STUDY OF TIME EXTENSIONS AND THE COST IMPLICATIONS IN CONSTRUCTION PROJECT SCHEDULING

SIU, MING FUNG

M.Phil

THE HONG KONG POLYTECHNIC UNIVERSITY

2011

The Hong Kong Polytechnic University

Department of Civil and Structural Engineering

Study of Time Extensions and the Cost Implications in Construction Project Scheduling

SIU, Ming Fung

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Philosophy

June 2011

CERTIFICATE OF ORIGINALITY

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ABSTRACT

Despite meticulous planning effort, extension to project completion time is commonplace on real-world construction projects due to increased scope and complexity of work at activity levels and lower productivity resulting from a wide range of practical constraints related to environment, equipment, labor, materials, and management. The project time extension (PTE, representing project delay) is largely attributed to activity time extensions (ATE, representing activity delay) which occur on multiple activities during the execution stage of a construction project. Time extension and the associated cost overspend are generally indicative of flawed project execution or potential project delivery failure in project management. Effective time control is vital to project planning, monitoring and control.

Approaches that are currently and commonly used for scheduling analysis in qualifying project and activity time extensions, such as critical path method (CPM) and earned value management (EVM), are analytically convoluted. In the traditional CPM framework, activity total float (TF) represents the amount of time by which an activity can be delayed without extending the scheduled project time. This classic definition fails to cope with project time extension effects resulting from complicated relationships between project and activity delays. On the other hand, earned value management

(EVM) assumes an ideal baseline schedule and thus is inadequate to tackle resource-constrained scheduling under delayed scenarios.

The focus of this research study has been therefore narrowed down to refining the TF definition in the CPM framework and improving the EVM framework, by characterizing the relationships between activity time extension (ATE) and project time extension (PTE). In this study, scheduling simulations are employed for accurate schedule analysis as the CPM schedule, in practice, entails imposing resource constraints on construction projects. Such constraints include resource daily available limits and non-working time defined by resource calendars. Commonly used scheduling simulation tools, Primavera® P3™ Project Planner (*P3*), is used to generate resource-constrained schedules in this research study.

The relationships between ATE and PTE are contrasted using evidence obtained from a simple project which is taken from Kraiem and Diekmann (1987). The results prove that the PTE-ATE relationship function exhibits high non-linearity when activity calendar constraints are imposed. Based on the in-depth understanding of ATE and PTE relationships, simulation-based activity TF determination methodologies are developed in this research to enable effective project time extension planning and control. TF, which is a non-negative activity attribute, provides a time control measure to control the

ATE and achieve the objective of avoiding or minimizing PTE. The algorithm is proposed to determine TF given a particular PTE level. Further, the algorithm is proposed to cope with a set of delayed activities, each of which experiences a certain level of ATE. The proposed TF determination methodologies provide the flexibility to characterize the relationships between project delay and multiple activity delays for a specific scenario. The simulation-based TF determination methodologies were successfully implemented on a highway widening construction project. The potential applications of project completion time control and activity delay analysis were demonstrated. The results prove that for a particular set of delayed activities, the ATE can be controlled based on TF evaluated by proposed methodologies, given a particular PTE level.

Project cost increase is generally a by-product of project time extension. The schedule and cost management integrated approach of EVM is currently widely utilized in tracking the project schedule and cost performances. It is found that EVM can only be applied to ideal scheduling scenarios without practical constraints and complicated activity-project delays. The EVM fails to account for dynamic changes of project status in terms of project time extension and cost overrun, potentially generating misleading project performance tracking indicators. Hence, EVM is refined based on an in-depth understanding of ATE and PTE gained in the TF determination study. This improved simulation-based approach was successfully applied in a simple project taken from Ahuja et al. (1994). The results indicated that this established EVM approach is conducive to truthfully reflecting the project performance status given a resource-constrained schedule subject to complicated activity-project delay scenarios. However, limitations are identified in terms of quantitatively assessing the project performance by tracking scope change, work done and actual expenses on a continuous basis; and seamlessly connecting EVM indicators with TF determined from schedule simulations. Those limitations present further research opportunities in the future.

