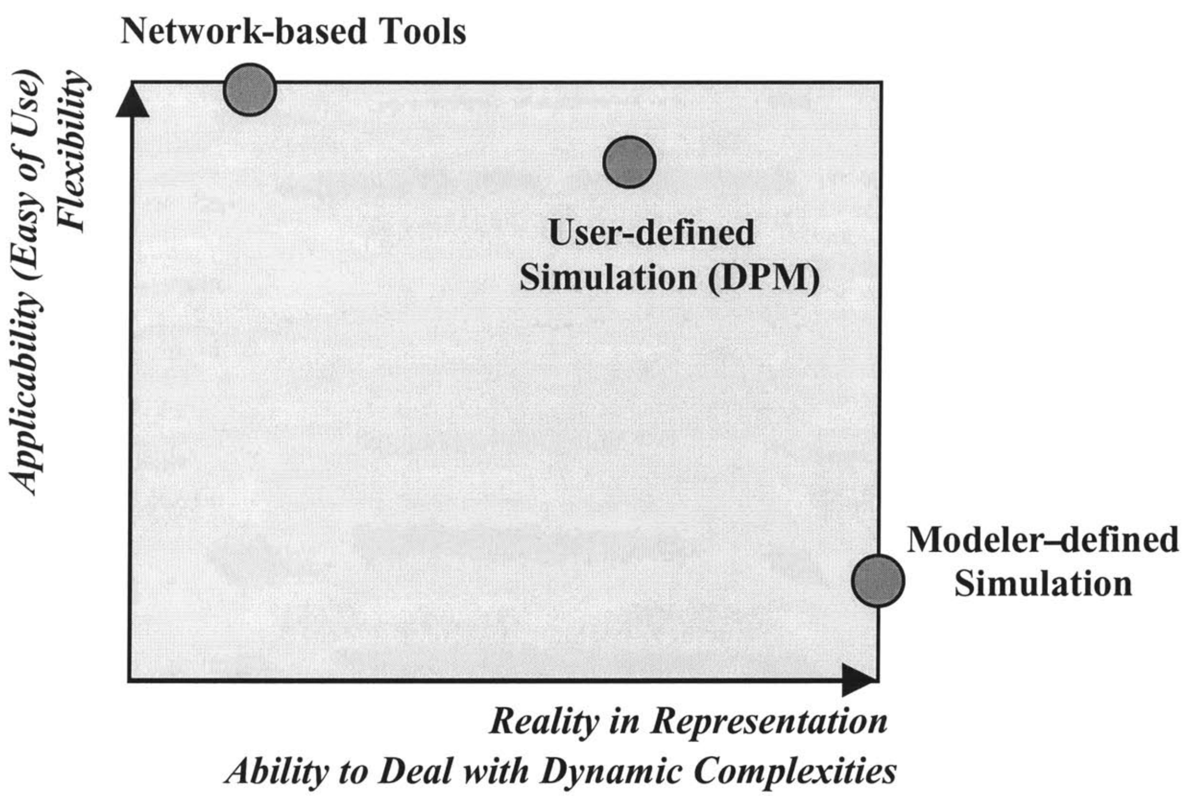


Figure 14: Relative Position of DPM [adapted from Park (2001)]

Table 3: Functions of DPM [adapted from Park (2001)]

	Tools \ Capability		Network Scheduling	Path Probability	Branching Probability and Loops	Precedence Relationships with lag/lead time	Capability to Deal with Uncertainty	Considering Feedbacks	Considering Activity Characteristics	Considering Human Reactions	Dynamic Resource Allocation and Leveling	Strategic Planning	Buffering	Flexibility in Project Size and Contents	Not Requiring Modeling or Programming Errorts
1	Netw ork-Based	CPM (Critical Path Method)	X											X	X
2		PERT (Program Evaluation and Review Technique)	X	X										X	X
3		GERT (Graphical Evaluation and Review Technique)	X	X	X			X						X	X
4		PDM (Precedence Diagramming Method)	X	X	X	X								X	X
5	Simulation-Based	CYCLONE (Cyclic Operations Netw ork),					X								
6		MUD (Model for Uncertainty Determination)					X								
7		INSIGHT (Interactive Simulation using Graphics Techniques)					X	X							
8		PLATFORM					X	X							
9		PRODUF (Project Duration Forecast)					X	X							
10		DYNASTRAT (DYNAmic STRATegy)					X	X			X				
11		CEV (Conditional Expected Value)					X	X							
12		SLAM (Simulation Language for Alternative Modeling)	X	X	X		X	X			X			X	
13		STROBOSCOPE (State and Resource Based Simulation)	X	X	X		X	X			X			X	
14		NETCOR (NETw orks under CORrelated uncertainty)	X	X			X	X							
15	Concurrent Engineering	DSM (Dependency Structure Matrix)						X				X		X	X
16		Strategic Decision Model						X				X		X	X
17		Overlapping Framew ork							X			X	X	X	X
18		Theory of Constraints	X	X									X	X	X
19		**DPM (Dynamic Planning and Control Methodology)**	X	X	X	X	X	X	X	X	X	X	X	X	X

* Note

1 DuPont Inc and UNIVAC Division of Remington Rand, 1958
2 US Navy and Booz-Allen Hamilton and Lockheed Co., 1958
3 Pritsker, 1966
4 Craig, 1964
5 Halpin, 1977
6 Carr, 1979
7 Paulson, 1983
8 Levitt & Kunz, 1985
9 Ahuja & Nadakumar, 1985
10 Padillar & Carr, 1991
11 Ranasinghe & Russell, 1992
12 Pritsker, 1994
13 Martinez, 1996
14 Wang and Demsetz, 2000
15 Eppinger, 1994
16 Alarcon & Bastias, 1998
17 Pena-Mora & Li, 2000
18 Goldratt, 1997
19 Pena-Mora & Park, 2001

Table 3 arrays the current network-based systems, simulation-based systems and concurrent engineering methods against DPM for a functionality comparison. The functions highlighted are network scheduling, path probability, branching probability and loops, precedence relationships with lead/lag time, capability to deal with uncertainty, considering feedbacks, considering activity characteristics, considering human reactions, dynamic resource allocation and leveling, strategic planning, buffering, flexibility in project size and content, and not requiring modeling or programming efforts.

5.5 CRITICAL BAND ACTIVITIES

As Meredith points out, critical tasks in practice constitute less than 10 percent of all project activities [Meredith et al., 1995]. DPM aims to effectively model dynamic variables on the 'critical band' of design and construction activities and the impact of those variables on the project performance in terms of time and costs as well as quality and safety. Variables considered in the dynamic modeling include: time and resource constraints; human factors such as staff experience; fatigue and schedule pressure; owner participation; institutional, physical and process constraints; site logistics; inherent risks as well as activity duration and precedence relationships. In addition, variables with significant time delays that should not be overlooked include problem discovery time, policy implementation behavior as well as policy reaction time. Major advantages of the model is that it can account for engineering, procurement, and construction activities; traditional design-bid-build or fast-tracked project delivery methods; management performance; schedule demands and the sense of urgency; and variable production rates. Some of the types of input needed by the model includes, but is not limited to: bid estimate/control budget; project activity durations; definition of 'critical band' criterion for schedule activities; logical constraints; staff experience; resource and time constraints; risk assessments; engineering requirements; and testing and commissioning requirements.

5.6 RELIABILITY BUFFERING

Reliability Buffers developed by Peña-Mora and Park [2001] to counter the subjective and unnecessary application of contingency buffers to schedule durations when scheduling work. Certain construction processes require technical buffers, such as fixed cure duration for concrete. However, management in planning its work may include a time contingency, which is intended of guaranteeing schedule performance by including schedule duration beyond what is technically required to accomplish the task. Management intends to ensure the overall schedule is met and avoid schedule disruptions in downstream activities. This practice of applying a time contingency, however, may lead to inappropriate allocation of resources and miscommunication on the urgency of completing the task, and as a result be inefficient to control the work [Peña-Mora and Park, 2001].

For example, three schedule activities 'A', 'B', and 'C' are each planned for a duration of 15 days with an intentional application of 5 days for time contingency and both 'A' and 'B' have a Finish-to-Start logic relationship to 'C'. Figure 15 is an illustration of this plan using bar graphs.

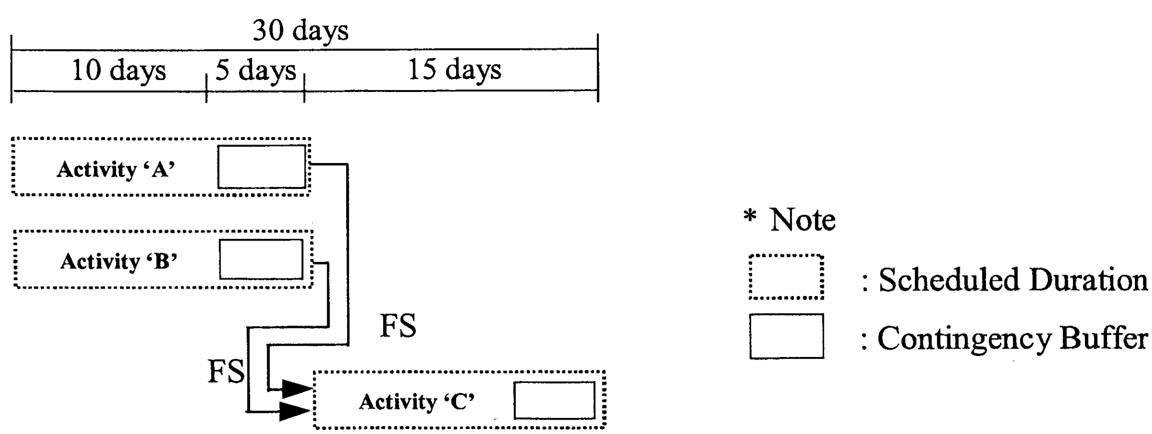


Figure 15: Planning Work using Contingency Buffers [adapted from Park (2001)]

If Activity 'A' finishes in 10 days and does not use its contingency buffer, but Activity 'B' does, Activity 'C' must unnecessarily wait five extra days to start. Figure 16 illustrates the actual work task completion.

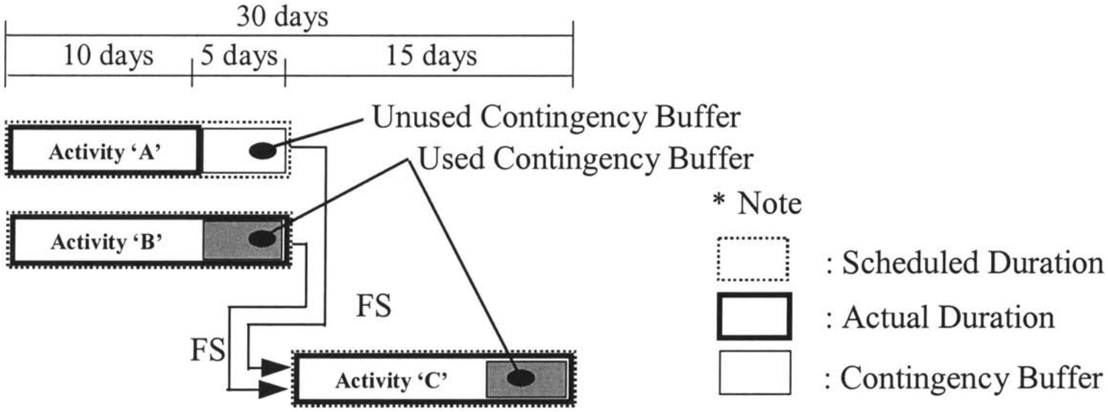


Figure 16: Impact of Contingency Buffer on Actual Work [adapted from Park (2001)]

This is an illustration of the ineffective use of contingency buffers for planning and controlling work. In contrast, Reliability Buffer aggressively protects the project schedule performance by pooling, re-sizing, re-locating, and re-characterizing the time contingency buffer. The individual contingency buffers from each schedule activity is removed and pooled for advantageous use. This pool can regulate the appropriate level of schedule pressure. Through the use of simulation applications, this methodology can be applied based on the characteristics of work activities and throughout the process steps. Figure 17 illustrates the removal of individual contingency buffers into the pool, which is available for all remaining work activities as needed. In addition, the reliability buffer is applied at the start of the downstream activity, which deters the use of the reliability buffer as a safety net to finish the activity, but rather starts the downstream activity sooner than without the reliability buffer.

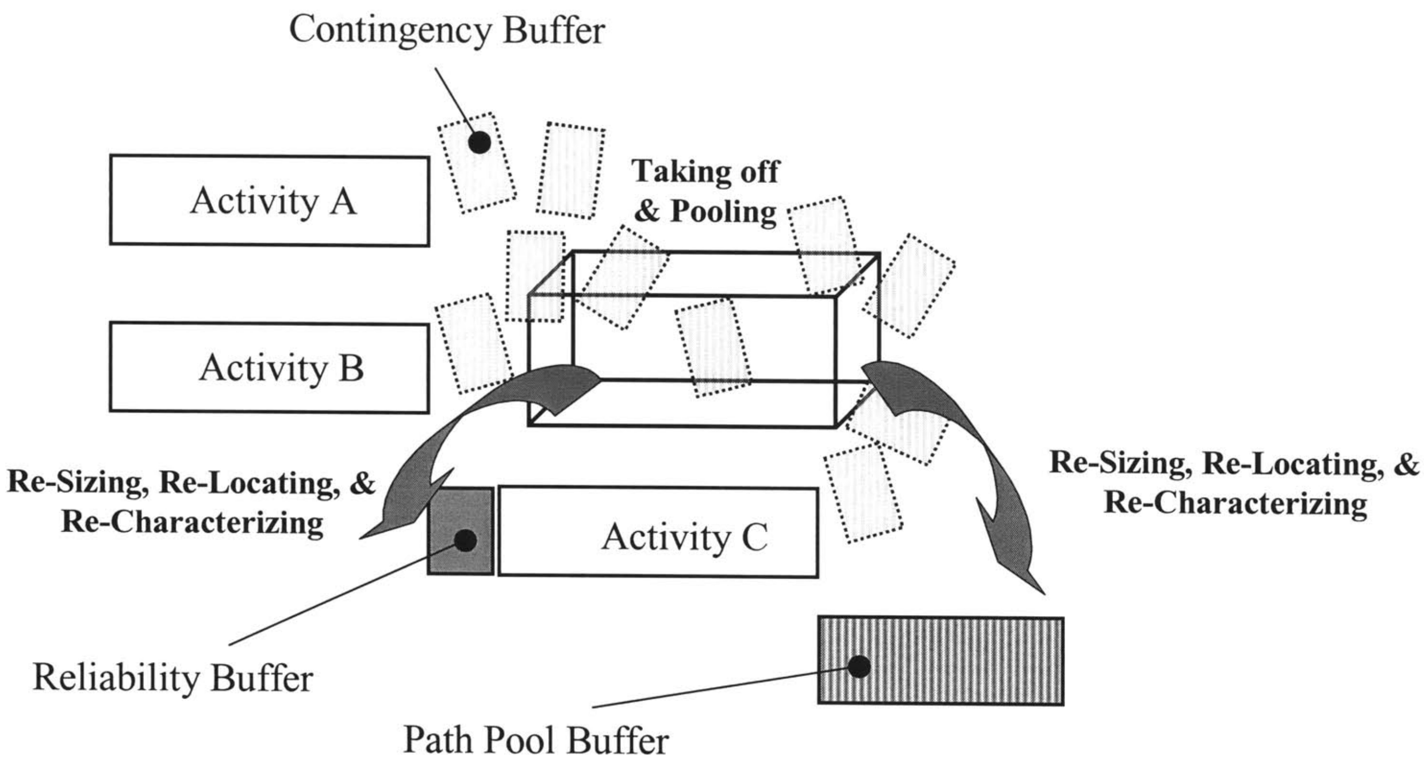


Figure 17: Reliability Buffer Pooling and Application [adapted from Park (2001)]

This application of reliability buffers is continuous throughout the project execution and as the progress of work tasks are completed either early, on-time, or delayed. The simulation environment allows the reliability buffers to be continuously updated and dynamic. Figure 18 illustrates an example of the dynamic buffering that can occur during work progress.

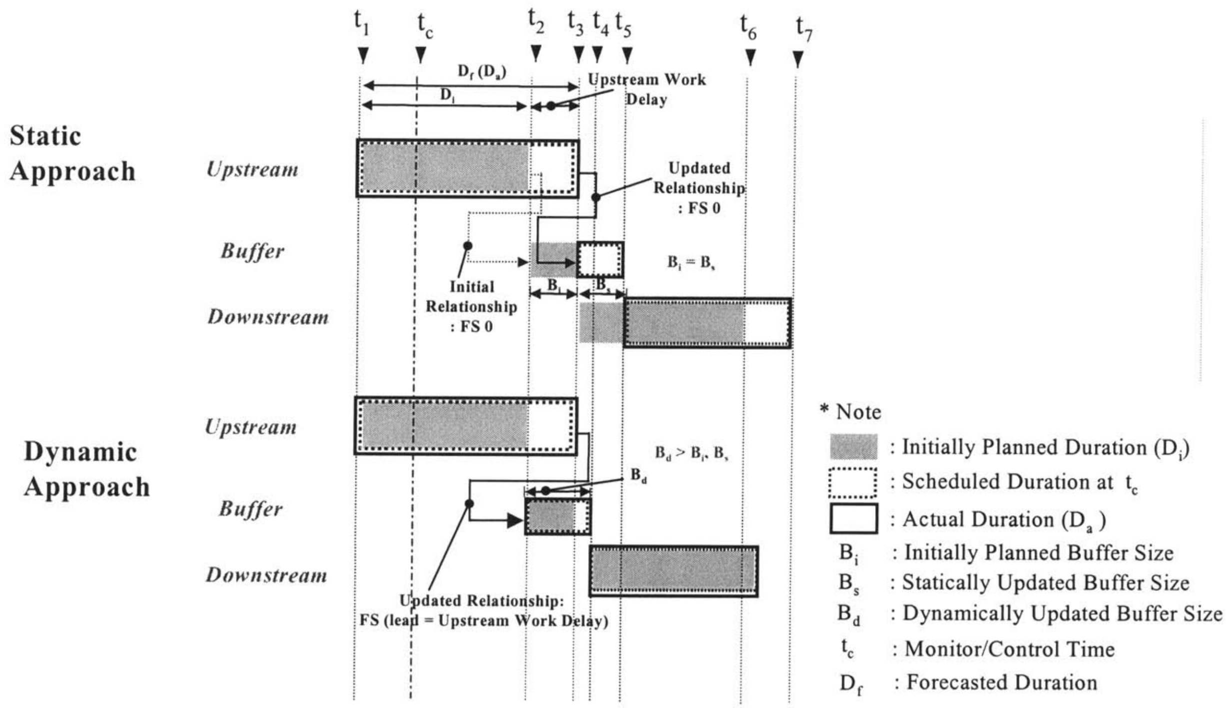


Figure 18: Example of Dynamic Buffering [adapted from Park (2001)]

Table 4 summarizes the patterns of buffer location and size variability depending on the precedence relationships and the simulation result of the upstream work duration and characteristics. For each schedule update, the remaining construction performance is updated based on actual work performed. The simulation applies the appropriate buffer sizes and locations and shifts work to be completed based what is advantageous for the downstream work based on its upstream work, minimizing the impact of upstream schedule disruptions [Peña-Mora and Park, 2001]. As a result, buffer sizes and locations are continuously changed throughout the project execution. In addition, the precedence logic relationships may be modified according to buffer size and location changes, for example, where the initial precedence relationship is a finish-to-start.

Table 4: Buffer Location and Precedence Relationship Change Patterns [adapted from Park (2001)]

Descriptions		Without Lags/Leads: Conditions	Diagram	Precedence Relationships	With Leads: Conditions	Diagram	Precedence Relationships	With Lags: Conditions	Diagram	Precedence Relationships
FS	Initial	Di = Df	Di, Bi	FS 0	Di = Df	Di, Bi	FS (-Li)	Di = Df	Di, Bi	FS (Li)
	Updated	Di > Df	Df, Bf	FS 0	Di > Df	Df, Bf	FS (-Li)	Di > Df	Df, Bf	FS (Li)
		Di < Df	Df, Bf	FS (-(Df-Di))	Di < Df	Df, Bf	FS (-(Li+Df-Di))	Di < Df	Df, Bf	FS (Li-(Df-Di))
FF	Initial	Di = Df	Di, Bi, BSi	FF 0	Di = Df	Di, Bi, BSi	FF (-Li)	Di = Df	Di, Bi, BSi	FF (Li)
	Updated	Di > Df	Df, Bf, BSf	FF 0 BSf = BSi+(Bi-Bf) -(Di-Df)	Di > Df	Df, Bf, BSf	FF (-Li) BSf = BSi+(Bi-Bf) -(Di-Df)	Di > Df	Df, B, BSf	FF (Li) BSf = BSi+(Bi-Bf) -(Di-Df)
		Di < Df	Df, Bf, BSf	FF 0 BSf = BSi-(Bf-Bi) +(Df-Di)	Di < Df	Df, Bf, BSf	FF (-Li) BSf = BSi-(Bf-Bi) +(Df-Di)	Di < Df	Df, Bf, BSf	FF (Li) BSf = BSi-(Bf-Bi) +(Df-Di)
SS	Initial	Di = Df	Di, Bi	SS 0		Di		Di = Df	Di, Bi	SS (Li)
	Updated	Di > Df	Df, Bf	SS 0		Not applicable by definition of reliability buffer		Di > Df	Df, Bf	SS (Li)
		Di < Df	Df, Bf	SS 0				Di < Df	Df, Bf	SS (Li)
SF	Initial		Di			Di		Di = Df	Di, Bi, BSi	SF (-Li)
	Updated		Not applicable by definition of reliability buffer			Not applicable by definition of reliability buffer		Di > Df	Df, Bf, BSf	SF (-Li) BSf = BSi+(Bi-Bf)
								Di < Df	Df, Bf, BSf	SF (-Li) BSf = BSi-(Bf-Bi)

* Note Di: Initially Planned Duration; Df: Forecasted Duration; Bi: Initially Planned Buffer Size; Bf: Forecasted Buffer Size; BSi: Initially Planned Buffer Start Time; BSf: Forecasted Buffer Start Time; Li: Initially Planned Lead or Lag

5.7 DPM SYSTEM ARCHITECTURE

Based on input variables and control actions initially supplied from the user, DPM forecasts project performance profiles. The same basis used in the bid estimate preparation, such as calculated unit price, will be transferred as initial model input, customized to the type of project as well as the means and methods of its execution. As the project evolves, DPM captures the as-built information to replace the estimated values with actual values with the goal to more accurately forecast project completion. DPM has the potential to not only create immediate performance benefits but also capture historical data, which will prove useful in assessing and quantifying impacts as well as improving bid and estimate performance. Figure 19 illustrates the system architecture that supports the DPM modeling environment.