Simulation-based activity total float determination methodologies and an enhancement of earned value management for time extension planning, tracking and control have been developed in this research. The newly developed methodologies, the complete project data set plus observations and findings generalized from case studies will add to the body of knowledge in project management. The deliverables and findings from this study will benefit construction practitioners in planning and control of challenging resource-constrained construction projects, providing a broader view of activity and project time extension analysis and the associated cost implications in construction project scheduling.

PUBLICATIONS

Technical Papers in Referred Journals

- Lu, M., **Siu, M. F.** and Chau, K. W. (2011) “Characterization of Project Time Extension Effects Resulting from Multiple Activity Delays on Resource-Constrained Construction Schedules.” *Journal of Construction Engineering and Management*, ASCE. (Under Review)
- **Siu, M. F.** and Lu, M. (2011) “Revisiting Total Float for Controlling Project Time Extensions on Resource-Constrained Construction Schedules.” *Journal of Construction Engineering and Management*, ASCE. (Under Review)

Conference Papers in Referred Proceedings

- **Siu, M. F.** and Lu, M. (2011) “Scheduling Simulation-Based Techniques for Earned Value Management on Resource-Constrained Schedules under Delayed Scenarios.” *Proceedings of Winter Simulation Conference 2011*, Dec. 11–14, 2011, Phoenix, Arizona, The United States of America. (In Press)

ACKNOWLEDGEMENTS

The content of this thesis would not have to come to reality without the strong research and teaching support of Dr. M. Lu (formerly affiliated with The Hong Kong Polytechnic University; currently with University of Alberta, Canada). We have been together in lectures, discussions about construction management research and many personal issues which are a part of life of all students. We have travelled together to conferences in such as Japan and have had fun with his family. These valuable memories always flash into my mind when research difficulties seemed overwhelming. His continual support and trust have enhanced not only my academic development and research criticality but also have contributed to the maturity necessary to cope with the rest of my life.

I wish to acknowledge the followings who have helped me with completing this thesis. Prof. K. W. Chau (The Hong Kong Polytechnic University) facilitated my research by providing technical advice, managing the financial accounts and administrating my industrial and academic examinations; Mrs. E. Anson (The Hong Kong Polytechnic University) supported me in the advancement of my undergraduate final report and postgraduate thesis, on one occasion in a coffee bar at midnight. She helped improve my technical writing skills and has been an emotional support during the study; Prof. M. Anson (The Hong Kong Polytechnic University) inspired my critical thinking in my research area and offered advice on the direction of my career; Thanks are also due to Dr. S. L. Tang (City University of Hong Kong) who transferred his management research knowledge to me as references; I would also like to express my heart-felt appreciation to the external examiners of my thesis: Prof. de la Garza (Virginia Tech) and Dr. X. Q. Zhang (Hong Kong University of Science and Technology). Thanks for their time and effort in providing comments for improving this thesis to the highest standard.

Thanks are also due to the research group members, including Dr. F. Dai, Dr. X. S. Shen, Mr. X. Liang, Mr. S. C. Lau, Mr. H. C. Lam, Mr. W. H. Chan, for their help and collaboration. Research meetings and constructive discussions helped drive this research. I also much appreciated the weekly games of squash which kept me physically healthy.

Over the past few years of research, I have developed close industrial partnerships with engineers and managers of leading construction companies in Hong Kong. I would like to express my sincere gratitude to all who facilitated my research work on construction sites, including Mr. M. F. Tang (Kin Wing Engineering Company Limited); Mr. Joseph H. Y. Kong and Mr. Lotus C. W. Au Yeung (Kum Shing Construction Company Limited); Mr. Eric K. I. Lo and Mr. William W. Y. Leung (Black & Veatch Hong Kong

Limited); Mr. Stephen K. K. Cheung (Leighton Contractors (Asia) Limited); Mr. C. S. Cheung (Ove Arup & Partners Hong Kong Limited); Mr. Parker W. L. Ko (MTR Corporation Limited); and Mr. Paul K. F. Yau and the associated geotechnical team members (Meinhardt (C&S) Limited).