5.8 SMART CELL

Model inputs are entered into the DPM simulation through the utilization of generic smart cells, which is itself an adaptation from the Design Structure Matrix (DSM) developed by Eppinger. Figure 20-a and 20-b illustrate the generic framework of the smart cell technology for an activity and for a relationships, respectively.

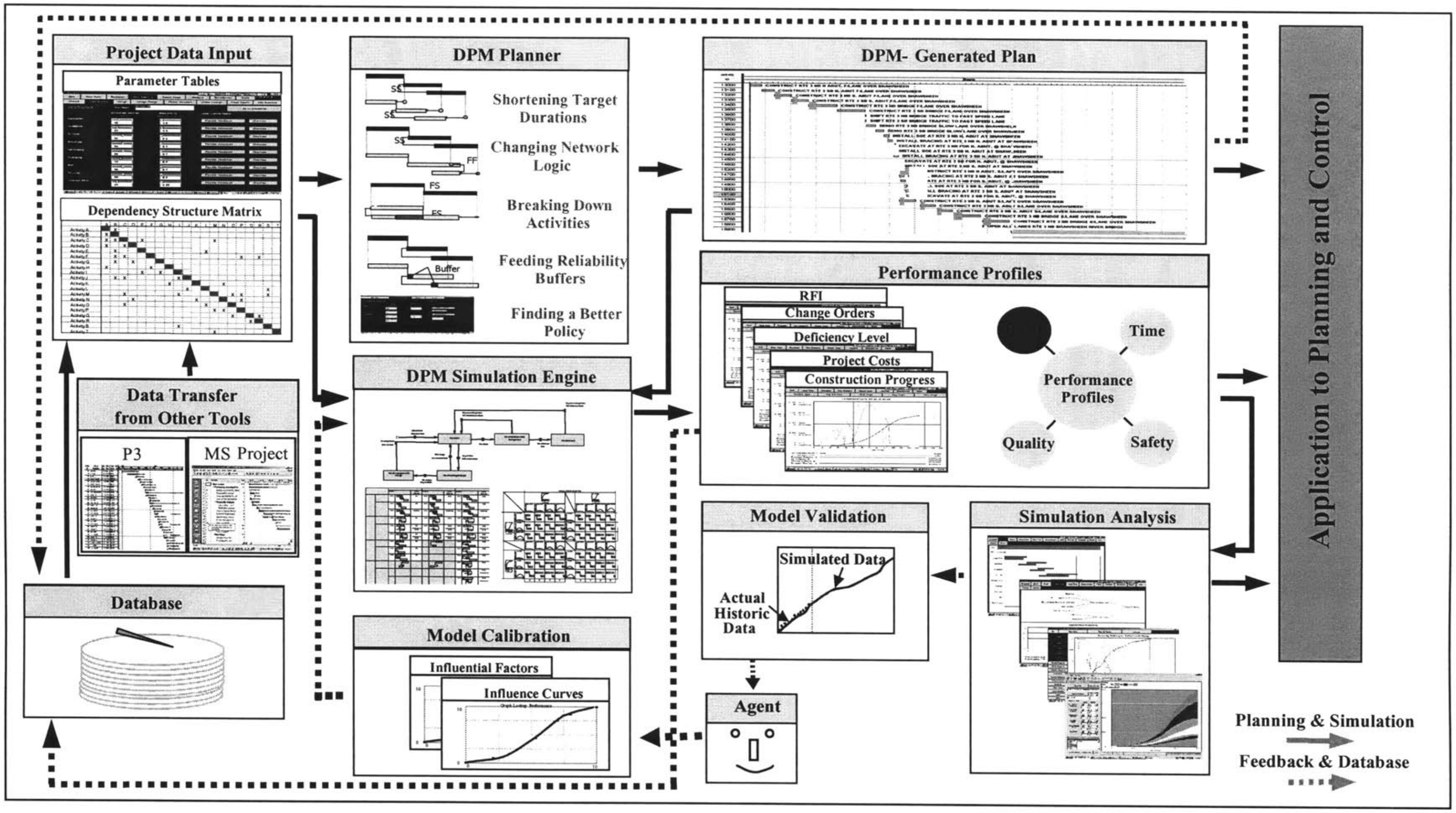


Figure 19: System Architecture of DPM [adapted from Park (2001)]

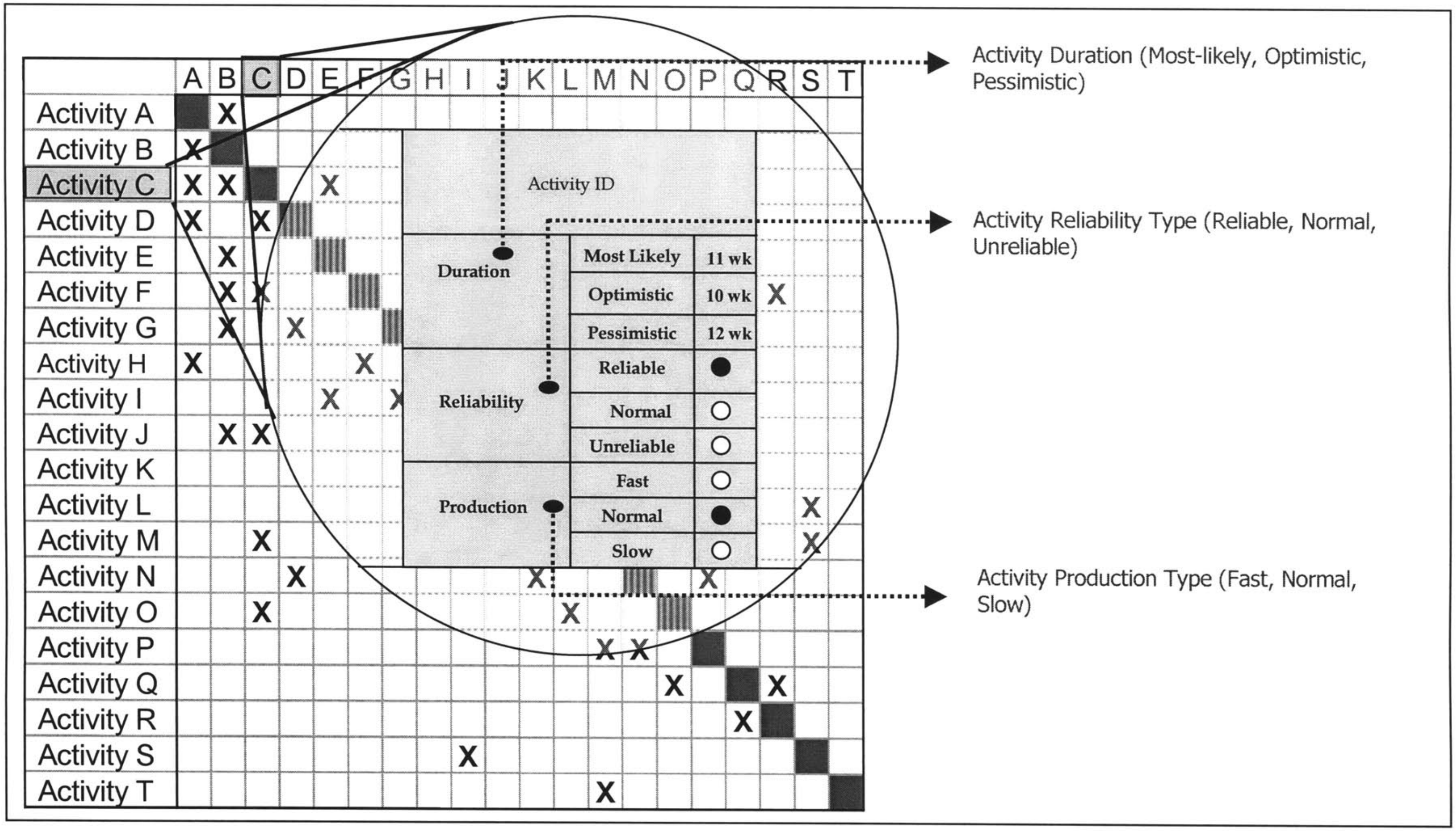


Figure 20-a: Generic Smart Cell for Activity [adapted from Park (2001)]

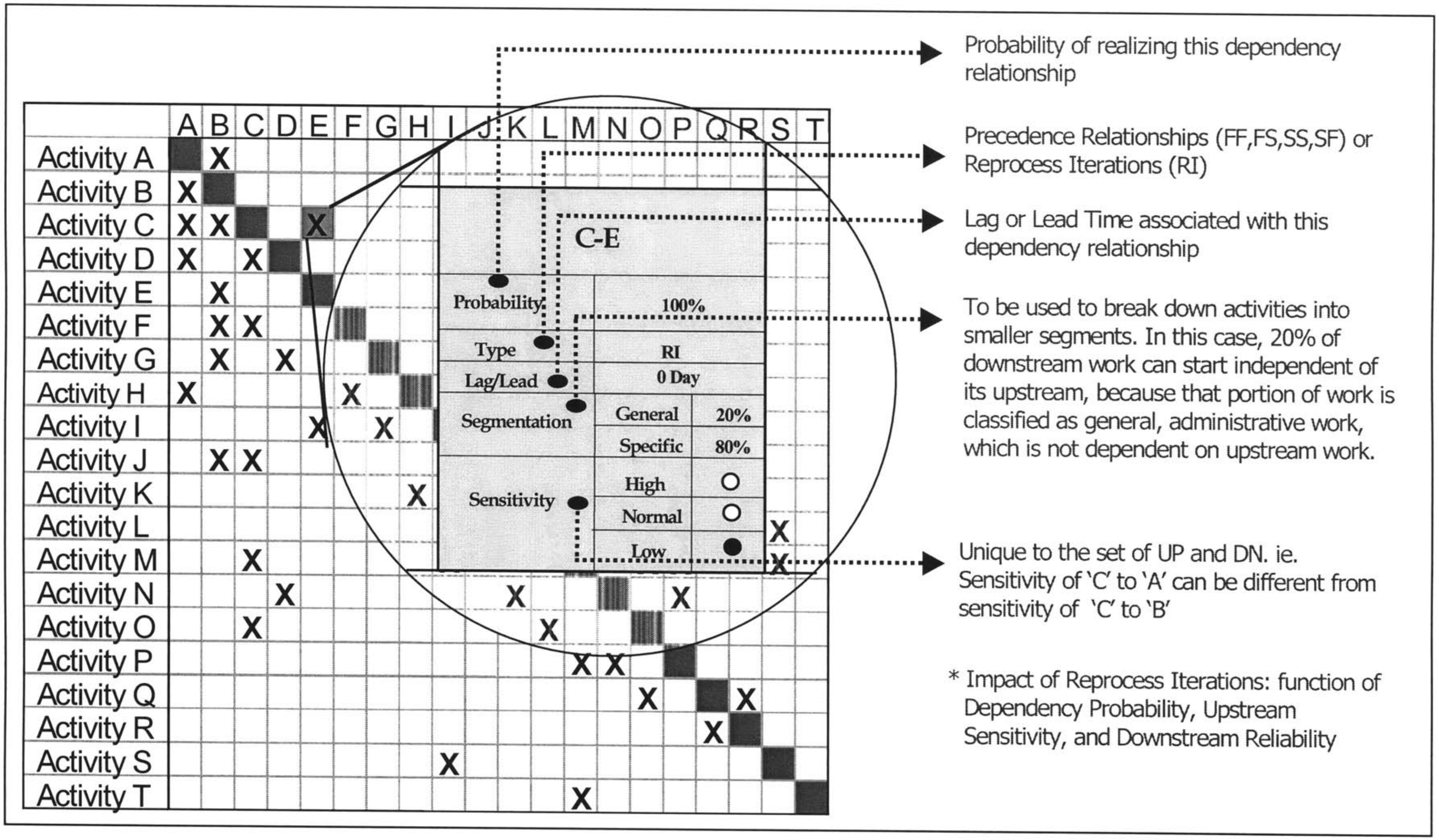


Figure 20-b: Generic Smart Cell for Relationship [adapted from Park (2001)]

5.9 WEB-BASED APPLICATION

DPM has the ability to be provided within a web-based planning and control environment, whereby a user can simulate DPM results with an active Java applet [Peña-Mora and Park, 2001]. The applet requests simulations of the data residing in the main server through a Java Remote Method Invocation (RMI). RMI simulates the source data and the simulation results are saved in the DPM database through Java Data Base Connectivity (JDBC).

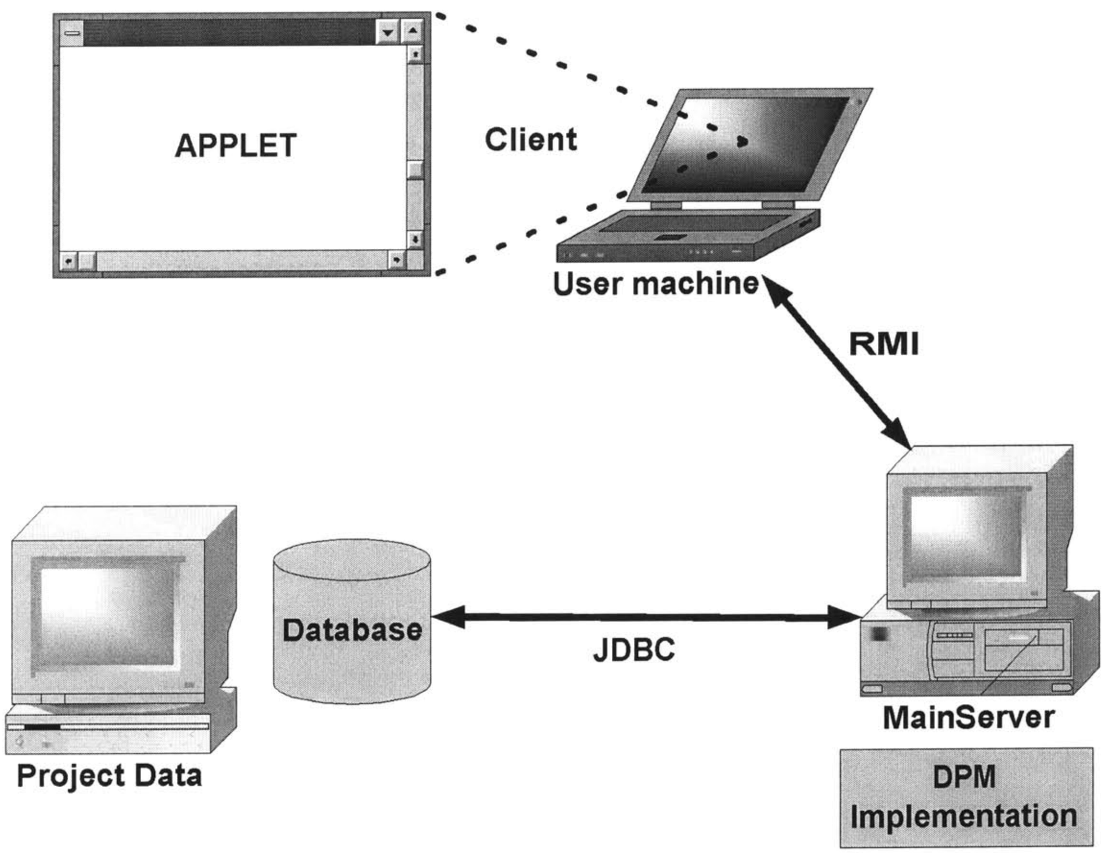


Figure 21: Web-based Production Diagram [adapted from Park (2001)]

For the web implementation of DPM, three main tools, Java programming language, Vensim, and RMI are extensively used. Java language makes DPM platform-independent. Furthermore, the utilization of Micro-Java supports hand-held devices without the limit by the operating system [Peña-Mora and Dwivedi, 2000]. In addition, Vensim, which is a powerful System Dynamics modeling tool, provides a simulation engine and analytical tools. Lastly, Java RMI is used 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. Such method calls appear the same as those operating on object in the same program [Deitel and Deitel, 1999].

Meanwhile, Figure 22 more specifically shows how distributed systems exchange data among them. User input can be transferred to DPM through Java RMI. Thereafter, Vensim.class calls venjava.dll, and in turn venjava.dll loads the Vensim DLL file. Through these processes, the DPM models are simulated. Once simulated, DPM shows the results through Java applet and save them in Oracle database through JDBC.

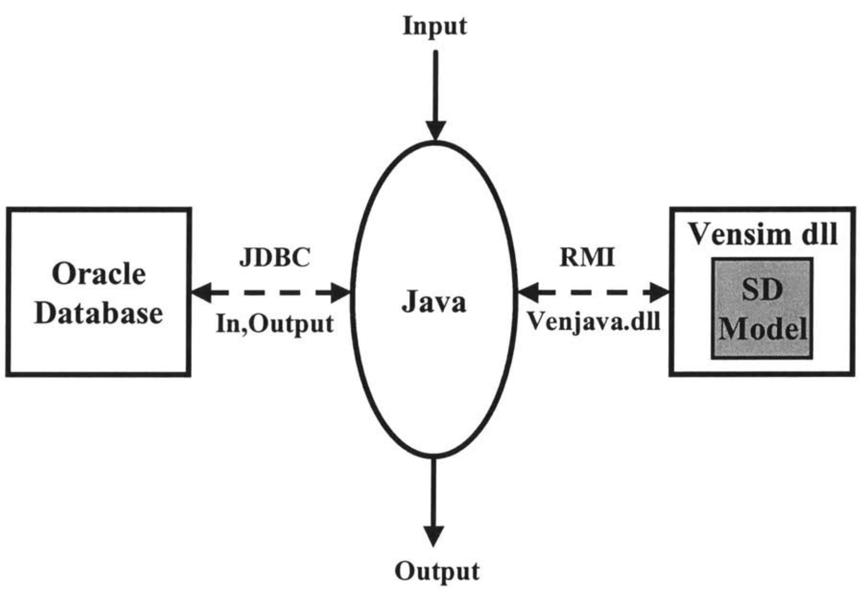


Figure 22: Scheme of Data Exchange in DPM Systems [adapted from Park (2001)]

In addition, by allowing data importing from Primavera, which is one of the most widely used project management software, DPM further increases its applicability. As conceptualized in Figure 23, DPM accesses and controls the SQL Server of Primavera Enterprise through JDBC driver. Meanwhile, Java RMI is used to connect the SQL server, considering that the Primavera SQL database can be located in remote places.

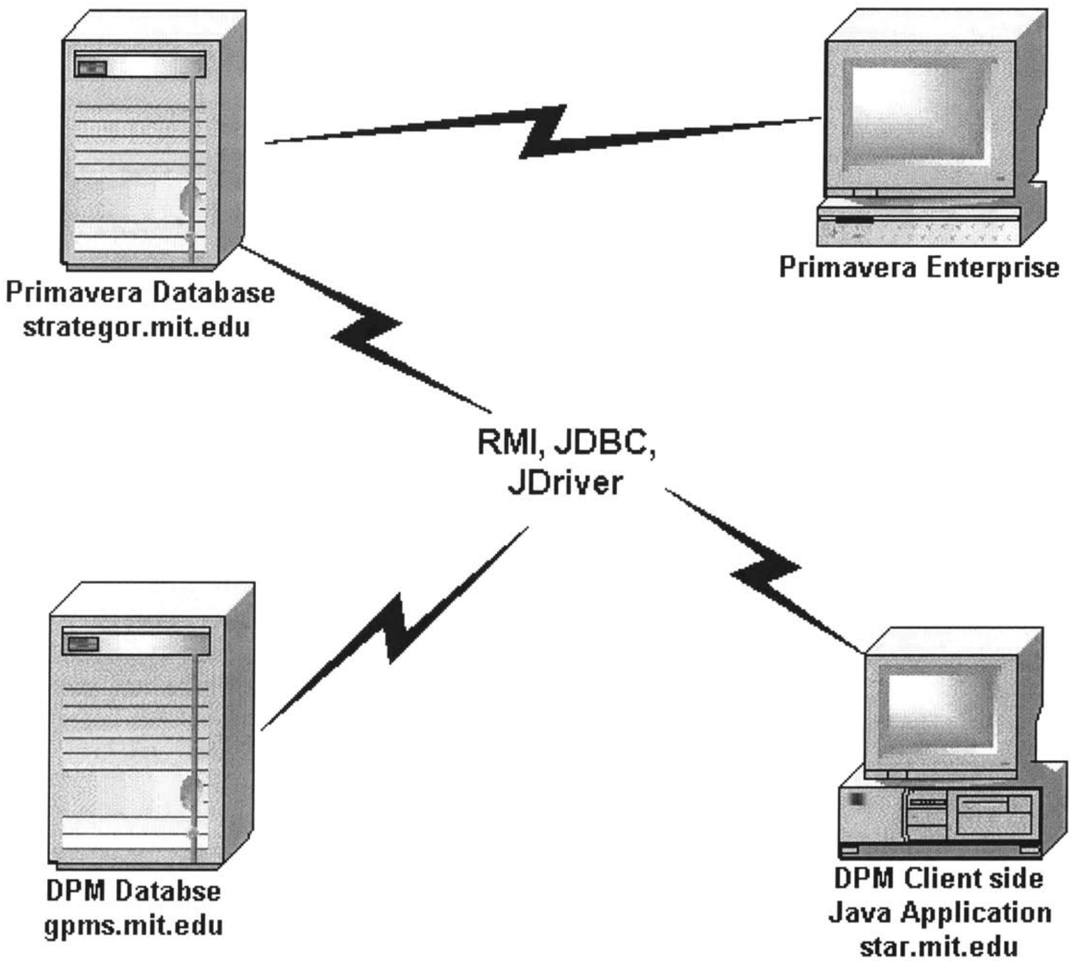


Figure 23: Data Exchange with Primavera [adapted from Park (2001)]

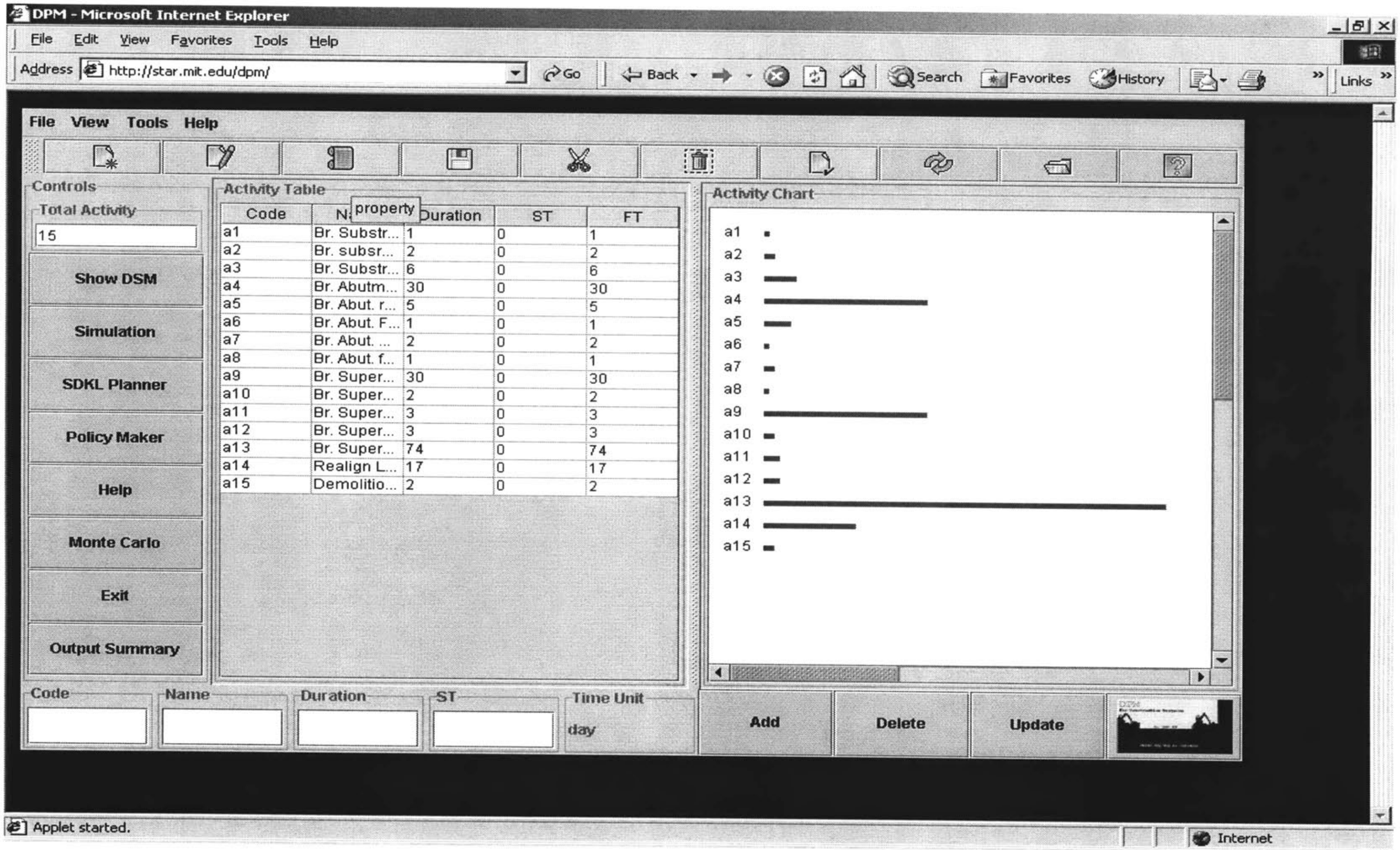


Figure 24: DPM Working on the Web [adapted from Park (2001)]

CHAPTER 6

CASE STUDY: ROUTE 3N

This chapter will present the case study in implementation of DPM on an active large-scale infrastructure project. The realities and challenges of introducing an innovative concept to a mature industry, the process steps to elicit the key information from project personnel, the means to execute this information retrieval, and the population of this information into the DPM system will be discussed and summarized.

6.1 PROJECT OVERVIEW

In August 2000, the Massachusetts Highway Department (MHD) awarded a $385 million Design-Build-Operate (DBO) contract to Modern Continental Companies, Inc. (MCC) for roadway improvements along State Route 3 from its intersection with State Route 128 in Burlington, MA north to its terminus at the State of New Hampshire border. Figures 25-A and 25-B illustrate the project location and boundary.

The design and construction phase is expected to span 42 months with beneficial occupancy of the entire roadway achieved in February 2004. Along the 21-mile stretch, the MCC team will widen the existing state roadway from four lanes to six lanes plus widen the existing seventeen bridges along the route to accommodate eight lanes should future traffic demand necessitate further reconstruction. In addition, thirteen bridge overpasses along Route 3 will require modifications, such as bridge abutment relocation, to accommodate the wider Route

3 roadway beneath. Of these thirteen overpass bridges, all but two will be reconstructed in a new alignment, either north or south of the existing bridge, to allow maintenance of traffic flow during construction. Subsequently, roadway and interchanges adjacent to these overpass bridges will require modifications to complete the overall intent of the project.

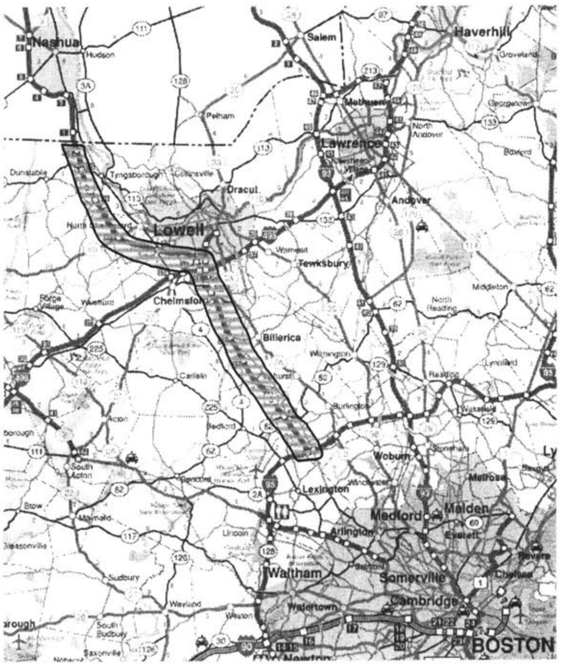


Figure 25-A: Map of Project Area

Courtesy of Massachusetts Turnpike Authority, 1999 (NTS)

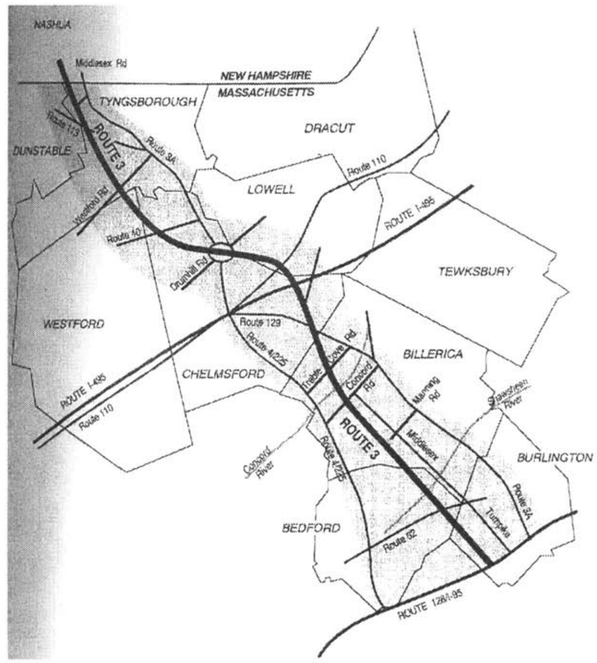


Figure 25-B: Map of Project Boundary

Courtesy of EOEA No. 5668[2] (NTS)

The project consists of a number of major types of work to be executed. The bulleted list below highlights the major components:

- Modifications of overpass bridges, including the setback of bridge abutments and bridge realignments to maintain local access during construction. In addition, several overpass bridges will be widened to accommodate traffic demands.
- Widening of existing bridges along Route 3 to accommodate four northbound and four southbound lanes, plus approximate roadway shoulders to comply with safety standards. This contract will only stripe the bridges for three northbound

[2] Commonwealth of Massachusetts Executive Office of Environmental Affairs, Environmental Assessment/Draft Environmental Impact Report, April 1997.

and three southbound lanes. The additional shoulderwidth will offer the motorists a wider clear zone for better highway visibility and greater degree of safety.

- Modification to the roadway drainage system as a result of increased runoff volume from increased roadway surface and roadway realignments.
- Widening, paving, and striping the roadway for three northbound and three southbound continuous traffic lanes, plus the adjacent on- and off-ramps and collector/distributor lanes, as applicable.

Figure 26 below identifies the location of the 30 bridges, which will undergo modification during the execution of the contract.

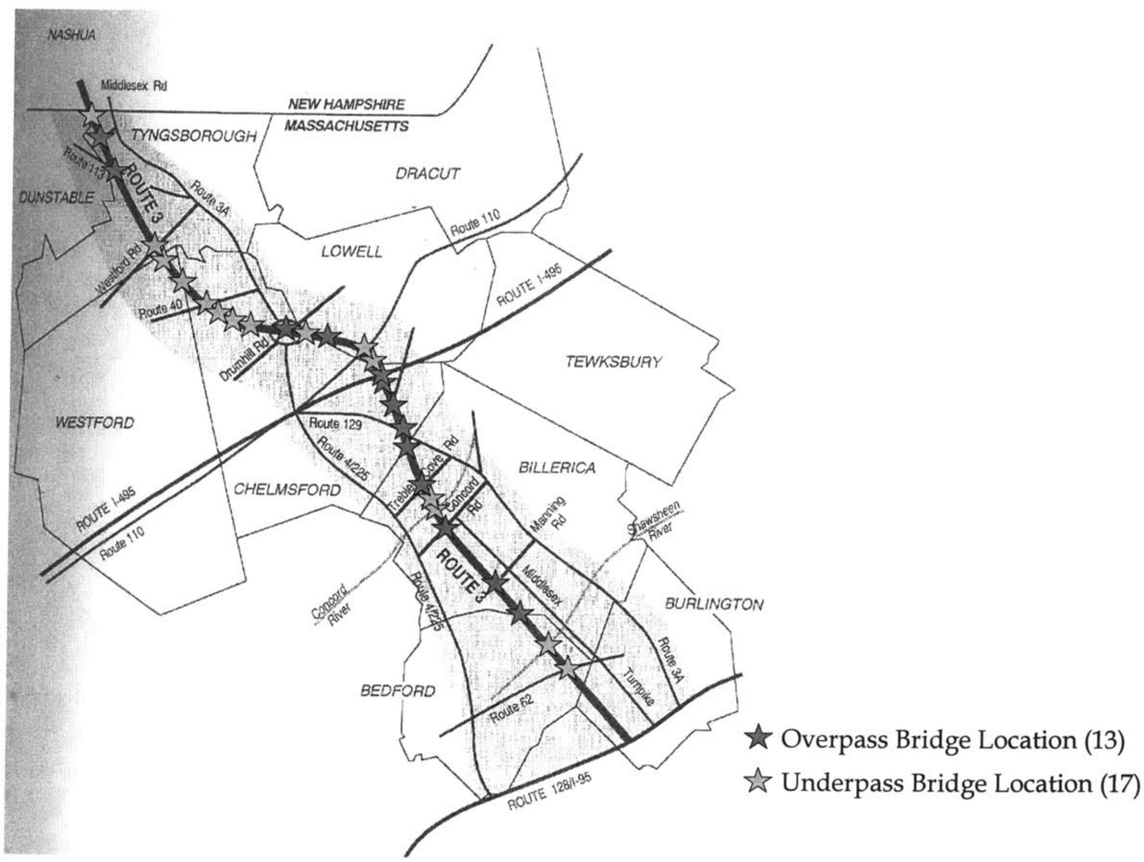


Figure 26: Location of To-be-Modified Bridges

As this project is intended to be a transportation improvement program, the scope of work to be executed includes common environmental mitigation efforts as well as new inter-modal transportation opportunities. The following list of bullets summarize these additional work elements to be completed:

- Establishment of eighteen areas within the project boundary to function as compensatory floodwater storage/wetland habitat as a mitigation measure for the disruption of wetland habitats at various locations along the roadway corridor. Where feasible, travel lane improvements occur within the existing median and retaining walls will be erected to minimize the impact on more valuable wetlands beyond the outer roadway shoulders.
- Erection of noise abatement barriers adjacent to noise sensitive receptors.
- Development of "Park & Ride" lots to encourage consolidation of single-occupancy vehicles into high-occupancy vehicles.

During the construction phase, MCC is required to design a traffic management plan such that the traffic operation throughout the corridor can be maintained at levels similar to pre-construction conditions. This effort is intended to minimize any further traffic diversions into the adjacent residential areas to avoid possible traffic delays on Route 3 as a result of on-going construction. Prior to the widening of Route 3, each of the overpass bridges will be rebuilt. One of the primary reasons for the relocation of all but two overpass bridges is to maintain traffic flow on the existing bridges and then switch traffic to the new bridge prior to demolition of the existing bridge. This construction sequence will minimize disruptions to the day-to-day commuter schedule. To facilitate construction and subsequent removal of existing overpass bridges, traffic on Route 3 will need to be interrupted for short periods to allow necessary construction activities to occur. This portion of the construction effort will likely occur during off-peak hours to minimize traffic disruption and diversion. Following replacement of the overpass bridges, reconstruction of Route 3 will commence.

Along with the staged construction sequence described above, the length of the corridor is divided into three construction segments. Starting from the south moving north, Section One is between Route 128 in Burlington and Route 129 in Billerica, Section Two is between Route 129 and the Drum Hill Rotary in Chelmsford, and Section Three is between the Drum Hill Rotary and the New Hampshire state line. During the entire construction period, MHD will post signs along Route 3 to encourage the use of existing public transportation systems in the area.

6.1.1 Project Objectives

Following the 30-year operation phase by the contractor, ownership of the roadway will transfer back to the Commonwealth of Massachusetts. MHD will be responsible for operation and maintenance of the roadway thereafter.

At the present time, Route 3 is a median-divided, four-lane limited access facility. It is the only limited access highway servicing the transportation needs of the entire Northern Middlesex Council of Governments (NMCOG) region to the north and a portion of the Metropolitan Area Planning Council (MAPC) region to the south. While other roadway alternatives within the vicinity exist (Interstate Route 95, Interstate Route 93, and Interstate Route 495), Route 3 is the only limited access facility with only two travel lanes in each direction. Operating under unacceptable Level of Service (LOS) E or F, as it currently does, represent traffic demands that are at or over the capacity of the highway facility. This type of heavy congestion in turn results in lost time, increased fuel consumption, increased safety problems, and heightened levels of driver frustrations. Based on the traffic patterns observed, the vehicular congestion is clearly related to work-related traffic during commuter travel times. Further, these traffic patterns indicate a direct correlation to increased commuter diversions onto parallel routes, such as Route 3A to the east and Route 4 to the west. These diversions cause substantial impacts to mobility within the area communities, lowering their quality of life and producing elevated volumes of traffic in residential areas. The last year of upgrades to the highway facility was performed in

1967 with the extension of the roadway from the Drum Hill Rotary to the State of New Hampshire state line. Given that roadways are typically designed to accommodate traffic demands 20 years in the future, Route 3 is a facility at or very near its originally anticipated design life.

During the intervening years since its completion, the economic development of this entire region has been inextricably tied to Route 3 and the access to employment and other destinations it provides. Land use along the corridor is varied. Development densities are most intense south of Interstate Route 495, with industrial and office development abutting the Route 3 right-of-way. While developments north of Interstate Route 495 are currently sparse, land use projections estimate that the majority of new developments will occur in this northern section. It is a prime goal for MHD that any roadway improvements support the continued maximization of the large public and private investments already committed to the region. By achieving this goal, this project will support both existing developments in and around the surrounding communities, and future developments that will most likely expand along the corridor. Because no new interchanges along Route 3 will be constructed, no lands currently without access will gain access and thus, there should be no imputes for location specific changes in zoning or land use.

Upon completion of the project, the citizens of the Commonwealth of Massachusetts as well as the motorists traveling between the State of New Hampshire and eastern Massachusetts will benefit from a safer and less congested roadway facility. The overall purpose of the project is to:

1) Improve capacity and/or capacity utilization along Route 3 such that overall corridor travel time (vehicle hours of travel) is reduced and, in so doing, travel demand can be met. By meeting as much of this demand as feasible, drivers will be attracted back to Route 3 and away from parallel routes to the maximum degree possible.
2) Improve vehicular safety along Route 3 by upgrading substandard conditions at interchanges and other points along Route 3, such that accidents and delays are reduced.

In addition to roadway improvements, construction of new "Park & Ride" facilities adjacent to the interchanges at Route 113 in the north and Route 62 in the south will occur. These facilities are intended to increase carpooling opportunities to decrease the traffic volume on the roadway.

6.1.2 Project Developer

The MCC team is responsible for the overall design, coordination, and construction of the roadway prior to an operational period for a term not to exceed 30 years. The MCC team structure is summarized in the table below:

Table 5: MCC Team Entities and Responsibilities

Team Entity	**Team Responsibility**
Modern Continental Companies, Inc.	Program Coordinator and Constructor
URS Corporation	Program Designer
Vanesse Hangen Brustlin, Inc.	Traffic Management Advisor
Cambridge Systematics, Inc.	Transportation Planning & Management Advisor
Keville Enterprises, Inc.	Quality Assurance Manager
Roy Jorgensen Associates, Inc.	Operations & Management Manager
The Smart Associates	Environmental Compliance Advisor
Environmental Consultants, Inc.	Environmental Compliance Advisor
Judith Nitsch Engineering, Inc.	Land Surveyor
Regan Communications	Community Outreach
Colt Communications	Community Outreach
Salomon Smith Barney	Financial Advisor
Raymond James & Associates, Inc.	Financial Advisor
Hinckley, Allen & Snyder	Legal Advisor

The following organizational chart clarifies each entity's major area of project management responsibility:

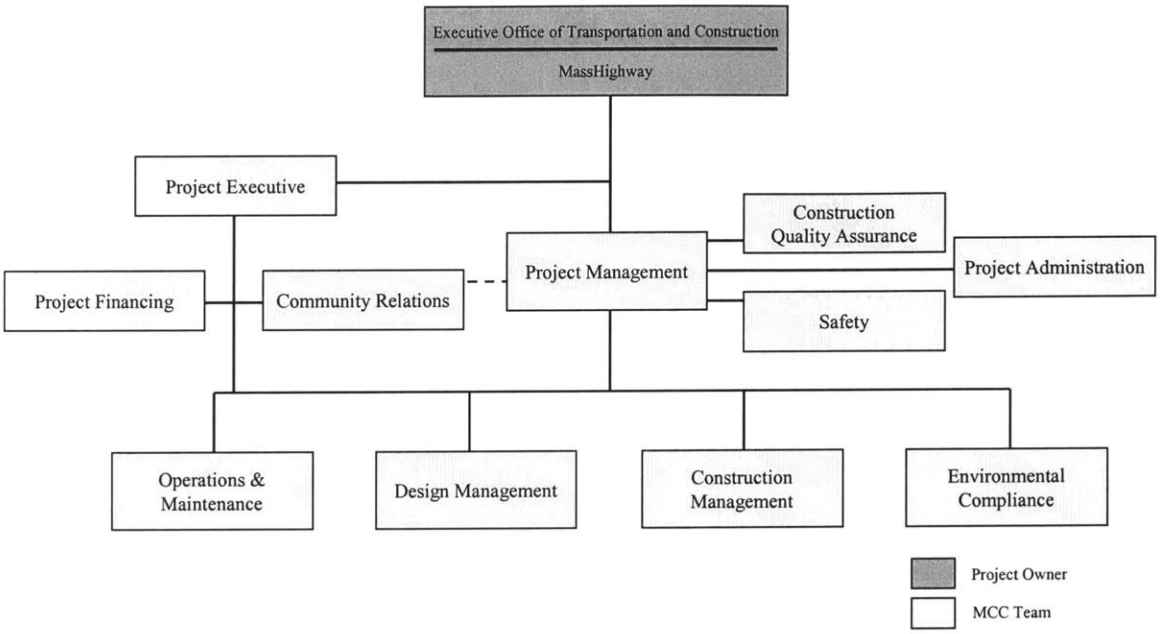


Figure 27: MCC Team Management Organizational Chart

6.1.3 Project Financing

To finance the design and construction of the project, the MCC Team will issue tax exempt bonds on behalf of the Commonwealth. The Massachusetts Legislature will reimburse the MCC Team through annual, periodic payments subject to appropriation. The lump sum contract obligates the MCC Team to perform all work necessary to obtain project completion within the time specified for the agreed price, subject only to certain specified limited exceptions. The exceptions are particularly restrictive to structure the project budget and financing appropriately and reduce the potential for cost overruns.