Most importantly, I would like to express my deep appreciation of the love and constant support, both emotional and financial offered by my partner, Miss Candy K. M. Yeung. Her companion has greatly enhanced my confidence, health and happiness. She provided me with shelter during an exceptionally difficult time, when I was totally without any other form of support. Candy, herself, helped relieve my financial burden by sharing her financial academic scholarship. Her patience and tolerance have contributed greatly in the advancement of my academic research studies.

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CHAPTER 1

INTRODUCTION

This chapter provides the research problem statement, research objectives and thesis organization.

1.1 Problem Statements

Despite meticulous planning effort, extension to project completion time is commonplace on real-world construction projects due to increased scope and complexity of work at activity levels and lower productivity resulting from a wide range of practical constraints related to environment, equipment, labor, materials, and management. The project time extension (PTE, representing project delay) is largely attributed to activity time extension (ATE, representing activity delay) which occur on multiple activities during the execution stage of a construction project. Time extension and the associated cost overspend are generally indicative of flawed project execution in project management. Effective time control is vital during project planning, monitoring and controlling stages. Approaches, currently and commonly used for scheduling analysis, critical path method (CPM) and earned value management (EVM), qualifying project and activity time extensions are analytically convoluted. Activity total float (TF) in traditional CPM framework fails to cope with the time extension owing to project and activity delays, while EVM assumes an ideal baseline schedule, is inadequate to tackle resource-constrained scheduling under delayed scenarios. The research objectives to be addressed in this research study are refining the TF definition in the CPM framework and improving the EVM framework, by characterizing the relationships between activity time extension (ATE) and project time extension (PTE).

1.2 Research Objectives

The research objectives are as follows:

1. To investigate and characterize the relationships between activity time extension and project time extension
2. To refine the activity total float definition in the critical path method framework and propose activity total float determination methodologies, based on the relationships between activity time extension and project time extension
3. To improve the earned value management in connection with activity time extension and project time extension in order to better cope with delay scenarios

1.3 Thesis Organizations

This thesis contains 6 chapters to cover literature review, research problem formulations, methodologies developments, summary of results and contributions achieved.

Chapter 1 introduces the problem statement related to the present study. The research objectives are identified based on the background described.

Chapter 2 gives the past and current scheduling research endeavors and fundamental understandings of construction management terminology. The graphical techniques for presenting a schedule network, named as activity-on-node (AON) diagram and precedence diagramming method (PDM), are introduced. Overview of project scheduling analysis technique, critical path method (CPM), is included. The CPM analysis and total float (TF) evaluation supported by the mainstream computer software subject to resource-constrained schedule are discussed. Another analytical technique named as earned value management (EVM) is also demonstrated, followed by reviewing the EVM applications on construction project in connection with project time extension. Concluding remarks are given in a summary of the research scope and focuses, and suggestions made for further development.

Chapter 3 is written based on a paper entitled "*Revisiting total float for controlling project time extensions on resource-constrained construction schedules*", submitted to *Journal of Construction Engineering and Management***,** *ASCE* for publication. This chapter introduces a new methodology for determining the total float (TF) for individual activities based on the relationships between activity time extension (ATE) and project time extension (PTE). The linear and non-linear relationships between ATE and PTE are contrasted in straightforward CPM analysis and CPM analysis under resource constraints based on scheduling simulation. Further demonstrations of how to determine TF in multiple project time delay scenarios in practical applications are given.

Chapter 4 is adapted from a paper entitled "*Characterization of project time extension effects resulting from multiple activity delays on resource-constrained construction schedules*", submitted to *Journal of Construction Engineering and Management*, *ASCE* for publication. This chapter furthers the TF determination problem defined in the Chapter 3 which concerns the delay on one activity at a time, and deals with a more complicated yet more realistic project scheduling setting that involves multiple activity delays on a resource-constrained schedule. If activity delays for each activity involved occur on a project resulting the time extension, how much float time is allowed on each activity involved such that a particular level of project time extension will not be prolonged further? Similar to Chapter 3, the PTE-ATE relationships are firstly characterized, followed by proposing a procedure to define TF given a particular PTE level and a particular set of delayed activities, each of which experiences a certain level of ATE. Practical applications of the proposed methodology are demonstrated.