6.2 MODEL IMPLEMENTATION PHASE

The matrix illustrated in Figure 28 summaries the milestone completion dates provided by the MCC Team in its preliminary baseline schedule.

Activity Description	Early Start	Early Finish	Total Float
Key 2 – MDEP Issue Chap 91 Waterway License		30APR01	109
MHD ROW Complete – Mitigation Sites	22OCT01		597
Key – Phase 1 of Segment 3 Complete		01OCT02	0
Key – Phase 1 of Segment 1 Complete		07NOV02	0
Key – Phase 1 of Segment 2 Complete		20NOV02	0
Key – Segment 3 Construction Complete		05DEC03	75
Key – Segment 1 Construction Complete		08DEC03	72
Key – Segment 2 Construction Complete		18FEB04	0
Milestone 2 – Substantial Completion 2/18/04		18FEB04	0
Milestone 1 – Final Acceptance Deadline 5/18/04		18MAY04	0

Figure 28: Route 3N Project Milestone Schedule Matrix – Start Date View

The MCC team has indicated that activities that calculate 90 workdays of float or less are considered within the 'critical band' of activities. MCC has defined this threshold criterion as the timeframe necessary to make appropriate procurement and logistical modifications.

From the standpoint of environmental approvals, multiple and interrelated permit requirements must be met in accordance with the standards established by the local conservation commissions, the Massachusetts Department of Environmental Protection (MA DEP) and the U.S. Army Corps of Engineers (ACOE). Two additional oversight agencies play an active role in the issuance of permits: Secretary of the Executive Office of Transportation and Construction (EOTC), an executive office of the Commonwealth of Massachusetts, and the Federal Highway

Administration (FHWA). The MCC Team is responsible for obtaining all environmental permits subsequent to the Secretary's Certificate and the FHWA Record of Decision. The necessary permits include a project-wide Variance from the Wetlands Protection Act, two Chapter 91 licenses, Section 401, Section 404 and NPDES permits. In addition, the Team will be responsible for filing notices of project changes with MEPA, as necessary.

6.2.1 Project Design Process

The development agreement entered by all parties requires three mandatory design submittals to MHD: (i) 35% design submittal, 65% design submittal, and 100% design submittal; (ii) type study and sketch plan for all bridges and retaining walls; and (iii) final design submittal for all bridges and retaining walls. Each submittal will include, as applicable, reference to clearance provided for a potential (future) fourth general purpose lane, relevant roadway drainage provisions, and relevant traffic maintenance/management provisions. During the design development phase, the Owner's role will consist of oversight to ensure compliance with established design criteria and within the approved quality control/quality assurance plan. "Over-the-shoulder" reviews by MHD will be tolerated and encouraged to expedite the process.

35% Design Submittal: This submittal is intended to identify the limits of the work, the horizontal and vertical geometrics, and the bridge clearances. Prior to the 35% design submittal, the MCC team must obtain written approval of all design exceptions from the Commonwealth, and if applicable from the FHWA.

65% Design Submittal: This submittal will include the developer's interpretation of the MHD highway design standards. This submittal will be accompanied by detailed construction drawings and specifications, including traffic maintenance plans and completed drainage design. Comments from MHD during the 35% design submittal review expect to be incorporated by this submittal.

100% Design Submittal: This submittal shall consist of detailed, complete and checked drawings, reports, and specifications necessary for construction. MHD's approval of this submittal will be designated as "Approved for Construction."

Type Study: As specified in the *MHD Bridge Manual*, the type study report will be submitted corridor-wide for review and approval for the selection of particular structure types. Cost analysis between the types is not necessary. Pertaining to the retaining walls, the most appropriate style for a specific site condition shall be included.

Sketch Plan: As specified in the *MHD Bridge Manual*, the sketch plan submittal will follow the type study report for review and approval by MHD. Submitted for each individual bridge, final bridge design shall not commence prior to MHD approval of the sketch plan.

Final Design Submittal: The intent of this submittal is to ensure consistency between the design submittals specific to this project with the standard format used by MHD.

The pavement design criterion is a 20-year design life and at turnover of the project to the Commonwealth, the pavement must have a remaining life of 10 years. Under these circumstances, MCC expects to repave the roadway 20 years after construction is complete.

Based on an initial assessment of the baseline schedule prepared by the MCC Team the conceptual design development work sequence, which includes initial plan, review, comment and approval cycles, is depicted in Figure 29.

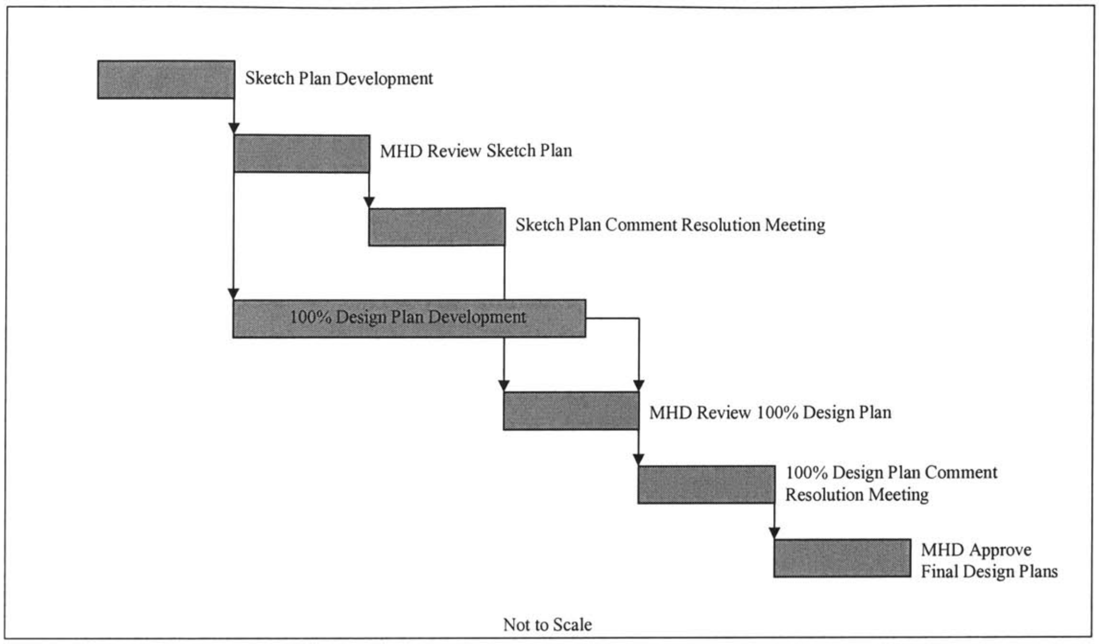


Figure 29: Conceptual Design Development Work Sequence

6.2.2 Bid Estimate Review

In reviewing the bid estimate prepared by the MCC Team, 61% of the total project costs are resident within four bid items. These items are listed in descending estimated cost value: Bridge Structures, Roadway Pavement Structures, Earthwork, and Design Services. Careful attention is necessary in the review of the Bridge Structures bid item. The cost of the Drum Hill Rotary Bridge modification from an existing rotary configuration with two bridges that span over Route 3 to one single-point diamond interchange bridge is NOT included within the Bridge Structures bid item, but is a separate bid item entitled Drum Hill Rotary ATC.

The bid is broken down into six cost categories: Labor, Permanent Materials, Construction Materials/Expenses, Equipment Ownership, Equipment Operation, and Subcontract. The four bid items listed above account for 58% of the Labor Costs, 84% of the Permanent Material Costs, 14% of the Construction Material/Expenses, 75% of the Equipment Ownership Costs, 78% of the Equipment Operation Costs, and 68% of the Subcontract Costs. Excluding the estimated manhours for Design Services, the three remaining bid items account for 78% of the total estimated manhours.

The three most costly bridges, which exceed an estimate of $4 million are: Concord River Bridge (underpass), Route I-495 Bridge (overpass), and Temporary Bridges at I-495 (overpass). The tables below summarize the types of bridges, their respective locations, and their approximate estimated costs in US$:

Table 6: Overpass Bridges by Segment, includes Estimated Costs for Bridge Structures

Bid Item Description	Cumulative Total Cost
Segment 1	
Old Billerica Rd/Rte 3	$2 million
Manning Rd/Rte 3	1 million
Concord Rd/Rte 3	2 million
Treble Cove Rd/Rte 3	3 million
Rangeway Rd/Rte 3	1 million
Route 129/Rte 3	3 million
Segment 2	
Lowell Conn/Rte 3	2 million
Riverneck Rd/Rte 3	1 million
Route I-495/Rte 3	4 million
Temp Bridge at I-495	4 million
Steadman St/Rte 3	2 million
Segment 3	
Route 113 (Kendall Rd)/Rte 3	3 million
Locust Ave/Rte 3	1 million

Table 7: Underpass Bridges by Segment, includes Estimated Costs for Bridge Structures

Bid Item Description	Cumulative Total Cost
Segment 1	
Route 3/Rte 62 (Burlington Rd)	$2 million
Route 3/Shawsheen River	3 million
Route 3/Concord River	4 million
Route 3/Farm Rd	1 million
Segment 2	
Route 3/River Meadow Brook	3 million
Route 3/Route 110 (Chelmsford St)	3 million
Route 3/Parkhurst Rd	2 million
Segment 3	
Route 3/Richardson Rd	2 million
Route 3/Stony Brook	2 million
Route 3/B&M Railroad	2 million
Route 3/Moor's Canal	2 million
Route 3/Main St	2 million
Route 3/Route 40 (Groton Rd)	2 million
Route 3/Ledge Rd	1 million
Route 3/Dunstable Rd	3 million
Route 3/Westford Rd	2 million
Route 3/SB Connector	2 million

6.3 INITIAL CASE STUDIES FOR MODEL VALIDATION

Due to the repetitive nature of the scope of work within this project, representatives of the two general bridge types (overpass and underpass) have been selected for model validation. The Shawsheen River Bridge has been selected as the underpass case study and the Treble Cove Road Bridge as the overpass case study. These bridges are not the first bridges scheduled for modification; seven bridges are scheduled to commence modification on March 12, 2001: Route 129 (overpass), Route 113 (overpass), Moor's Canal (underpass), Main St. (underpass), Route 40 (underpass), Ledge Rd. (underpass), and Dunstable St. (underpass) Bridges. The site locations of the two case study bridges relative to the overall project are identified in Figure 30.

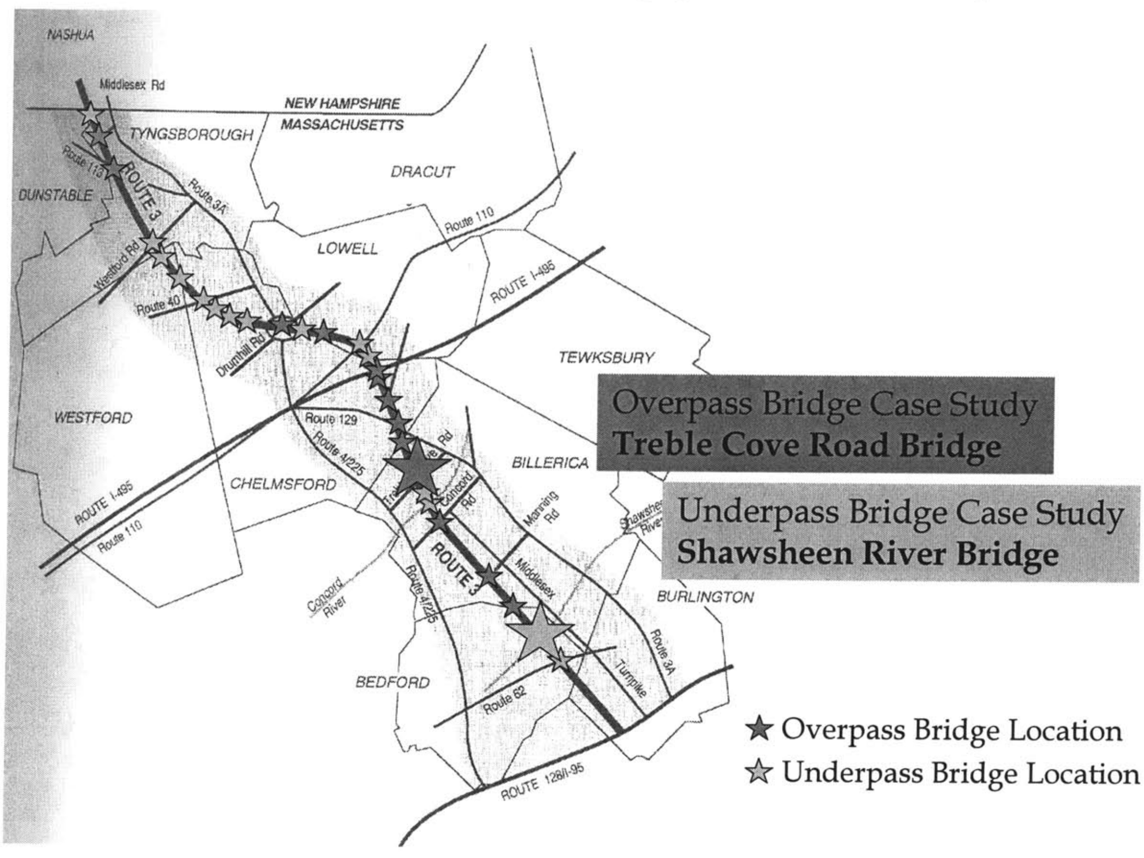


Figure 30: Site Locations of Initial Case Study Bridges

6.3.1 Shawsheen River Bridge – Underpass Bridge Case Study

The existing underpass bridge is located in Bedford, MA. Figure 31 is a project photo taken by the MCC Team of the existing bridge.

Figure 31: Photo of Existing Shawsheen River Bridge [compliments of the MCC Team]

The scope of work is representative of the seventeen underpass bridge widening modifications within this contract. For this particular bridge, approximately 800 feet of retaining wall both north and south of the bridge will be placed along the interior Route 3 median. Figure 32 is a snapshot of the design drawing in plan view.

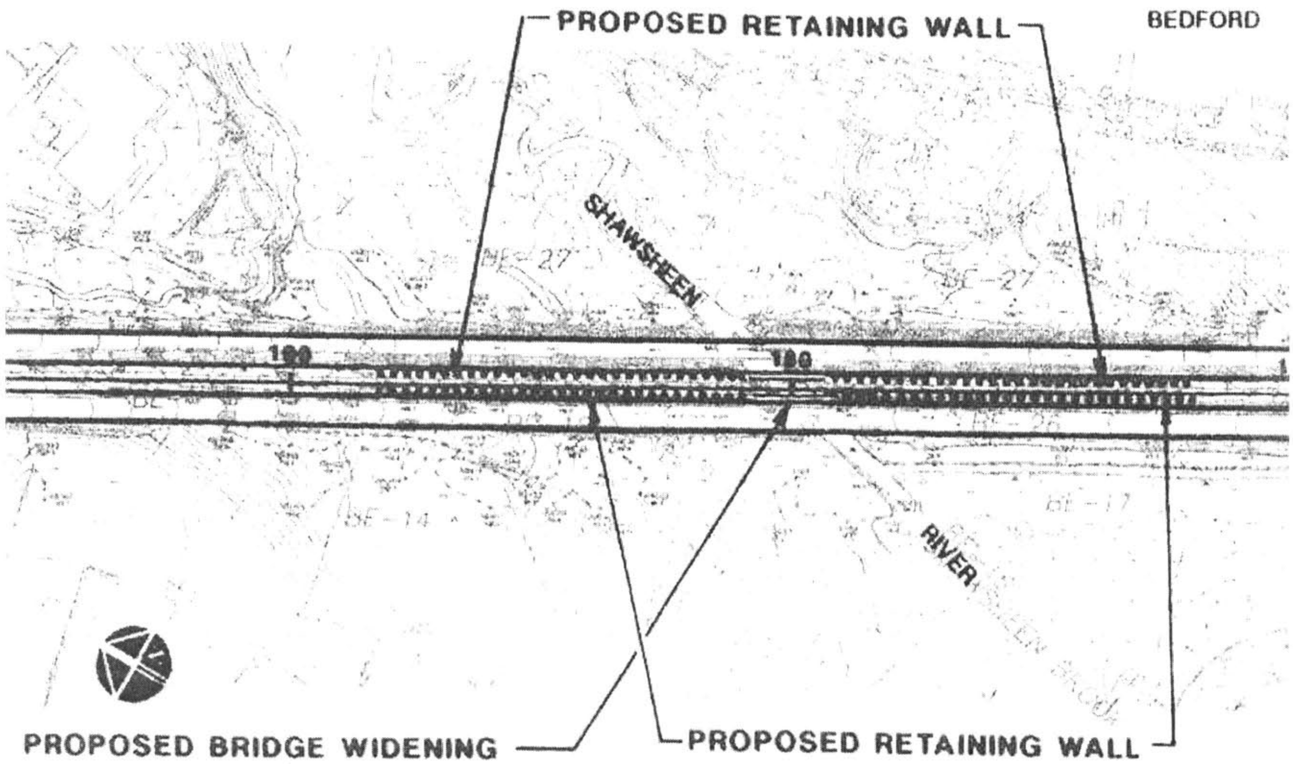


Figure 32: Plan View of Shawsheen River Bridge Modification (NTS)

Figure 33 is a schedule fragnet from the P3 schedule specific to the Shawsheen River Bridge modification. The overall fragnet planned duration from design development activities through construction spans the time period between November 20, 2000 and December 8, 2003.

As the schedule fragnet indicates, MCC design development activities are predecessor activities to MCC on-location construction activities. While several procurement activities have float values outside the 'critical band', the majority of design and construction activities reside within this 'critical band'.

For visual clarity, the above schedule fragnet has been condensed into several hammocks, as illustrated in Figure 34.

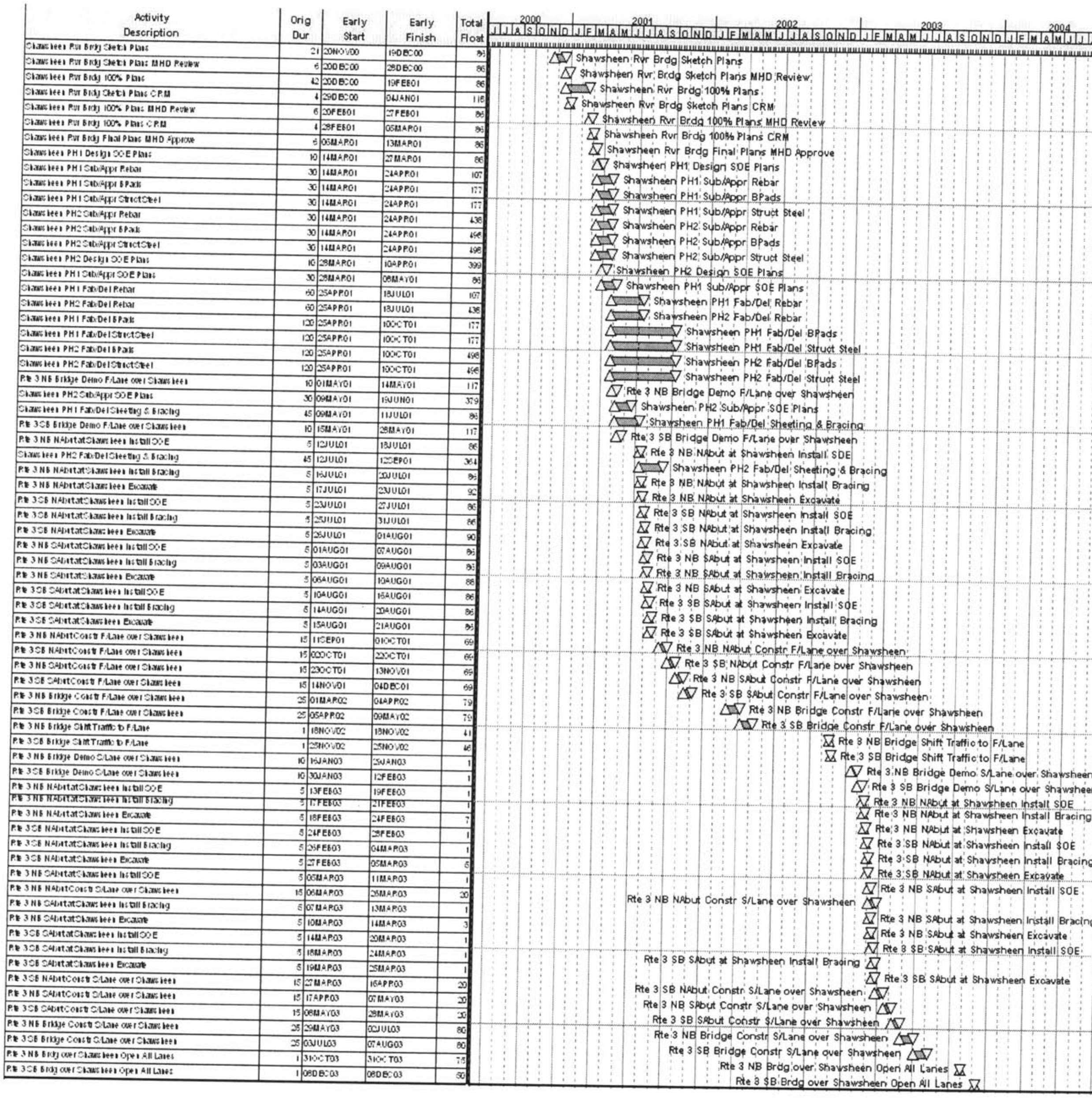


Figure 33: Shawsheen River Bridge Schedule Fragnet – Start Date View

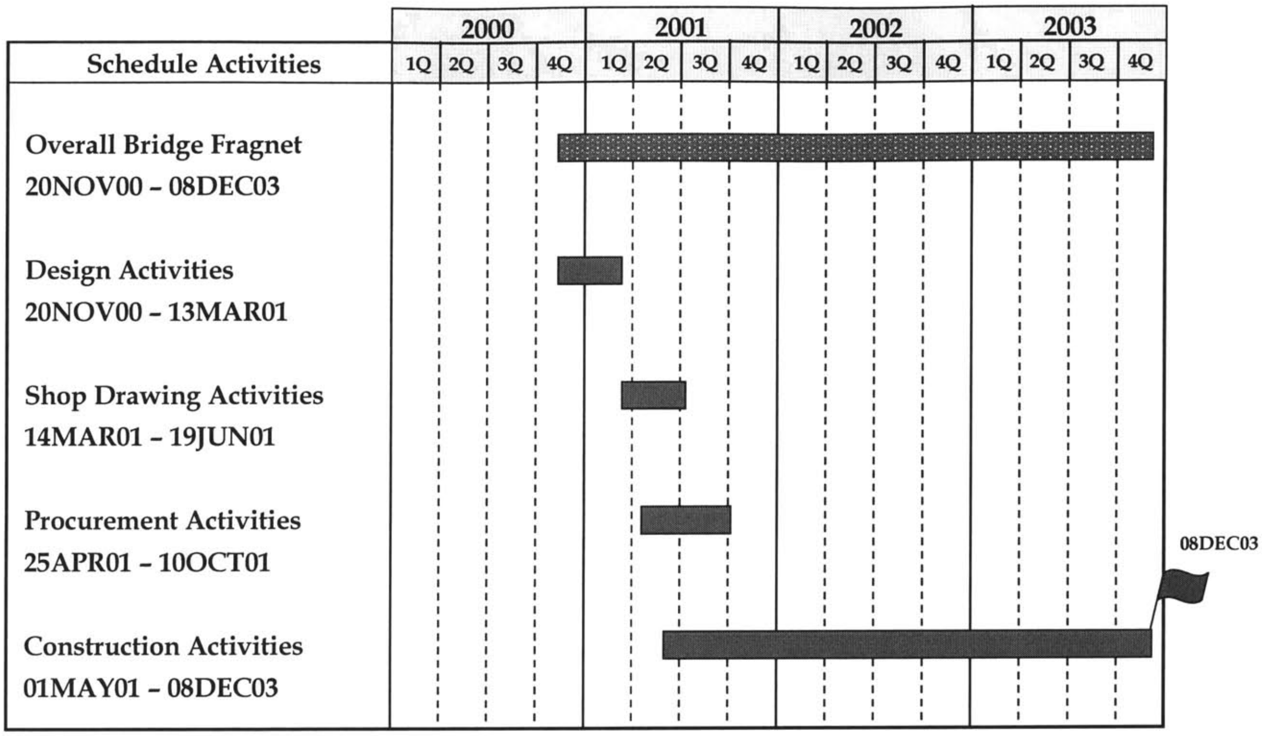


Figure 34: Shawsheen River Bridge Schedule Hammock Activities

Several schedule activities have calculated float values less than or equal to 5 workdays, which should be characterized as on the critical path. These schedule activities are:

- Rte 3 NB & SB Bridge – Demo Slow Lane over Shawsheen
- Bridge Abutment Activities, as summarized in the following matrix:

	NB North Abutment	SB North Abutment	NB South Abutment	SB South Abutment
Install SOE	✓	✓	✓	✓
Install Bracing	✓	✓	✓	✓
Excavate		✓	✓	✓

For our initial model inputs, the schedule fragnet for Shawsheen River Bridge was isolated from the rest of the project schedule. What remained within the schedule fragnet are the interdependent activity ties placed by the project scheduler for the execution of the scope of work. Table 8 captures these interdependent activities ties, which originated from the as-planned P3 project schedule.

Table 8: Shawsheen River Bridge Schedule Fragnet Activity Relationships

Rel	Lag	Non-Driving Predecessors	Rel	Lag	Driving Predecessors	PRIMARY ACTIVITY
					**************************	**BRIDGE RELOCATION**
		NONE			NONE	**Rte 3 NB Bridge Demo F/Lane over Shawsheen**
		NONE	FS	0	Rte 3 NB Bridge Demo F/Lane over Shawsheen	Rte 3 SB Bridge Demo F/Lane over Shawsheen
		NONE	FS	0	Shawsheen Rvr Brdg Final Plans MHD Approve	Shawsheen PH1 Design SOE Plans
FS	0	Shawsheen Rvr Brdg Final Plans MHD Approve	FS	0	Shawsheen PH1 Design SOE Plans	Shawsheen PH2 Design SOE Plans
		NONE	FS	0	Shawsheen Rvr Brdg Final Plans MHD Approve	Shawsheen PH1 Sub/Appr Rebar
		NONE	FS	0	Shawsheen Rvr Brdg Final Plans MHD Approve	Shawsheen PH1 Sub/Appr BPads
		NONE	FS	0	Shawsheen Rvr Brdg Final Plans MHD Approve	Shawsheen PH1 Sub/Appr Struct Steel
		NONE	FS	0	Shawsheen Rvr Brdg Final Plans MHD Approve	Shawsheen PH2 Sub/Appr Rebar
		NONE	FS	0	Shawsheen Rvr Brdg Final Plans MHD Approve	Shawsheen PH2 Sub/Appr BPads
		NONE	FS	0	Shawsheen Rvr Brdg Final Plans MHD Approve	Shawsheen PH2 Sub/Appr Struct Steel
		NONE	FS	0	Shawsheen PH1 Design SOE Plans	Shawsheen PH1 Sub/Appr SOE Plans
FS	0	Shawsheen PH2 Design SOE Plans	FS	0	Shawsheen PH1 Sub/Appr SOE Plans	Shawsheen PH2 Sub/Appr SOE Plans
		NONE	FS	0	Shawsheen PH1 Sub/Appr SOE Plans	Shawsheen PH1 Fab/Del Sheeting & Bracing
FS	0	Rte 3 SB Bridge Demo F/Lane over Shawsheen	FS	0	Shawsheen PH1 Fab/Del Sheeting & Bracing	Rte 3 NB NAbut at Shawsheen Install SOE
		NONE	FS	0	Shawsheen PH1 Sub/Appr Rebar	Shawsheen PH1 Fab/Del Rebar
		NONE	FS	0	Shawsheen PH2 Sub/Appr Rebar	Shawsheen PH2 Fab/Del Rebar
		NONE	FS	0	Rte 3 NB NAbut at Shawsheen Install SOE	Rte 3 NB NAbut at Shawsheen Install Bracing
		NONE	SS	1	Rte 3 NB NAbut at Shawsheen Install Bracing	Rte 3 NB NAbut at Shawsheen Excavate
		NONE	FS	0	Rte 3 NB NAbut at Shawsheen Install Bracing	Rte 3 SB NAbut at Shawsheen Install SOE
		NONE	SS	2	Rte 3 SB NAbut at Shawsheen Install SOE	Rte 3 SB NAbut at Shawsheen Install Bracing
FS	0	Rte 3 NB NAbut at Shawsheen Excavate	SS	1	Rte 3 SB NAbut at Shawsheen Install Bracing	Rte 3 SB NAbut at Shawsheen Excavate
		NONE	FS	0	Rte 3 SB NAbut at Shawsheen Install Bracing	Rte 3 NB SAbut at Shawsheen Install SOE
		NONE	SS	2	Rte 3 NB SAbut at Shawsheen Install SOE	Rte 3 NB SAbut at Shawsheen Install Bracing
FS	0	Rte 3 SB NAbut at Shawsheen Excavate	SS	1	Rte 3 NB SAbut at Shawsheen Install Bracing	Rte 3 NB SAbut at Shawsheen Excavate
		NONE	FS	0	Rte 3 NB SAbut at Shawsheen Install Bracing	Rte 3 SB SAbut at Shawsheen Install SOE
		NONE	SS	2	Rte 3 SB SAbut at Shawsheen Install SOE	Rte 3 SB SAbut at Shawsheen Install Bracing
FS	0	Rte 3 NB SAbut at Shawsheen Excavate	SS	1	Rte 3 SB SAbut at Shawsheen Install Bracing	Rte 3 SB SAbut at Shawsheen Excavate
FS	0	Shawsheen PH1 Fab/Del Rebar	FS	0	Rte 3 SB NAbut at Shawsheen Excavate	Rte 3 NB NAbut Constr F/Lane over Shawsheen
		NONE	FS	0	Rte 3 NB NAbut Constr F/Lane over Shawsheen	Rte 3 SB NAbut Constr F/Lane over Shawsheen
FS	0	Shawsheen PH2 Sub/Appr SOE Plans	FS	0	Shawsheen PH1 Fab/Del Sheeting & Bracing	Shawsheen PH2 Fab/Del Sheeting & Bracing
FS	0	Rte 3 SB SAbut at Shawsheen Excavate	FS	0	Rte 3 SB NAbut Constr F/Lane over Shawsheen	Rte 3 NB SAbut Constr F/Lane over Shawsheen
		NONE	FS	0	Shawsheen PH1 Sub/Appr BPads	Shawsheen PH1 Fab/Del BPads
		NONE	FS	0	Shawsheen PH1 Sub/Appr Struct Steel	Shawsheen PH1 Fab/Del Struct Steel
		NONE	FS	0	Shawsheen PH2 Sub/Appr BPads	Shawsheen PH2 Fab/Del BPads
		NONE	FS	0	Shawsheen PH2 Sub/Appr Struct Steel	Shawsheen PH2 Fab/Del Struct Steel
		NONE	FS	0	Rte 3 NB SAbut Constr F/Lane over Shawsheen	Rte 3 SB SAbut Constr F/Lane over Shawsheen
FS	0	Shawsheen PH1 Fab/Del BPads	FS	0	Rte 3 SB SAbut Constr F/Lane over Shawsheen	Rte 3 NB Bridge Constr F/Lane over Shawsheen
FS	0	Shawsheen PH1 Fab/Del Struct Steel				
FS	0	Rte 3 SB NAbut Constr F/Lane over Shawsheen	FS	0	Rte 3 NB Bridge Constr F/Lane over Shawsheen	Rte 3 SB Bridge Constr F/Lane over Shawsheen
		NONE	FS	0	Rte 3 SB Bridge Constr F/Lane over Shawsheen	Rte 3 SB Bridge Shift Traffic to F/Lane
		NONE	FS	0	Rte 3 SB Bridge Constr F/Lane over Shawsheen	Rte 3 NB Bridge Shift Traffic to F/Lane
		NONE	FS	0	Rte 3 NB Bridge Shift Traffic to F/Lane	Rte 3 NB Bridge Demo S/Lane over Shawsheen
FS	0	Rte 3 SB Bridge Shift Traffic to F/Lane	FS	0	Rte 3 NB Bridge Demo S/Lane over Shawsheen	Rte 3 SB Bridge Demo S/Lane over Shawsheen
FS	0	Shawsheen PH2 Fab/Del Sheeting & Bracing	FS	0	Rte 3 SB Bridge Demo S/Lane over Shawsheen	Rte 3 NB NAbut at Shawsheen Install SOE
		NONE	SS	2	Rte 3 NB NAbut at Shawsheen Install SOE	Rte 3 NB NAbut at Shawsheen Install Bracing
		NONE	SS	1	Rte 3 NB NAbut at Shawsheen Install Bracing	Rte 3 NB NAbut at Shawsheen Excavate
		NONE	FS	0	Rte 3 NB NAbut at Shawsheen Install Bracing	Rte 3 SB NAbut at Shawsheen Install SOE
		NONE	SS	2	Rte 3 SB NAbut at Shawsheen Install SOE	Rte 3 SB NAbut at Shawsheen Install Bracing
FS	0	Rte 3 NB NAbut at Shawsheen Excavate	SS	1	Rte 3 SB NAbut at Shawsheen Install Bracing	Rte 3 SB NAbut at Shawsheen Excavate
		NONE	FS	0	Rte 3 SB NAbut at Shawsheen Install Bracing	Rte 3 NB SAbut at Shawsheen Install SOE
		NONE	SS	2	Rte 3 NB SAbut at Shawsheen Install SOE	Rte 3 NB SAbut at Shawsheen Install Bracing
FS	0	Rte 3 SB NAbut at Shawsheen Excavate	SS	1	Rte 3 NB SAbut at Shawsheen Install Bracing	Rte 3 NB SAbut at Shawsheen Excavate
		NONE	FS	0	Rte 3 NB SAbut at Shawsheen Install Bracing	Rte 3 SB SAbut at Shawsheen Install SOE
		NONE	SS	2	Rte 3 SB SAbut at Shawsheen Install SOE	Rte 3 SB SAbut at Shawsheen Install Bracing
FS	0	Rte 3 NB SAbut at Shawsheen Excavate	SS	1	Rte 3 SB SAbut at Shawsheen Install Bracing	Rte 3 SB SAbut at Shawsheen Excavate
FS	0	Shawsheen PH2 Fab/Del Rebar	FS	0	Rte 3 SB NAbut at Shawsheen Excavate	Rte 3 NB NAbut Constr S/Lane over Shawsheen
		NONE	FS	0	Rte 3 NB NAbut Constr S/Lane over Shawsheen	Rte 3 SB NAbut Constr S/Lane over Shawsheen
FS	0	Rte 3 SB SAbut at Shawsheen Excavate	FS	0	Rte 3 SB NAbut Constr S/Lane over Shawsheen	Rte 3 NB SAbut Constr S/Lane over Shawsheen
		NONE	FS	0	Rte 3 NB SAbut Constr S/Lane over Shawsheen	Rte 3 SB SAbut Constr S/Lane over Shawsheen
FS	0	Shawsheen PH2 Fab/Del BPads	FS	0	Rte 3 SB SAbut Constr S/Lane over Shawsheen	Rte 3 NB Bridge Constr S/Lane over Shawsheen
FS	0	Shawsheen PH2 Fab/Del Struct Steel				
		NONE	FS	0	Rte 3 NB Bridge Constr S/Lane over Shawsheen	Rte 3 NB Brdg over Shawsheen Open All Lanes
FS	0	Rte 3 SB NAbut Constr S/Lane over Shawsheen	FS	0	Rte 3 NB Bridge Constr S/Lane over Shawsheen	Rte 3 SB Bridge Constr S/Lane over Shawsheen
		NONE	FS	0	Rte 3 SB Bridge Constr S/Lane over Shawsheen	Rte 3 SB Brdg over Shawsheen Open All Lanes

The cost of this bridge in the bid estimate is approximately $3 million with more than half in the Permanent Materials cost category.

6.3.2 Treble Cove Bridge – Overpass Bridge Case Study

The existing overpass bridge is located in Billerica with Route 3 on- and off-ramps located to the north of the overpass bridge. Figure 35 is a project photo taken by the MCC Team of the existing bridge.

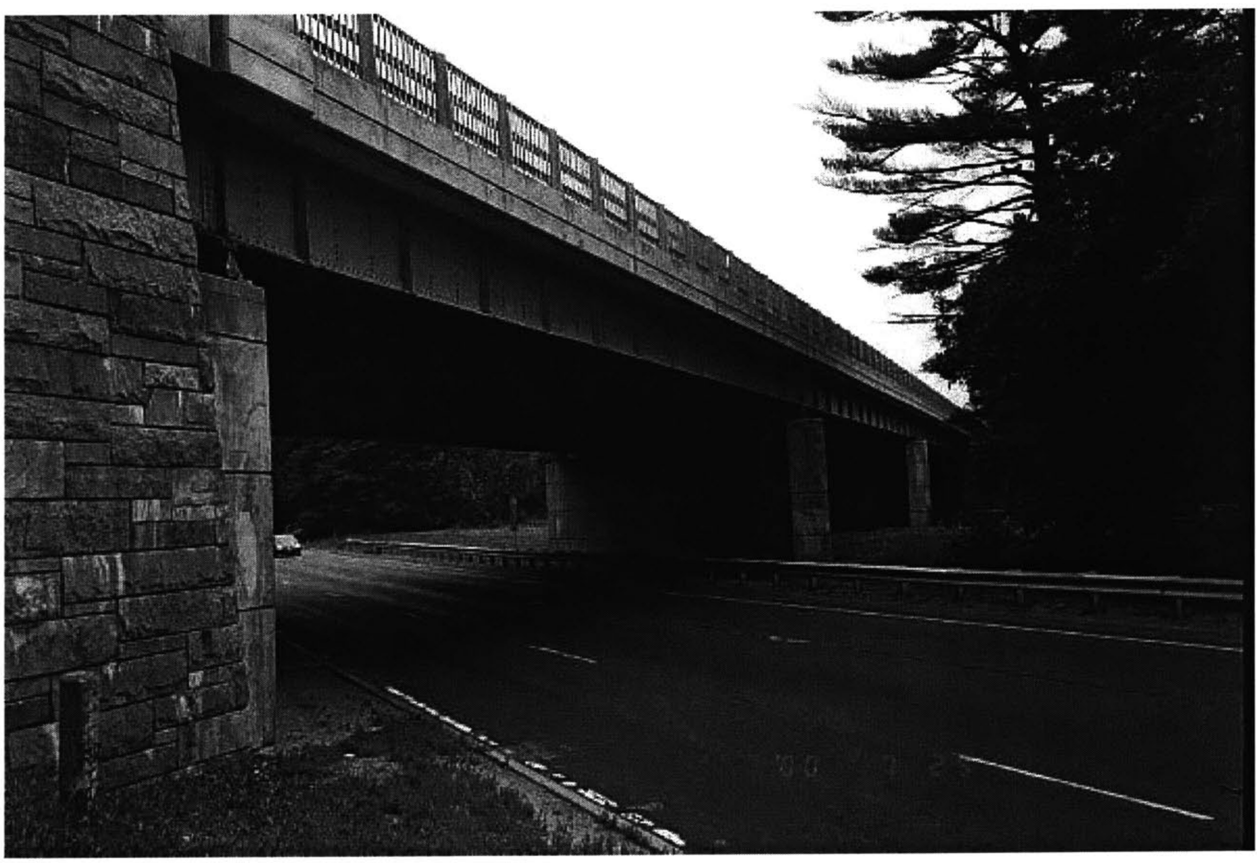


Figure 35: Photo of Existing Treble Cove Bridge [compliments of the MCC Team]

The scope of work is representative of the ten overpass bridge relocations within this contract. This particular bridge will not only be relocated to the north of the existing bridge, but widened as well. Figure 36 is a snapshot of the design drawing in plan view.