Chapter 5 is edited based on an accepted paper entitled "*Scheduling simulation-based techniques for earned value management on resource-constrained schedules under delayed scenarios*" published in *Proceedings of Winter Simulation Conference 2011*, *Phoenix*, *Arizona*, *The United States of America*. This chapter gives an improved EVM methodology, in connection with activity time extension and project time extension. Applications of this established approach on a resource-constrained schedule under delay scenarios are described and the deficiencies of EVM indicators are revealed.

Chapter 6 gives the summary of the thesis and recapitulates the contributions of this research study.

Appendix A presents the details of a highway widening construction project, including the activity and resource requirements.

Appendix B gives the features and interfaces of commonly used scheduling simulation tools, including Primavera® P3™ Project Planner (*P3*), and Primavera® P6™ Project

Management (*P6*).

CHAPTER 2

RESEARCH BACKGROUND AND LITERATURE REVIEW

Project planning, monitoring and control are essential steps in construction engineering and management. To deliver a successful project, time and cost objectives must be fulfilled. Regular checking, adjustment, re-planning and execution are often made to the schedule. The schedule is used as a guide to control the pace of activities and to enable timely completion (Nunnally 2001). This chapter provides the past and current scheduling research endeavors and fundamental understandings of construction management terminology. The graphical techniques for presenting a schedule network, named as activity-on-node (AON) diagram and precedence diagramming method (PDM), are introduced. Overview of analytical technique, namely critical path method (CPM), for project scheduling analysis is included. Computer scheduling software is introduced for automatic CPM scheduling analysis. The traditional CPM analyses and the resulting TF values applied on convoluted resource-constrained schedule are discussed. Another analytical technique named as earned value management (EVM) is also demonstrated. The EVM applications on construction project with time extension are reviewed. The concluding remarks are drawn in the form of giving a summary of the research scope and focuses, and suggestions made for further development.

2.1 Project Scheduling Network Representation

To express the scheduling network, activity-on-node (AON) diagram and precedence diagramming method (PDM) network diagram are introduced. Professor John W. Fondahl proposed the AON diagram in 1961 (Fondahl 1987, 1991). The AON diagrams directly places the activity on the node as shown in Fig. 2.1. The arrows illustrate activity dependencies and only the finish-to-start (F/S) relationship is allowed. Further, the PDM introduced by H. B. Zachry in 1964 (O'Brien and Plotnick 2010), utilizes smart activity relationships to sequence activities and express the project scheduling network. The smart relationships include start-to-start (S/S), finish-to-finish (F/F), start-to-finish (S/F) and finish-to-start (F/S). The lead and lag time can be imposed to allow for concurrent activity executions. For instance, the activities A and B are concurrently executed two days after the start of Activity A (Fig. 2.2). The activity fragmentations are avoided by using the PDM. Both AON and PDM maintain the technology constrained precedence relationships. They are two predominant tools for representing project scheduling network.

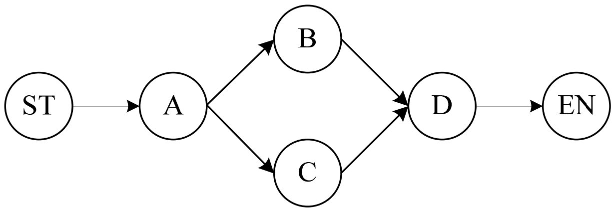


Fig. 2.1: AON network diagram

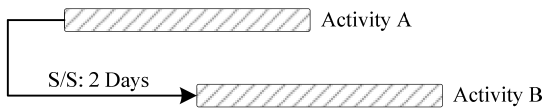


Fig. 2.2: PDM network diagram

2.2 Critical Path Method for Project and Activity Time Analysis

The wide adoption of critical path method (CPM) for project scheduling originated in 1950s, and was formalized by Morgan R. Walker of DuPont and James E. Kelley, Jr. of Remington Rand (Kelley and Walker 1959). CPM has a widespread use in construction applications. The method is applied to calculate the activity early start time (ES) and late start time (LS), early finish time (EF) and late finish time (LF), by forward and backward passes as shown in Fig. 2.3 (a) and (b) respectively. The analyzed schedule is used to estimate the planned activity start and finish time as well as project completion time.

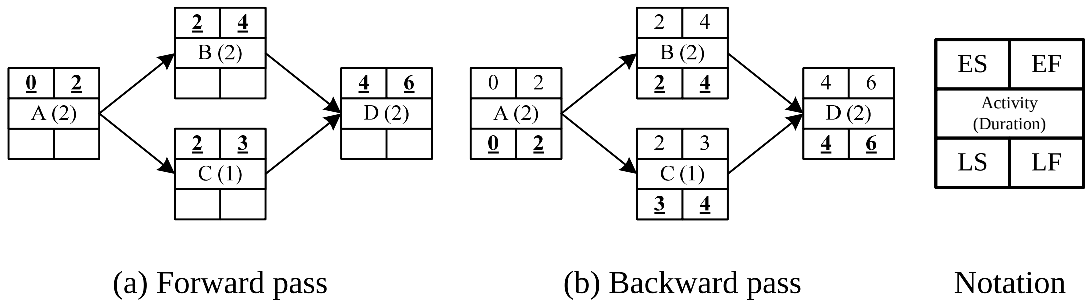


Fig. 2.3: CPM forward and backward passes

As a result of the CPM, TF can be calculated as the difference between ES and LS, or EF and LF as Eq. (2.1). The TF, which is attributed to individual activities, represents the amount of time by which an activity can be delayed without extending the scheduled project completion time. The TF serves as a cushion to absorb activity suspension and delay during project execution. Critical path forms by joining the activities own zero TF. For instance, Activities A, B, C and D composes the project scheduling network as shown in Fig. 2.3, by Eq. (2.1), the TF of Activities A, B and D are calculated as 0 day, while activity C owns 1-day TF. This implies activity C can be delayed for one day without affecting the 6-day project completion time. The Path A-B-D is the critical path. Further *e*-day activity time extension (ATE) results in *e*-day project time extension (PTE). This linear relationship is valid for non-resource-constrained schedules. The CPM scheduling software, Primavera® P3™ Project Planner (*P3*) and the Primavera® P6™ Project Management (*P6*), has currently evolved. The computerization takes advantage of automatic and accurate scheduling analysis, in terms of increasing construction process complexity.

$$TF = LS - ES = LF - EF \tag{2.1}$$

This traditional CPM is only valid when the schedules are non-resource-constrained (Hegazy 1999). The techniques can be well-applied in non-resource-constrained schedules without considering any limited resource availabilities and multiple calendars during project execution. A continuous form of critical path can always be found. The TF evaluated is useful for controlling activity and project delays. However, this traditional approach has limited values in addressing resource-constrained schedules in practical construction scheduling (Fondahl 1961).

2.3 Critical Path Method subject to Resource-Constrained Schedules

On construction projects, driving resources including skilled laborers and equipment collaborate on a particular activity and are engaged for certain time duration in order to accomplish activity completion. Matching driving resources for activity execution is analogous to scheduling a “meeting” on time slots when all the resources involved are commonly available (Lu et al. 2008). However, to complicate the scheduling analysis, various driving resources may have different daily provision limits and operate on different work-day calendars. The inevitable interruptions on activity progress due to matching resources could make CPM analysis inaccurate, and the resulting TF values do not hold traditional definitions and thus become confusing (Lu and Li 2003; Kim and de la Garza 2005). These researchers concurred that the TF determination is convoluted and the schedule analysis results can be misleading when the schedule is highly constrained by resource availability and calendars, thus compromising the application of critical path scheduling analysis.