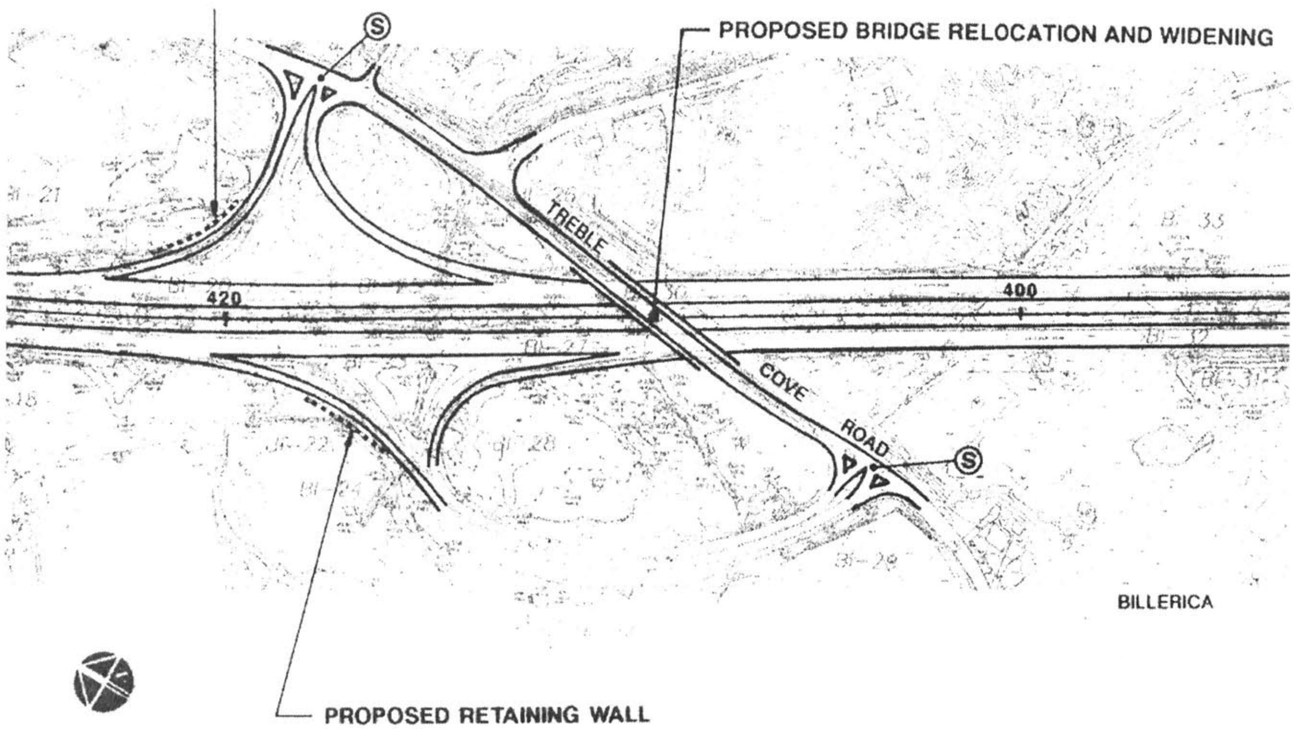


Figure 36: Plan View of Treble Cove Road Bridge Relocation (NTS)

Figure 37 is a schedule fragnet specific to the Treble Cove Road Bridge relocation. The overall fragnet planned duration from right-of-way activities through construction spans the time period between August 30, 2000 and July 2, 2003.

As the schedule fragnet indicates, MHD right-of-way activities are predecessor activities to MCC design development that are predecessor activities to MCC on-location construction activities. While the MHD right-of-way activities have float values outside the 'critical band', the design and construction activities reside within this 'critical band'.

Activity Description	Orig Dur	Early Start	Early Finish	Total Float
ROW - MHD Survey SB Treble Cove Rd	10	30AUG00	13SEP00	347
ROW - MHD Survey NB Treble Cove Rd	10	30AUG00	13SEP00	347
ROW - Legal Desc SB Treble Cove Rd	5	14SEP00	20SEP00	347
ROW - Legal Desc NB Treble Cove Rd	5	14SEP00	20SEP00	347
ROW - Appraisal SB Treble Cove Rd	10	21SEP00	04OCT00	347
ROW - Appraisal NB Treble Cove Rd	10	21SEP00	04OCT00	347
ROW - MHD Appr Apprsls SB Treble Cove Rd	15	05OCT00	26OCT00	347
ROW - MHD Appr Apprsls NB Treble Cove Rd	15	05OCT00	26OCT00	347
Treble Cove Rd Bridge Utility Test Pit	3	25OCT00	27OCT00	108
ROW - Land Acqustn Proc SB Treble Cove Rd	90	27OCT00	07MAR01	347
ROW - Land Acqustn Proc NB Treble Cove Rd	90	27OCT00	07MAR01	347
Treble Cove Rd Brdg Sketch Plans	21	27FEB01	27MAR01	47
Treble Cove Rd Brdg Sketch Plans MHD Review	6	28MAR01	04APR01	82
Treble Cove Rd Brdg 100% Plans	47	28MAR01	31MAY01	47
Treble Cove Rd Brdg Sketch Plans CRM	6	05APR01	12APR01	82
Treble Cove Rd Brdg 100% Plans MHD Review	7	01JUN01	11JUN01	47
Treble Cove Rd Brdg 100% Plans CRM	6	12JUN01	19JUN01	47
Treble Cove Rd Brdg Final Plans MHD Approve	6	20JUN01	27JUN01	47
Treble Cove Rd Bridge Design SOE Plans	10	28JUN01	12JUL01	51
Treble Cove Rd Bridge Sub/Appr BPads	30	28JUN01	09AUG01	47
Treble Cove Rd Bridge Sub/Appr Struct Steel	30	28JUN01	09AUG01	47
Treble Cove Rd Bridge Sub/Appr Rebar	30	28JUN01	09AUG01	62
Treble Cove Rd Bridge Sub/Appr SOE Plans	30	13JUL01	23AUG01	51
Treble Cove Rd Bridge Fab/Del Rebar	60	10AUG01	01NOV01	62
Treble Cove Rd Bridge Fab/Del BPads	120	10AUG01	29JAN02	47
Treble Cove Rd Bridge Fab/Del Struct Steel	120	10AUG01	29JAN02	47
Treble Cove Rd Bridge Fab/Del Sheet & Brace	45	24AUG01	25OCT01	51
Treble Cove Rd Bridge EAbut Setup Workzone	10	16OCT01	29OCT01	49
Treble Cove Rd Bridge EAbut Install SOE	10	30OCT01	13NOV01	49
Treble Cove Rd Bridge WAbut Setup Workzone	10	30OCT01	13NOV01	49
Treble Cove Rd Bridge EAbut Excavate	10	02NOV01	16NOV01	49
Treble Cove Rd Bridge WAbut Install SOE	10	14NOV01	27NOV01	49
Treble Cove Rd Bridge WAbut Excavate	10	19NOV01	30NOV01	49
Treble Cove Rd Bridge Center Pier Install SOE	10	28NOV01	11DEC01	49
Treble Cove Rd Bridge Center Pier Excavate	10	03DEC01	14DEC01	49
Treble Cove Rd Bridge Construct New EAbut	15	05DEC01	26DEC01	40
Treble Cove Rd Bridge Construct New WAbut	15	27DEC01	17JAN02	40
Treble Cove Rd Bridge Construct New Ctr Pier	15	18JAN02	07FEB02	40
Treble Cove Rd Bridge Notify BA for Relocation	1	05APR02	05APR02	19
Treble Cove Rd Bridge Construct Superstructure	25	05APR02	09MAY02	0
Treble Cove Rd Bridge Bell Telephone Cable	80	06MAY02	26AUG02	19
Treble Cove Rd Bridge Relocate Gas Line	15	10MAY02	30MAY02	0
Treble Cove Rd Bridge Relocate Water Line	15	31MAY02	20JUN02	0
Treble Cove Rd Bridge Install Telephone DB	15	21JUN02	12JUL02	0
Treble Cove Rd Bridge Realign Treble Cove Rd	10	15JUL02	26JUL02	0
Treble Cove Rd Bridge Realign Rte 3 NB Ramps	20	29JUL02	23AUG02	0
Treble Cove Rd Bridge Realign Rte 3 SB Ramps	20	26AUG02	20SEP02	0
Treble Cove Rd Bridge Shift Traff to New Bridge	1	23SEP02	23SEP02	0
Treble Cove Rd Bridge Demo Existing Ctr Span	10	24SEP02	07OCT02	0
Treble Cove Rd Bridge Demo Existing EAbut	10	05JUN03	18JUN03	30

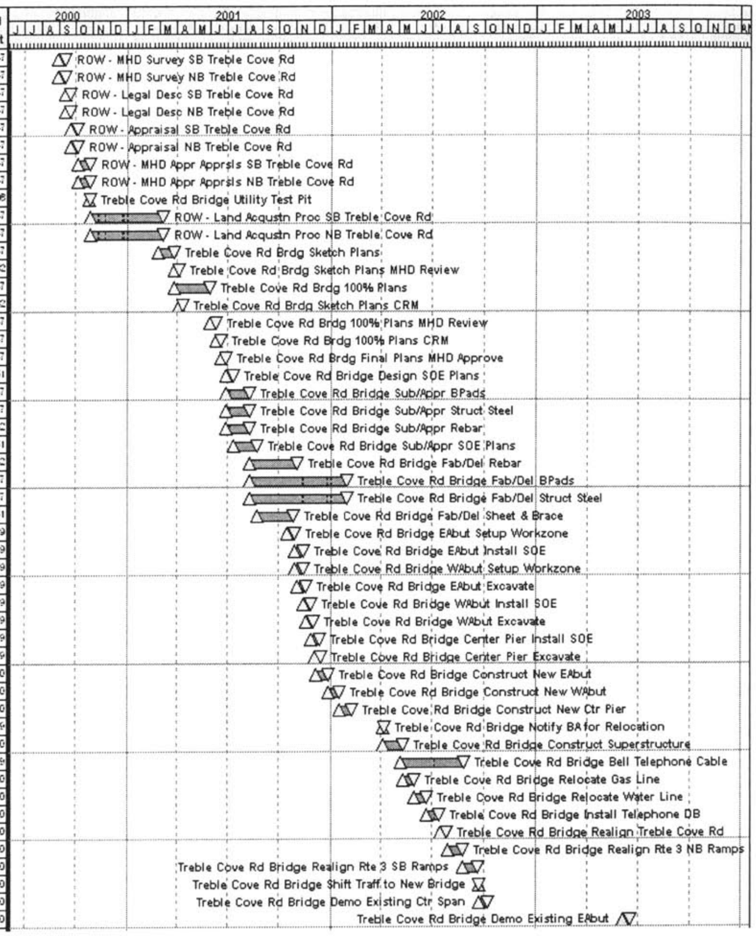


Figure 37: Treble Cove Road Bridge Schedule Fragnet – Start Date View

For visual clarity, the above schedule fragnet has been condensed into several hammocks, as shown in Figure 38.

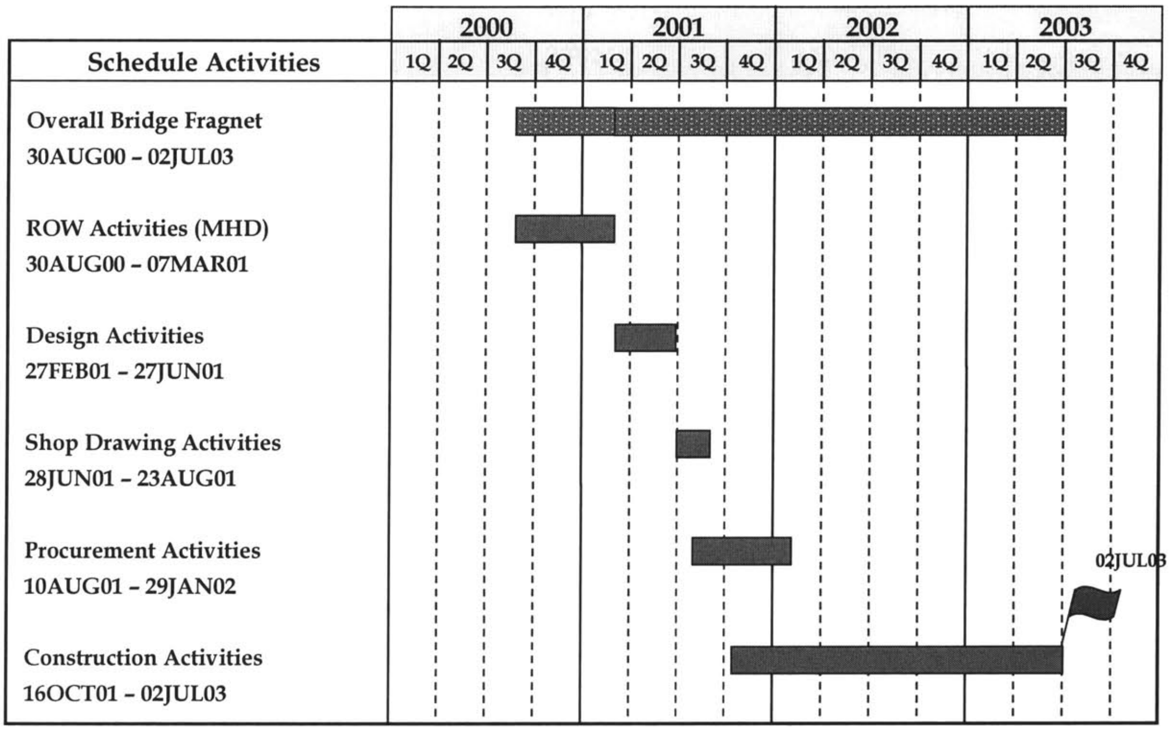


Figure 38: Treble Cove Road Bridge Schedule Hammock Activities

Several schedule activities have calculated float values less than or equal to 5 workdays, which should be characterized as on the critical path. These schedule activities are:

- Construct Superstructure
- Relocate Gas Line
- Relocate Water Line
- Install Telephone Ductbank
- Realign Treble Cove Road
- Realign Rte 3 NB & SB Ramps
- Shift Traffic to New Bridge
- Demo Existing Center Span

For our initial model inputs, the schedule fragnet for Treble Cove Road Bridge was isolated from the rest of the project schedule. What remained within the schedule fragnet are the interdependent activity ties placed by the project scheduler for the execution of the scope of work. Table 9 captures these interdependent activities ties, which originated from the as-planned P3 project schedule.

Table 9: Treble Cove Road Bridge Schedule Fragnet Activity Relationships

Rel	Lag	Non-Driving Predecessors	Rel	Lag	Driving Predecessors	PRIMARY ACTIVITY
					*************************	BRIDGE RELOCATION
		NONE			NONE	**Treble Cove Rd Bridge Utility Test Pit**
		NONE			NONE	**Treble Cove Rd Bridge EAbut Setup Workzone**
		NONE			NONE	**Treble Cove Rd Bridge Demo Existing EAbut**
		NONE	FS	0	Treble Cove Rd Bridge EAbut Setup Workzone	Treble Cove Rd Bridge WAbut Setup Workzone
		NONE	FS	0	Treble Cove Rd Bridge Demo Existing EAbut	Treble Cove Rd Bridge Demo Existing WAbut
		NONE	FS	0	Treble Cove Rd Brdg Final Plans MHD Approve	Treble Cove Rd Bridge Design SOE Plans
		NONE	FS	0	Treble Cove Rd Brdg Final Plans MHD Approve	Treble Cove Rd Bridge Sub/Appr Rebar
		NONE	FS	0	Treble Cove Rd Brdg Final Plans MHD Approve	Treble Cove Rd Bridge Sub/Appr BPads
		NONE	FS	0	Treble Cove Rd Brdg Final Plans MHD Approve	Treble Cove Rd Bridge Sub/Appr Struct Steel
		NONE	FS	0	Treble Cove Rd Brdg Final Plans MHD Approve	Treble Cove Rd Bridge Sub/Appr SOE Plans
		NONE	FS	0	Treble Cove Rd Bridge Sub/Appr SOE Plans	Treble Cove Rd Bridge Fab/Del Sheet & Brace
		NONE	FS	0	Treble Cove Rd Bridge Sub/Appr Rebar	Treble Cove Rd Bridge Fab/Del Rebar
FS	0	Treble Cove Rd Bridge EAbut Setup Workzone	FS	0	Treble Cove Rd Bridge Fab/Del Sheet & Brace	Treble Cove Rd Bridge EAbut Install SOE
		NONE	SS	3	Treble Cove Rd Bridge EAbut Install SOE	Treble Cove Rd Bridge EAbut Excavate
FS	0	Treble Cove Rd Bridge WAbut Setup Workzone	FS	0	Treble Cove Rd Bridge EAbut Install SOE	Treble Cove Rd Bridge WAbut Install SOE
		NONE	SS FS	3 0	Treble Cove Rd Bridge WAbut Install SOE Treble Cove Rd Bridge EAbut Excavate	Treble Cove Rd Bridge WAbut Excavate
FS FS	0 0	Treble Cove Rd Bridge EAbut Install SOE Treble Cove Rd Bridge Fab/Del Rebar	FS	0	Treble Cove Rd Bridge EAbut Excavate	Treble Cove Rd Bridge Construct New EAbut
		NONE	FS	0	Treble Cove Rd Bridge WAbut Install SOE	Treble Cove Rd Bridge Center Pier Install SOE
		NONE	SS FS	3 0	Treble Cove Rd Bridge Center Pier Install SOE Treble Cove Rd Bridge WAbut Excavate	Treble Cove Rd Bridge Center Pier Excavate
FS FS	0 0	Treble Cove Rd Bridge WAbut Install SOE Treble Cove Rd Bridge WAbut Excavate	FS	0	Treble Cove Rd Bridge Construct New EAbut	Treble Cove Rd Bridge Construct New WAbut
FS FS	0 0	Treble Cove Rd Bridge Center Pier Install SOE Treble Cove Rd Bridge Center Pier Excavate	FS	0	Treble Cove Rd Bridge Construct New WAbut	Treble Cove Rd Bridge Construct New Ctr Pier
		NONE	FS	0	Treble Cove Rd Bridge Sub/Appr BPads	Treble Cove Rd Bridge Fab/Del BPads
		NONE	FS	0	Treble Cove Rd Bridge Sub/Appr Struct Steel	Treble Cove Rd Bridge Fab/Del Struct Steel
FS FS FS	0 0 0	Treble Cove Rd Bridge Construct New EAbut Treble Cove Rd Bridge Construct New WAbut Treble Cove Rd Bridge Construct New Ctr Pier	FS FS	0 0	Treble Cove Rd Bridge Fab/Del BPads Treble Cove Rd Bridge Fab/Del Struct Steel	Treble Cove Rd Bridge Construct Superstructure
FS	0	Treble Cove Rd Brdg Final Plans MHD Approve	SS	0	Treble Cove Rd Bridge Construct Superstructure	Treble Cove Rd Bridge Notify BA for Relocation
FS	0	Treble Cove Rd Bridge Utility Test Pit	FS	0	Treble Cove Rd Bridge Construct Superstructure	Treble Cove Rd Bridge Relocate Gas Line
		NONE	FS	0	Treble Cove Rd Bridge Relocate Gas Line	Treble Cove Rd Bridge Relocate Water Line
FS	0	Treble Cove Rd Bridge Construct Superstructure	FS	0	Treble Cove Rd Bridge Relocate Water Line	Treble Cove Rd Bridge Install Telephone DB
FS FS FS FS	0 0 0 0	ROW - Land Acqustn Proc SB Treble Cove Rd ROW - Land Acqustn Proc NB Treble Cove Rd Treble Cove Rd Bridge Construct Superstructure Treble Cove Rd Bridge Relocate Water Line	FS	0	Treble Cove Rd Bridge Install Telephone DB	Treble Cove Rd Bridge Realign Treble Cove Rd
		NONE	FS	0	Treble Cove Rd Bridge Realign Treble Cove Rd	Treble Cove Rd Bridge Realign Rte 3 NB Ramps
FF	15	Treble Cove Rd Bridge Install Telephone DB	FS	20	Treble Cove Rd Bridge Notify BA for Relocation	Treble Cove Rd Bridge Bell Telephone Cable
FS	0	Treble Cove Rd Bridge Realign Treble Cove Rd	FS	0	Treble Cove Rd Bridge Realign Rte 3 NB Ramps	Treble Cove Rd Bridge Realign Rte 3 SB Ramps
FS FS	0 0	Treble Cove Rd Bridge Construct Superstructure Treble Cove Rd Bridge Bell Telephone Cable	FS	0	Treble Cove Rd Bridge Realign Rte 3 SB Ramps	Treble Cove Rd Bridge Shift Traff to New Bridge
		NONE	FS	0	Treble Cove Rd Bridge Shift Traff to New Bridge	Treble Cove Rd Bridge Demo Existing Ctr Span

For DPM model input variables and parameters, the schedule activities were assessed to distinguish their production rate types, the reliability of the production results, and the sensitivity of the interdependent schedule activities. From this assessment, a preliminary overlapping framework was developed based on the characteristic of the activity interdependency. This information was then transferred to the current DPM model and simulation runs were conducted and compared to the non-simulated results, in particular, the duration of time to complete the work.

Since the simulation results can be no better than the data entered, the next step in the research is to understand the process between estimated productivities used to develop the bid price, how this translates to the as-planned schedule, and the thought process in applying contingencies for unforeseen circumstances throughout this process. The research may uncover fatal flaws in the transfer of information upon which the project team relies or that the multiple process iterations produce a tool modified greatly from the original plan.

The cost of this bridge in the bid estimate is slightly more than the Shawsheen River Bridge with a higher percentage of the overall cost in the Permanent Materials cost category.

6.4 TREBLE COVE BRIDGE MODEL INPUT ELICITATION EXERCISE

Figure 39 presents the initial questionnaire prepared as a framework for eliciting model inputs in a systematic manner. Prior to our initial questionnaire presentation, a mock trial was preformed to better understand how the audience might react to the questionnaire format. From the questionnaire, the following matrix, Table 10, summarizes and illustrates the range of answers elicited when the questionnaire was used as a framework, but the test subject was given the liberty of answering the questionnaire as it seemed fit. At the conclusion of this exercise, the questionnaire was modified in an attempt to better frame the desired elicitations. The revised questionnaire, presented at the January 26, 2001 meeting with MCC, is presented in Figure 40.

DPM MODEL INPUT ELICITATION QUESTIONNAIRE

Q1: How susceptible is this activity to change, both owner-initiated and changed field conditions? If a change occurs, how far will this ripple through the schedule?

Q2: What is the degree of confidence that this schedule activity will be done correctly the first time? What is the mechanism to verify its accuracy? Name factors that could contribute to poor workmanship?

Q3: If its predecessor activity was changed from the original plan, how will this activity be affected?

Q4: If its predecessor activity was done incorrectly, how will this activity be affected?

Q5: Name factors that would create high productivity; Name factors that would create low productivity. What factors are most likely to be encountered?

Q6: Are the results/benefits of this activity observed instantaneously, near the start of the activity, near the end of the activity?

Q7: Would an additional labor crew double the expected productivity? Do you expect labor shortage problems?

Q8: Given a changed field condition, will redesign be necessary? Will an owner-directive be necessary? What kind of documentation of the change is necessary? Could work progress in the field uninhibited by the change? Will a corrective action plan be drafted and reviewed? Will traffic management plans need revision? Will community notification be necessary? Could change require revised equipment and labor resource needs? Could additional procurement be necessary?

GENERAL QUESTIONS

QA: How much liberty is given to the MCC Team to control work and impacts without owner involvement? What could the weak link be to rapid decision-making?

QB: What is the expected level of cooperation with local utility companies? How flexible is the procedure for utility relocations, if changes in the field are encountered? If utility redesign becomes necessary, what will the utility companies require?

QC: What known schedule contingencies are in place?

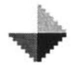
QD: Discuss ideal staggering/staging of work. When does the overlap of work become impossible?

Figure 39: Original Model Input Elicitation Questionnaire

Table 10: Sample Questionnaire Elicitations Responses to Questions for Installation of Support of Excavation (SOE)

		Expected to Address				Actually Addressed		
	Original Question	Production Type	Reliability	Sensitivity	Sample Answers	Production Type	Reliability	Sensitivity
Q1:	How susceptible is this activity to change, both owner-initiated and changed field conditions? If a change occurs, how far will this ripple through the schedule?				Activity susceptible to delay/impacts if unexpected boulders/obstructions (likely) or unknown active utilities (unlikely) encountered while driving SOE. Successor activity (excavate) cannot start until SOE activity complete. Ripple contained to this activity. Given impenetratable obstructions, damage to sheet piling may occur. Additional probe drilling may be required. Additional grouting (to stop water penetration) or jack hammering (for obstruction removal) may be necessary.			
Q2:	What is the degree of confidence that this schedule activity will be done correctly the first time? What is the mechanism to verify its accuracy? Name factors that could contribute to poor workmanship?				Would listen for telltale signs when obstructions were hit and when to stop driving the piling. Wouldn't necessarily rely on design calculations; field personnel would more likely go with own experience and gut feel than what the engineer had designed. Under ideal soil conditions (with minimal obstructions) expect activity to be performed efficiently and without the necessity for removing partially driven sheet pile, replacing new sheet pile, and re-driving. Would be concerned if pile driving near old masonry structures; structural integrity could be compromised by driving or vibrating activity. Accuracy verified by field survey. Potential poor workmanship if SOE is made of poor quality material, recycled from previous job, mishandled during offloading (crimping edges with choker) or flying the piling to its location, or damaged by hitting obstructions.			
Q3:	If its predecessor activity was changed from the original plan, how will this activity be affected?				Several unexpected changes in a predecessor activity could occur: unexpected utility relocation, violation of environmental impact statement, violation of OSHA regulation, or roadway drainage revisions could delay the start of this activity. An unexpected utility line hit would kick off a series of unexpected activities: contract work stopped, confirm leak, repair leak, and rethink coordination of utility with SOE and more importantly with bridge abutment. If utility runs adjacent to one abutment, this abutment location might need to be moved; could require revision to bridge girder length and procurement. If utility runs between the two abutments, second abutment could need revision.			

		Expected to Address				Actually Addressed		
	Original Question	Production Type	Reliability	Sensitivity	Sample Answers	Production Type	Reliability	Sensitivity
Q4:	If its predecessor activity was done incorrectly, how will this activity be affected?				SOE could be modified to accommodate errors by using different sheet pile size, changing the overall dimension, or changing SOE style (pile and lagging vs. sheet pile, or a hybrid mix-and-match). If pile and lagging option is exercised, lagging construction between the piles would run concurrently with and making inefficient its successor activity, excavation, since additional hand excavation might be necessary. If abutment formwork intended to be supported by or field welded to SOE, SOE redesign may require formwork attachment modifications as well. Don't expect that SOE redesign will require PE stamp of approval; redesign can be performed on the fly in the field. After driving complete, do not expect to need additional surveying unless benchmarks for subsequent work are on the SOE, field surveys will be required to monitor the benchmarks and verify that they are not moving. If after installation moving vehicle or other large object strikes SOE, field survey to verify integrity may be necessary.			
Q5:	Name factors that would create high productivity; Name factors that would create low productivity. What factors are most likely to be encountered?				High productivity – Sand/clay soil properties, no large obstructions, minimum 4 foot offset from adjacent structures or physical constraints. Low productivity – thick clay or gravel soil properties, boulders or large impenetratable obstructions, less than 4 foot offset from adjacent structures or physical constraints or a necessity to demolish an existing structure in the desired location of the SOE. Likely conditions are highly variable.			
Q6:	Are the results/benefits of this activity observed instantaneously, near the start of the activity, near the end of the activity?				SOE is only valuable when fully driven and able to support the design loads; at the end of the activity.			
Q7:	Would an additional labor crew double the expected productivity? Do you expect labor shortage problems?				No; productivity dictated more by the pile driving machinery and the given soil conditions rather than by labor crew size. Yes; hard to find good labor pool.			

		Expected to Address				Actually Addressed		
	Original Question	Production Type	Reliability	Sensitivity	Sample Answers	Production Type	Reliability	Sensitivity
Q8:	Given a changed field condition, will redesign be necessary? Will an owner-directive be necessary? What kind of documentation of the change is necessary? Could work progress in the field uninhibited by the change? Will a corrective action plan be drafted and reviewed? Will traffic management plans need revision? Will community notification be necessary? Could change require revised equipment and labor resource needs? Could additional procurement be necessary?				Given large obstructions, redesign/modifications may be necessary, no owner-directive required, all within MCC's risk/responsibility, corrective action plan waived since work done on the fly. SOE modification required before any further work can proceed, impact on traffic management plan only if traffic shift delayed, no community notification necessary, no change out of equipment expected, no labor crew change necessary, procurement of additional SOE material may be necessary.			
QA:	How much liberty is given to the MCC Team to control work and impacts without owner involvement? What could the weak link be to rapid decision-making?							
QB:	What is the expected level of cooperation with local utility companies? How flexible is the procedure for utility relocations, if changes in the field are encountered? If utility redesign becomes necessary, what will the utility companies require?							
QC:	What known schedule contingencies are in place?							
QD:	Discuss ideal staggering/staging of work. When does overlap of work become impossible?							

DPM MODEL INPUT ELICITATION QUESTIONNAIRE
(as of 26JAN01)

PREDECESSOR-RELATED QUESTIONS

Q1: What are task predecessors? Any related utility work?

Q2: What are necessary material deliveries? What are related shop drawing submittal approvals?

Q3: What if a predecessor activity was changed from the original plan, how will this activity be affected?

Q4: If its predecessor activity was done incorrectly, how will this activity be affected?

TASK SPECIFIC QUESTIONS

Q5: What are the labor and equipment needs? Are they readily available?

Q6: Is the task production instantaneously, completed near the start of the activity, completed near the end of the activity, or generally linear?

Q7: Name factors that would create high productivity; Name factors that would create low productivity. What factors are most likely to be encountered? What are the potential weather impacts and their likely impact to the schedule?

Q8: Would an additional labor crew double the expected productivity? Do you expect labor shortage problems?

Q9: What is the degree of confidence that this schedule activity will be done correctly the first time? Name factors that could contribute to poor workmanship.

Q10: How susceptible is this activity to change, both owner-initiated and due to changed field conditions? If a change occurs, how far will this change ripple through the schedule?

Q11: Given a changed field condition, will redesign be necessary? Will an owner-directive be necessary? What kind of documentation of the change is necessary? Could work progress in the field uninhibited by the change? Will a corrective action plan be drafted and reviewed? Will traffic management plans need revision? Will community notification be necessary? Could change require revised equipment and labor resource needs? Could additional procurement be necessary?

Figure 40: Model Input Questionnaire used during January 26, 2001 Meeting

During this meeting several functional bridge activities were discussed and summarized in Figure 41. Figure 42 clarifies the model input values.

PRIMARY ACTIVITY	Bid-Based Duration	Production Type	Reliability	Sensitivity	Buffering
BRIDGE RELOCATION	BRIDGE RELOCATION	BRIDGE RELOCATION	BRIDGE RELOCATION	BRIDGE RELOCATION	BRIDGE RELOCATION
Bridge Abutment Formwork Erection	236 CH	S - 0.25	0.6	0.75	NA
Bridge Abutment Rebar Installation	Sub-contract	S - 0.25	0.8	0.75	NA
Bridge Abutment Formwork Closure	Not Available	I - 1.0	0.8	0.75	NA
Bridge Abutment Concrete Placement	12 CH	I - 1.0	0.8	0.75	NA
Bridge Abutment Formwork Striping	Not Available	L - 0.5	0.8	0	NA

Figure 41: Treble Cove Bridge Model Inputs – Meeting #1

DPM MODEL INPUT GUIDE

1a: Production Type is based on a 5-point scaling system (1.0, 0.75, 0.50, 0.25, 0.0)

1b: In general, a fast production type is rated as 0.75, linear is 0.5, slow is 0.25, instantaneous is 1.0, and job support or maintenance type activities over a fixed duration is 0.0

1c: If any activity completes in one shift, production type defaults to instantaneous

2a: Reliability is based on a 7-point scaling system (1.0, 0.8, 0.6, 0.5, 0.4, 0.2, 0.0)

2b: In general, highly reliable is rated 0.8, fairly reliable is 0.6, "flip-of-the-coin" is 0.5, fairly unreliable is 0.4, highly unreliable is 0.2, "as-sure-as-a-rocke-blast" or "as-sure-as-a-chemical-reaction" is 1.0, and "luck-of-the-lottery" is 0.0

3a: Sensitivity is based on a 5-point scaling system (1.0, 0.75, 0.50, 0.25, 0.0)

3b: In general, highly sensitive is rated as 0.75, sensitive is 0.5, insensitive is 0.25, absolutely sensitive is 1.0, and absolutely insensitive is 0.0

4: The extreme values of the scaling system (1.0 and 0.0) are more appropriately valued at 0.95 and 0.05, respectively

5: Durations are based on days, derived from bid-based crew hours

6: Durations need to be able to factor in: Weather, Environment (business relationships, locale, site specifics), Variable Productivity (optimistic, pessimistic, most likely)

Figure 42: Model Input Guide

In preparation for the follow-up meeting to complete the elicitation of model inputs for the Treble Cove Bridge, the questionnaire was re-modified in an attempt to better frame the desired elicitations. The revised questionnaire, presented at the February 16, 2001 meeting with MCC, is presented in Figure 43.

DPM MODEL INPUT ELICITATION QUESTIONNAIRE
(as of 16FEB01)

Q1: What is the expected production rate for this activity: slow and steady with a particular inflection point when the rate will change, generally linear, quick out of the gate with production tailing off at the end, or instantaneous? Given a non-linear production rate, what key events modify the production rate?

Q2: What are the key drivers to increase productivity? What are key motivators, de-motivators?

Q3: What key events/factors affect the ability to complete the task efficiently? What events/factors contribute to inefficient task completion?

Q4: What is the likelihood that this scope of work will be completed error-free?

Q5: What is the likelihood that this scope of work will be affected by a change initiated by the designer, by changed field conditions?

Q6: What are some common errors to predecessor scope of work? Can the error be absorbed in the work in progress? Or, will the error initiate rework in predecessor scope of work or modification of the work in progress, which will significantly impact the task duration?

Q7: What are some common changes to predecessor scope of work? Can the changes be absorbed in the work in progress? Or, will the change initiate rework in predecessor scope of work or modification of the work in progress, which will significantly impact the task duration?

Q8: How would an error in this scope of work impact successor activities?

Q9: How would a change in this scope of work impact successor activities?

Q10: How would inclement weather impact this scope of work? How much schedule time could typically be lost to inclement weather?

OVERALL MODEL INPUT PARAMETERS TO KEEP IN MIND

Labor availability, equipment availability, material availability

Figure 43: Model Input Questionnaire used during February 16, 2001 Meeting

During this meeting several functional bridge activities were discussed and summarized in Figure 44.

PRIMARY ACTIVITY	Bid-Based Duration	Production Type	Reliability	Sensitivity	Buffering
BRIDGE RELOCATION	BRIDGE RELOCATION	BRIDGE RELOCATION	BRIDGE RELOCATION	BRIDGE RELOCATION	BRIDGE RELOCATION
Bridge Substructure Setup Workzone	6 CH	L - 0.5	0.8	0.25	NA
Bridge Substructure Install SOE	14 CH	S - 0.25	0.8	0.25	NA
Bridge Substructure Excavation	44 CH	S - 0.25	0.8	0.5	NA
Bridge Superstructure Fab BPads & Girders	Subcontract	L - 0.5	0.8	0.25	NA
Bridge Superstructure Set Bearing Pads	Subcontract	L - 0.5	0.8	0.5	NA
Bridge Superstructure Set Bridge Girders	26 CH	L - 0.5	0.8	0.5	NA
Bridge Superstructure Bolt-up Diaphragms	26 CH	S - 0.25	0.8	0.5	NA
Bridge Superstructure Deck Construction	593 CH	S - 0.25	0.8	0.25	NA
Realign Local Road	132 CH	S - 0.25	0.6	0.5	NA
Demolition of Existing Bridge Structures	18 CH	S - 0.25	0.6	0.75	NA

Figure 44: Treble Cove Bridge Model Inputs – February 16, 2001 Meeting

Table 11: Input Data for the Treble Cove Bridge Model [adapted from Park (2001)]

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	2 ss3	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

* Note

1. Default Precedence Relationship: FS0
2. Genral 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

6.5 TREBLE COVE BRIDGE MODEL INPUTS TO DPM

The knowledge gained through the meetings with contractor was summarized in matrix format (see Table 11) prior to insertion to the DPM, specifically through the population of the smart cells through the web-based portal. Figure 45 is a close-up of the DSM specific for the Treble Cove Bridge model inputs translated from the Table 11 matrix.

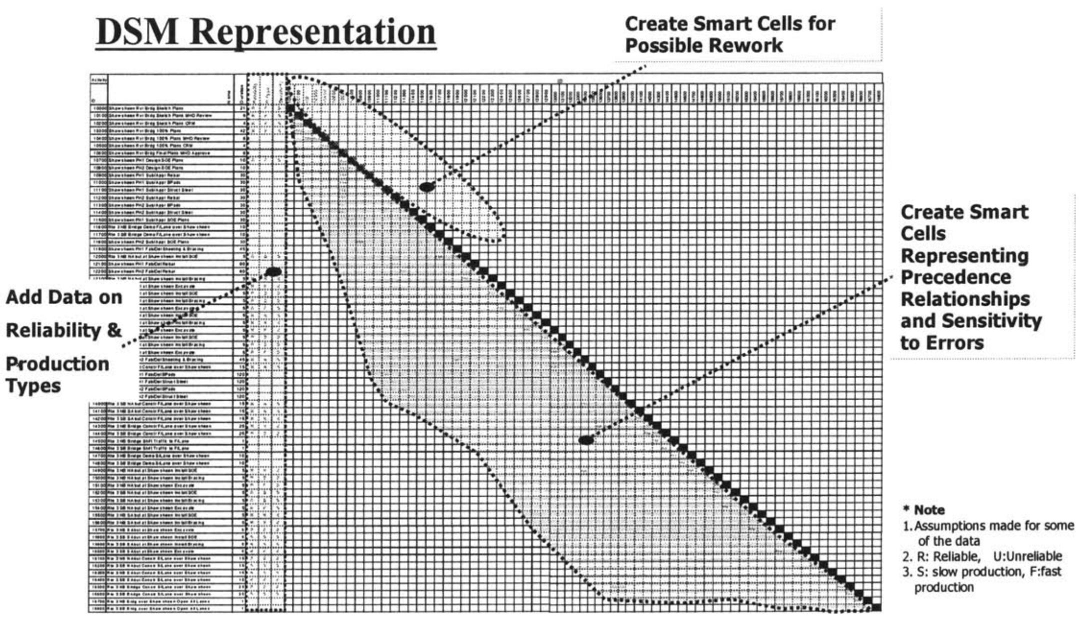


Figure 45: DSM Representation of Treble Cove Model Inputs [adapted from Park (2001)]

6.6 TREBLE COVE BRIDGE MODEL SIMULATION RESULTS

Figure 46 is the graphical layout of the work activities for the Treble Cove Bridge adapted from the construction schedule developed by the contractor utilizing P3, a common commercially available scheduling software application. Figure 47 is the construction schedule generated by DPM using the same source information as P3 supplemented by the information elicited from the interviews with the contractor.

Activity ID	Activity Description	Orig Dur
1	Sketch Plans	33
2	Final Plans	66
3	ROW Acquisition	130
4	Shop Drawing Submittals	35
5	Shop Drawing Review/BPads	30
6	Shop Drawing Review/Struct	30
8	Shop Drawing Review/SOE	30
7	Shop Drawing Review/Rebar	30
10	Steel Fabrication/BPads	120
11	Steel Fabrication/Strutural Steel	120
9	Steel Fabrication/Rebar	60
12	Steel Fabrication/Sheet &	45
13	Prepare Site for Abutment E/W	33
14	Prepare Site for Center Pier	13
15	Construct Abutment E/W	30
16	Construct Center Pier	15
17	Set BPads and Girders	5
19	Bell Telephone Cable	80
18	Construct Superstructure	20
20	Relocate Gas Line	15
21	Relocate Water Line	15
22	Install Telephone DB	15
23	Realign Treble Cove Rd	10
24	Realign Rte 3 NB Ramps	20
25	Realign Rte 3 SB Ramps	20
26	Demolish Existing Ctr Span	10
27	Demolish Existing EAbut	10
28	Demolish Existing WAbut	10

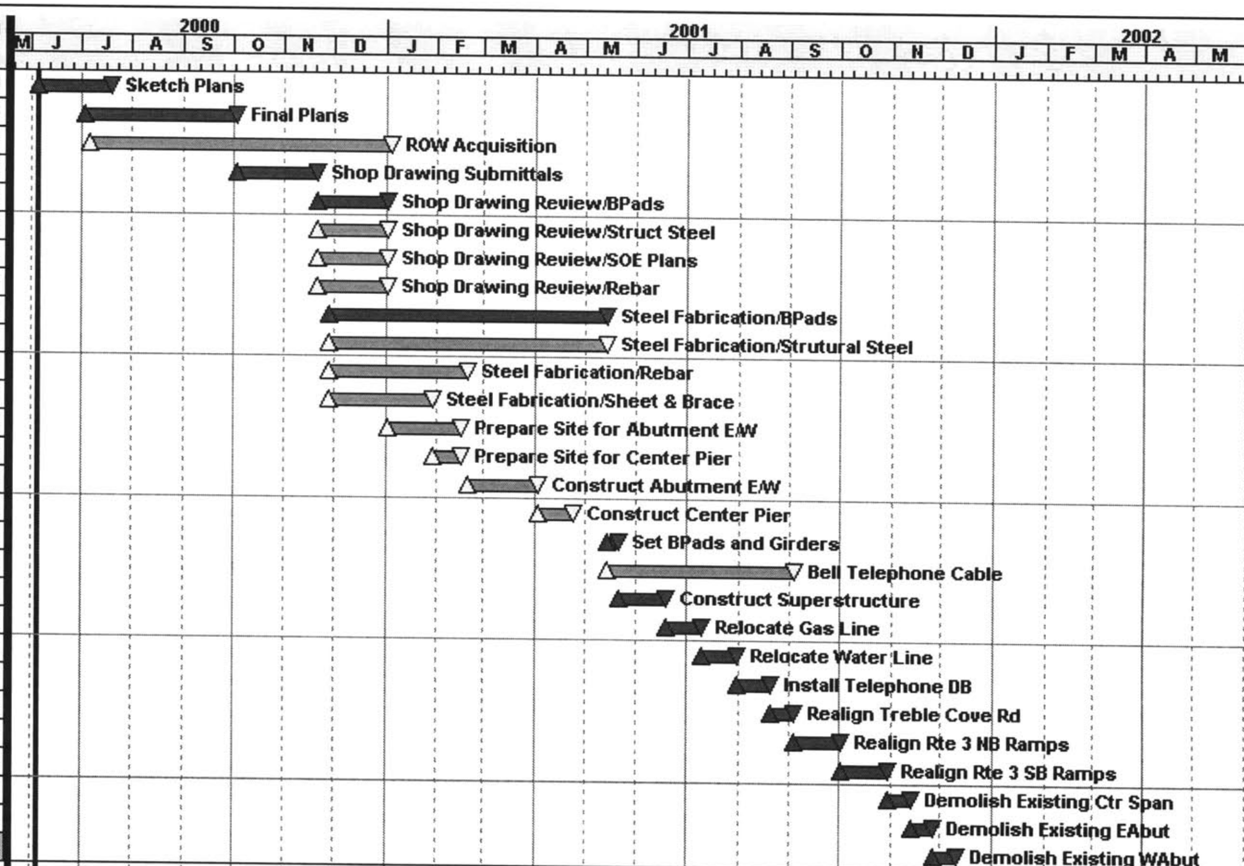


Figure 46: Primavera-Generated Activity Durations [adapted from Park (2001)]