The Project Management Institute (2007) specifies the TF as "the total amount of time that a scheduled activity may be delayed from its EF to LF without extending the project time." The TF serves as an effective instrument to control project and activity time delays (Zack 1992; Zack 1993; Thomas et al. 1995; Ndekugri et al. 2008). However, Householder and Rutland (1990) pointed out that resource constraints on a project significantly limit the application value of TF. The classic TF definition potentially breaks down on resource-constrained projects and TF on certain activities may not exist (Fondahl 1991). The critical path is discontinuous in the resource-constrained schedule contrasting the continuous form subject to non-resource-constrained one. Kim and de la Garza (2003) proposed an algorithm of resource-constrained critical path method (RCPM) by incorporating resource dependencies in a CPM schedule, in order to calculate the true values of TF and piece together the discontinuous critical path into a continuous one. The linear relationships between project and activity time extensions do not hold in resource-constrained schedule. Resource constraints imposed on a construction schedule would further lead to anomalous schedule analysis results describing the project and activity status (Korman and Daniels 2003). Thus, the TF evaluated by scheduling software, such as *P3* and *P6*, can be misleading and erroneous (Kim and de la Garza 2003; Lu and Lam 2008) for delay analysis and control.

In addition, there is an increasing preference to employing CPM-based delay analysis techniques on construction projects (Holloway 2002). Nonetheless, there is no standard delay analysis method available. Stakeholders can choose any techniques to support their arguments (Arditi and Pattanakitchamroon 2008). The delay analysis based on the resource-constrained schedule is proved to be trustworthy (Ibbs and Nguyen 2007). However, challenges associated with solving a tightly constrained schedule along with limited availability of scheduling data reduce the reliability of such delay analysis (Arditi and Pattanakitchamroon 2006, 2008; Kallo 1996). The analysis and control of activity and project time extensions remain ill-defined problems in scheduling analysis.

2.4 Refining Critical Path Method based on Scheduling Simulation

The problems mentioned in previous section motivate this research study to revisit and refine CPM, by precisely quantifying TF and characterizing complicated non-linear relationships between activity delays and project delays. The TF of an activity is a non-negative activity attribute, devised as a time control measure in order to effectively keep ATE in check while avoiding or minimizing PTE. The activity delays are analyzed and controlled given specific PTE or with ATE on multiple activities.

Resource-constrained schedules can be generated by mathematical programming formulation or scheduling simulation which is based on heuristic rules and discrete event simulation. The scheduling simulation approaches can handle construction projects of practical size and complexity more effectively. Such approaches, including the resource-constrained critical path method (de la Garza and Kim 2005) and resource-activity critical path method (Lu and Li 2003), can generate feasible resource-constrained schedules for CPM analysis. Because it is difficult to apply analytical methods or mathematical formulations to characterize the relationships between ATE and PTE and determine the TF, scheduling simulation is employed in this research study.

The simulation technology, implemented in this research study, is an ideal methodology to generate and analyze the resources-constrained schedule. Pritsker et al. (1989) defined the simulation as "building a logical model of a system". Scheduling simulation is the ideal methodology to represent complex logical and resource constraints in analyzing a resource-constrained schedule, though the simulation is deterministic (e.g. activity times are constants). However, a valid scheduling simulation can be readily adapted to a stochastic simulation by representing activity times as statistical distributions. By simulation of logical work flows, the construction execution performances such as project completion time could be easily examined (Halpin 1977; Kartam and Ibbs 1996; Sawhney et al. 1998). Based on the simulation model, the schedule can be simulated by tracking the changes of the status of a construction system or a construction project at discrete time points. A resource-constrained schedule can be evaluated in a more realistic fashion (Lu 2003; Lu and Chan 2004; Lu and Lam 2008; Lu et al. 2008; Chan and Lu 2009), in contrast with the mathematical formulations which may not sufficiently account for all the relevant practical constraints.

The mainstream scheduling software, *P3* and *P6*, are both capable to conduct scheduling simulation. Because errors potentially arise from backward pass analysis in determining TF (de la Garza and Kim 2005; Lu and Lam 2008), both *P3* and *P6* are evaluated and compared in conducting forward pass scheduling simulation under resource constraints. Note both CPM forward and backward passes are graphically illustrated in Fig. 2.3 (a) and (b), respectively. The resource constraints are concerned with daily available limits and work-day calendars of driving resources. The unavailability of resources would interrupt activity execution (Lu and Lam 2008), causing potential activity and project time extensions. It is found that the scheduling results are dependent on (1) daily provision limits of resources and (2) calendar settings specified for activities and resources. In particular, the consideration of calendar constraints in the scheduling analysis is also related to the specified activity type.

In *P3*, "Task", "Independent" and "Meeting" activity types are commonly defined. A *Task-type* activity only applies activity calendars while ignoring any resource calendars. An *Independent-type* activity is controlled by the calendars of driving resources; however, different driving resources work independently without entailing resource matching and simultaneous engagement. In contrast, a *Meeting-type* activity is executed only when all the driving resources, required, are available at the same time; activity execution is scheduled on common work days on different calendars of driving resources (Harris 2008). The *Meeting-type* activity coincides with the driving resources matching discussion in the previous section. Note *P3* displays activity duration for activities of either "independent" or "meeting" types as the time span from the activity start date to the date when all the driving resources complete respective work contents on the current activity, subject to resource calendars (not activity calendars) imposed. In contrast, *P6* only differentiates two activity types, namely: “Task Dependent” and “Resource Dependent”, which are essentially equivalent to “Task” and “Independent” types of *P3*, respectively. *P6* classifies the *meeting-type* activities as *resource dependent-type*. The *resource dependent-type* activities are scheduled factoring in driving resources’ work-day calendars. Nonetheless, it is noteworthy that the functionality of different driving resources “meeting” on a particular activity is missing in *P6*. In other words, *P6* does not enable resource scheduling by matching different driving resources on their common work days according to respective resource calendars. As such, in contrast with *P3*, the available activity types in *P6* are not relevant or applicable to resource-constrained construction scheduling applications, which commonly require matching multiple resources that operate on different calendars in practice.

In *P3*, the project network is defined by linking activity blocks according to activity precedence relationships. Combining resource leveling features with meeting-activity type and interruptible activity duration, *P3* is capable of accurately updating the project completion time in the forward pass scheduling simulation, subject to different resource calendars being imposed on multiple driving resources. Note the simulated schedule is deterministic as the activity duration can only be inputted as constants in *P3*. In this research study, *P3*, being a standard and cost-effective methodology for construction project management (Galloway 2006a, 2006b), is chosen as the scheduling simulation software for precisely generating resource-constrained schedules, and characterizing TF based on the relationships between ATE and PTE. Thus, it is possible to develop TF determination methodologies by employing *P3* forward pass scheduling simulation.

The foci of Chapter 3 and 4 are to revisit and refine the TF definitions in the CPM framework. The algorithms are proposed to determine TF for an individual activity given a particular PTE level (Chapter 3), or with a set of delayed activities, each of which experiences a certain level of ATE (Chapter 4). A simple case study taken from Kraiem and Diekmann (1987) is used for contrasting linear and non-linear relationships between ATE and PTE, and demonstrating proposed TF determination methodologies. The simple project definition is given in Chapter 3. The proposed methodology is then compared and discussed with resource-constrained critical path method (RCPM) by using the two examples included in Kim and de la Garza (2003). To further demonstrate the applications of proposed methodologies under practical constraints, a highway widening construction project is drawn upon. The project is taken from a *P3* installation example and modified by adding resource constraints. The project details, such as the project scheduling network and resource requirements, are included in Appendix A. The results show that the PTE-ATE relationships are characteristic of high non-linearity by imposing resource constraints. Based on the in-depth understanding of ATE and PTE relationships, effective time planning and control methodologies enabled by activity total float determination methodologies have been developed. The proposed TF determination methodologies provide the flexibility to characterize the relationships between project and activity delays on a practical construction project.