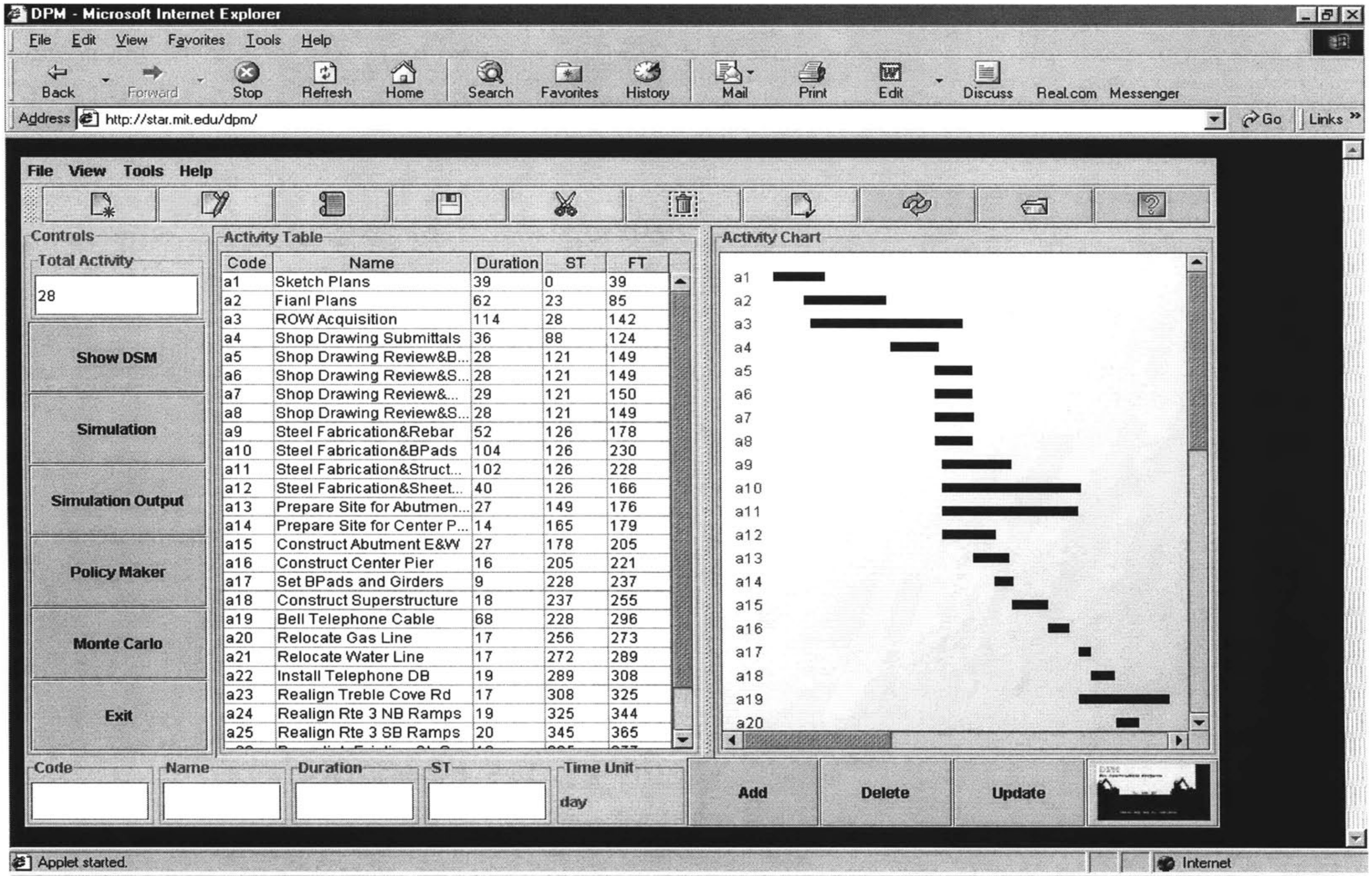


Figure 47: DPM-Generated Schedule for Treble Cove Bridge [adapted from Park (2001)]

Figure 48 is a snapshot of a DPM sample simulation graphical output comparing the change in value of several model variables across the time horizon used in the model. The base project progress without reliability buffering (blue cumulative line) is provided for comparison purposes against the project progress curve utilizing reliability buffering (bold red cumulative line). In addition, the variables for "Remaining Pool Buffer Ratio" and "Workforce Utilization" have been graphed along with the progress curves. In this snapshot the "Remaining Pool Buffer Ratio" is the graph that steps down across time and the "Workforce Utilization" has a lot of variability across time, generally decreasing across time.

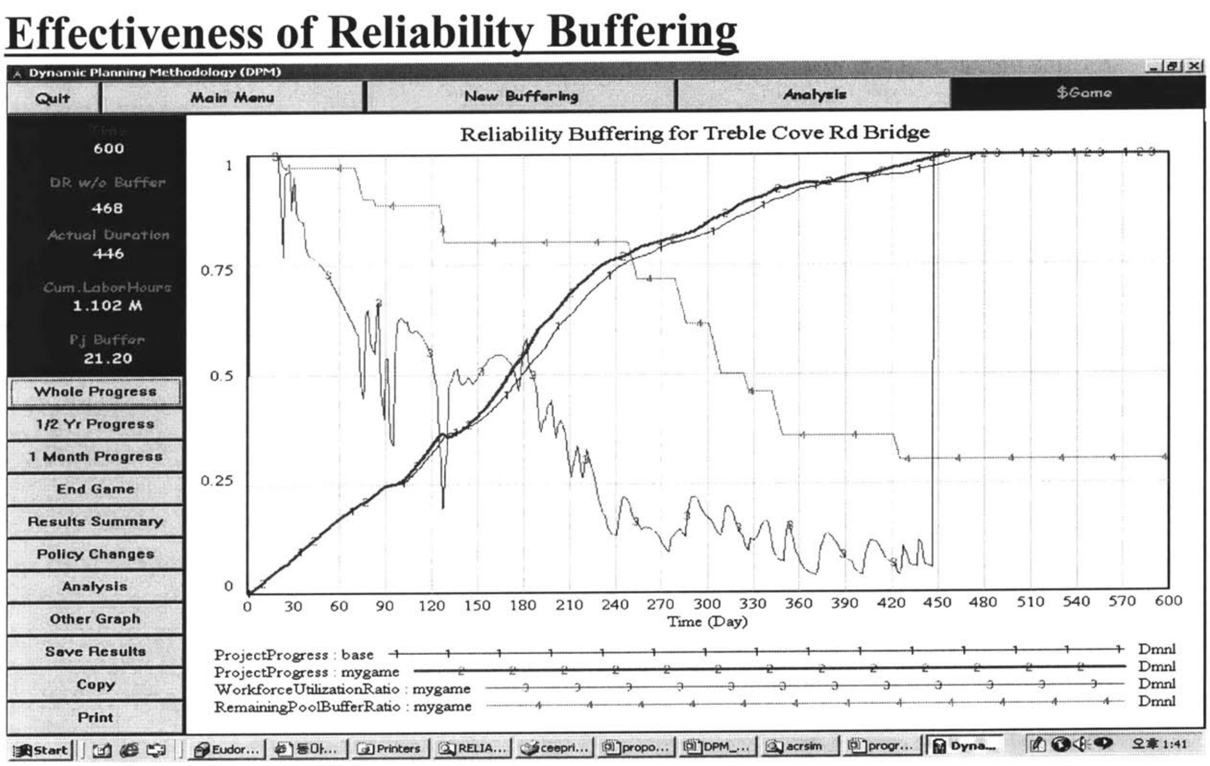


Figure 48: Sample Simulation Run Graphical Output [adapted from Park (2001)]

Figure 49 is a snapshot of the DPM results in a tabular format. This format includes the start time and finish time for each schedule activity along with the summary of the quantity of reliability buffer and the activity duration.

Simulated Performance Including Reliability Buffer

Activity Name(code)	ST	FT	RB	DR
Land Acquisition SB(a1)	0	89	0	89
Land Acquisition NB(a2)	0	89	0	89
Sketch Plan(a3)	0	23	0	23
Sketch Plan MHD Review(a4)	23	29	0	6
100% Plan(a5)	23	75	2	52
Sketch Plan CRM(a6)	29	35	0	6
100% MHD Review(a7)	75	83	1.4	8
100% Plan CRM(a8)	83	89	0	6
Final Plan MHD Appr(a9)	89	95	0	6
Design SOE Plans(a10)	95	109	0	14
Sub/Appr BPads(a11)	95	128	0	33
Sub/Appr Struct Steel(a12)	95	128	0	33
Sub/Appr Rebar(a13)	95	127	0	32
Sub/Appr SOE Plans(a14)	95	127	0	32
Fab/Del Rebar(a15)	127	191	4	64
Fab/Del B Pads(a16)	128	254	3	126
Fab/Del Struct Steel(a17)	128	254	3	126
Fab/Del Sheet & Brace(a18)	127	177	4	50
Bridge Realign(a19)	349	371	2	22
EAbutSetup WorkZone(a20)	177	191	0	14
EAbut Install SOE(a21)	177	194	0	17
WAbutSetup WorkZone(a22)	191	210	1	19
EAbut Excavate(a23)	180	201	1	21
WAbut Install SOE(a24)	194	211	1	17
WAbut Excavate(a25)	197	214	0	17
Center Pier Install SOE(a26)	211	226	0	15
Center Pier Excavate(a27)	214	231	0	17
Construct New EAbut(a28)	201	218	0	17
Construct New WAbut(a29)	218	241	2	23
Construct New Ctr Pier(a30)	241	259	0	18
Not/BA for Relocation(a31)	254	255	0	1
Construct Supter Str(a32)	254	286	0	32
Bell Telephone Cable(a33)	275	354	0	79
Relocate Gas Line(a34)	286	309	0	23
Relocate Water Line(a35)	309	327	0	18
Install Telephone DB(a36)	327	349	1	22
Reallg Rte 3 NB Ramps(a37)	371	401	2	30
Reallg Rte 3 SB Ramps(a38)	401	425	0	24
Shift Traffic to New Br(a39)	425	426	0	1
Demo Existing Ctr(a40)	426	436	0	10
Demo Existing EAbut(a41)	436	446	0	10
Demo Existing WAbut(a42)	446	456	0	10

Figure 49: Tabular Result of Treble Cove Model Simulation [adapted from Park (2001)]

6.7 SHAWSHEEN RIVER BRIDGE MODEL INPUTS TO DPM

Extrapolating the model inputs from the Treble Cove Model as appropriate, the model inputs for the Shawsheen River Bridge Model would be as illustrated in Figure 50.

PRIMARY ACTIVITY	Bid-Based Duration	Production Type	Reliability	Sensitivity	Buffering
BRIDGE WIDENING	BRIDGE WIDENING	BRIDGE WIDENING	BRIDGE WIDENING	BRIDGE WIDENING	BRIDGE WIDENING
Demolition of Fast Lane on Existing Bridge	20 CH	S - 0.25	0.6	0.75	NA
Bridge Substructure Install SOE	30 CH	S - 0.25	0.8	0.5	NA
Bridge Substructure Excavation	28 CH	S - 0.25	0.6	0.75	NA
Bridge Substructure Construct Bridge Abutments	153 CH	S - 0.25	0.8	0.5	NA
Bridge Superstructure Fast Lane Construction	1000 CH	L - 0.5	0.8	0.25	NA
Traffic Switch to Newly-Constructed Fast Lane	32 CH	L - 0.5	0.8	0.25	NA
Demolition of Slow Lane on Existing Bridge	20 CH	S - 0.25	0.6	0.75	NA
Bridge Substructure Install SOE	30 CH	S - 0.25	0.8	0.5	NA
Bridge Substructure Excavation	28 CH	S - 0.25	0.6	0.75	NA
Bridge Substructure Construct Bridge Abutments	153 CH	S - 0.25	0.8	0.5	NA
Bridge Superstructure Slow Lane Construction	1000 CH	L - 0.5	0.8	0.25	NA

Figure 50: Shawsheen River Bridge Model Inputs from Extrapolation

6.8 SHAWSHEEN RIVER BRIDGE MODEL SIMULATION RESULTS

Simulation results for the Shawsheen River Model were not developed within this thesis. The author welcomes a follow-up from an eager student to execute the model inputs to generate the simulation results.

CHAPTER 7

TRANSITION OF THE METHODOLOGY FROM RESEARCH TO PRACTICAL APPLICATION

This chapter outlines the efforts to date by the research team to transition this research to practical applications in the construction industry. Why does the research team endeavor to transition the technology from research to practical applications? It is the firm belief of the research team that the construction industry lacks the tool that we endeavor to create to properly control and manage the execution of large-scale projects. It is through our efforts that the industry will have access to this advanced project management tool that will provide meaningful decision-supporting results, which in turn will lead to more profitable projects.

7.1 INCORPORATING PROJECT DATA INTO THE MODEL

Over several progress meetings with the case study contractor, the research team has collected project data resident in existing software systems as well as project data that currently reside with the individuals tasked to execute the project. This data has been incorporated in the model as appropriate. These meetings are a litmus paper with respect to the level of effort needed to extract the project data required by the DPM model. At this time, it does not appear that the existing project management process was compromised by the research teams involvement to extract the project data.

7.2 MODEL CALIBRATION TO ACTUAL PERFORMANCE

At this point in the research, the model has not yet been calibrated against actual data and performance. The project data entered is for future construction work that has yet to commence in actuality. The research team has been provided project data of actual work performed, but the research team has not yet incorporated this data into the model. Model calibration is forthcoming. It is anticipated that the calibration will be in two forms: calibration of table functions and calibration of model algorithms.

At this time the model algorithms weigh the contribution of model variables to a single model variable in a mathematically specified matter. In other words, several variables contribute to the behavior of another single variable, but the weighting of the individual contributions to the model variable has not been fully tested. In order to ensure the model accurately replicates past performance, calibration of both table functions and model algorithms are still required.

7.3 MODEL CALIBRATION TO ENSURE REASONABLE FORECASTS

Model calibration serves two purposes: first, validation that actual performance can be replicated and second, that these algorithms can with reasonable expectations accurately and reliably forecast future performance. Calibration to actual performance increases reliability on future projections, given reasonable expectations that not every future event can be planned or anticipated. Given that the model has not yet been calibrated to actual performance, the current model outputs of performance projections should be evaluated in terms of broad, general expectations.

7.4 DISCLOSING THE TECHNOLOGY

At this time the technology developed by the research team has been disclosed for purposes of filing a technology patent. The disclosure of the technology reveals to entities outside the research institution of the methodology developed. This is the first step in protecting the intellectual property created at the institution. This is a prerequisite for filing a patent to protect the intellectual property created at the research institution from other entities that may develop similar intellectual property.

7.5 PATENTING THE TECHNOLOGY

The process of patenting the technology involves several steps: disclosing the technology, researching the database of patents approved to avoid potential infringement of existing technology, developing claims that distinguish this technology from other existing or non-existing technologies, and filing a patent, in the case of this technology, with the United States Patent and Trademark Office. This research team chose to file a provisional patent application prior to a full patent application in order to protect the intellectual property while the final details on the technology claims and referenced patents are further and completely developed. In the case of this technology, a patent attorney has been engaged to provide legal support and advice and assist in both the provisional and full patent application submittals. It should be noted that the patent applicant is the Massachusetts Institute of Technology (M.I.T.) and the inventors are Dr. Feniosky Peña-Mora and Dr. Moonseo Park.

7.6 ELICTING INTEREST FROM THE CONSTRUCTION INDUSTRY

With the technology protected, the research team sought interest from the construction industry, the main industry that the research targets. Through informal focus groups, the research team can reasonably predict that that construction industry has strong interests in the potential of the technology being applicable to practical usage by the industry. Several discussions with various industry entities confirm the research team's belief that this technology will be well received by the construction industry. The important steps in the implementation process will be its flexibility, accuracy, and most importantly, ease of use.

7.7 ELICTING INTEREST FROM EXISTING SOFTWARE VENDORS

At this time the research team has provided a general overview of the technology developed to an existing estimating software developer. This particular vendor has expressed strong interest in keeping abreast of new developments and when and how the two systems can be incorporated. The research team expects to reach out to other existing software vendors, when the time is appropriate, to illicit further interest in the technology and how to properly integrate the systems for meaningful results.

7.8 REFINING THE TECHNOLOGY

It is expected that even after model calibration some level of model refinement should be expected. It is unknown at this time to what extent this effort will entail. It will be clearer after the model calibration phase is successfully completed.

7.9 PACKAGING THE TECHNOLOGY

The research team intends to direct most of its immediate efforts on the user interface to the DPM model. Ease of use is a paramount issue to ensure successful implementation and market penetration of the technology to the construction industry. Our focus will be to create an interface that is relatively intuitive and that the output results are meaningful. The user will engage with the DPM model through project management leverage points that again are intuitive.

7.10 MARKETING THE TECHNOLOGY

Selling the concept and penetrating the market are the final steps in the conversion of the research efforts to a commercially viable product that a potential customer can purchase. At this time the marketing strategy has not been fully developed. This effort is expected to be initiated in earnest when the refining and packaging of the model is further developed.

CHAPTER 8

CONCLUSIONS

In conclusion, market demands for maximum results at minimum costs are expected to continuously increase; the construction industry is no exception. Producing a quality product in the least amount of time for the least amount of money continues to challenge project managers day-to-day, and project-to-project. Concurrently, orchestrating such a production becomes more complex as the project dynamics increase and work activities overlap impacting additional work activities. To keep up with such complex and variable project dynamics, DPM has been developed to address these conditions head on. A superior alternative to the traditional network-based approaches as well as the simulation-based approaches developed to date, DPM uses a user-defined modeling approach, considers dynamic feedbacks among variables, and reduces sensitivity to changed conditions (both intentional and unintentional). These fundamental concepts and logics have been materialized by incorporating reliability buffering contents and concurrent engineering principles into system dynamics models and schedule networking concepts of CPM, PDM, PERT, GERT, and SLAM. Moreover, DPM is intended to serve as both an initial planning tool as well as a control tool during project execution.

8.1 POTENTIAL IMPACT

If the construction industry embraces DPM, current industry standards would be shattered. For example, the concepts of total float, free float, float suppression, and use of project float will need modification, and the concept of critical path would be replaced by critical band activities.

DPM will give project managers the tool to simulate various project scenarios to select among a number of options to keep in line with various project objectives. DPM can be utilized as a management tool offering multiple insights to innovative and cost-effective means to get the job done on-time, within budget, and safely, while building a quality product.

The simulation results generated by DPM offer quantifiable measures in contrast to the limited empirical analyses used for common benchmark analyses, such as loss of productivity, or where empirical analyses are not even available. In addition, DPM offers insight to management's leverage points to ensure effective policies are implemented.

8.2 APPLICABILITY

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. For example, SLAM [Pritsker, 1994] and STROBOSCOPE [Martinez, 1996] provide an integrated simulation environment, in which users can model project development processes using graphic representations of simulation components. However, the use of those tools still requires a lot of modeling experience, making it difficult for users (presumably, construction managers or engineers) without having modeling skills to apply them to construction [Peña-Mora and Park (2001)].

DPM will improve upon the current management tools used to plan efficient operations, track and maintain planned productivity, and manage schedule and cost impacts. DPM will offer a significant advancement in planning and controlling processes and work activities, which are subject to multiple changes. During the planning process, DPM will identify opportunities to plan work activities and optimize work sequences subject to limited and variable resources.

During project execution, the change events can be tracked to more accurately assess the ripple effect on the overall system. Importantly, DPM will offer management the ability to adjust for a change in the "to-go" plan through the most cost-efficient and productive means available. Lastly, the actual performance will be retained providing the means for continuous improvement, thereby closing the feedback loop. DPM provides a robust plan to absorb both potential and unforeseen impacts to the project cost and/or project schedule. DPM facilitates on-time project delivery within an established budget for large-scale infrastructure projects by enhancing planning, monitoring and control capabilities. With the adoption of DPM, the management team will have a tool adaptable to changing circumstances that includes past resource experiences, continuously updated with current and relevant experiences. DPM can be integrated with a firm's existing estimating and costing system thereby expanding the knowledge base for future applications.

8.3 FURTHER DEVELOPMENT

While this thesis addressed the challenges of eliciting project information for input to DPM, calibration of forecast to actuals was not completed within this thesis submittal. Calibration of the simulated environment to actual conditions experienced by the contractor is an important area for further research development.

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