2.5 Earned Value Management for Project Time and Cost Control

Earned value management (EVM) is regarded as an effective time-cost integration methodology for tracking project progress and characterizing project performances in project control. EVM emerged as a financial analysis specialty in United States Defense Agencies in 1967, as part of the cost/schedule control systems criteria (C/SCSC) and the performance measurement system. The techniques have been widely applied to the manufacturing industry since 1980s. In 1996, the United States Defense Agencies formalized the C/SCSC as the earned value management system. The Project Management Institute further standardized EVM terminologies in “a guide to the project management body of knowledge” in 2000 (Project Management Institute 2005, 2008).

EVM establishes the analytical relationships between the budget cost, actual cost and the work done to allow better assessment of activity time and budget requirements

(McConnell 1985). EVM techniques integrate the project scope, schedule and cost in order to indicate project performances at a particular time point.

Three parameters, *planned value* (PV), *earned value* (EV) and *actual cost* (AC), lay the EVM foundation (Fig. 2.4). The PV is the planned budget cost serving as a baseline to guide project execution; the EV is the budget cost based on the work performed which is calculated by multiplying activity budget and the percentage of work completed; the AC is the actual cost of completed work.

All activities are recorded as “completed”, “incomplete” or “processing” along with percentages of work completed for schedule updating on the data date. Project performance indicators such as *cost variance* (CV), *schedule variance* (SV), *cost performance index* (CPI) and *schedule performance index* (SPI) can be calculated (Table 2.1). These parameters indicate up-to-date cost and time performances. A negative CV value or a CPI value less than one implies the project is over-budget, while a positive SV value or a SPI value higher than one means ahead-of-schedule.

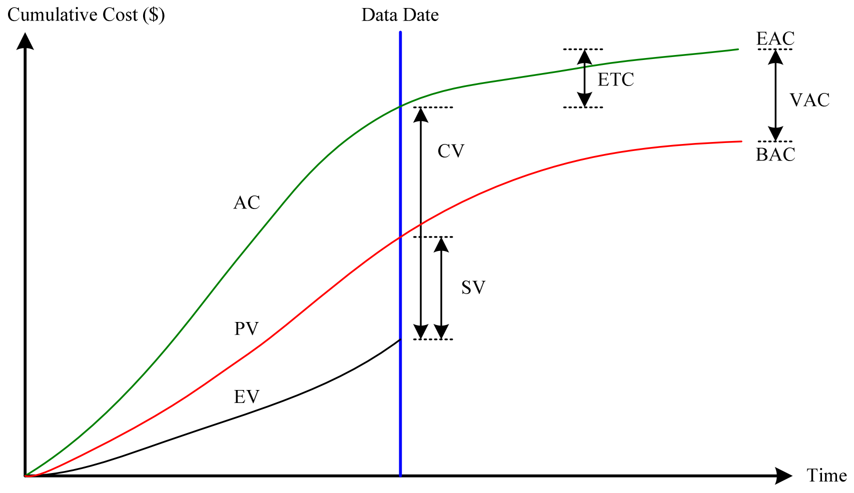


Fig. 2.4: EVM parameters overview

EVM enables forecasting project performance at the scheduled project completion date based on the most current project performances at a data date. In Fig. 2.4 and Table 2.2, the definitions of *budget at completion* (BAC), *estimate to completion* (ETC), *estimate at completion* (EAC) and *variance at completion* (VAC) are illustrated. BAC is the budget planned to be expended in completing the project (mathematically, it is the summation of PV on completion of the project). ETC is the predicted expense to complete the project (Table 2.3). The VAC value, which indicates the future cost performance, implies cost overrun (negative) or saving (positive) likely to occur upon project completion. The *to-complete performance index* (TCPI) indicates the project performance trend (Table 2.4). TCPI can be evaluated based on either EAC or BAC. Project productivity improvement is indicated if the TCPI value is greater than one, and vice versa. Based on the EVM indicators, project managers can effectively monitor and forecast project performances on a continuous basis.

Indicator	Formula
Cost Variance (CV)	EV – AC
Schedule Variance (SV)	EV – PV
Cost Performance Index (CPI)	$\frac{EV}{AC}$
Schedule Performance Index (SPI)	$\frac{EV}{PV}$

Table 2.1: EVM basic formula

Forecasting Indicator	Formula
Estimate At Completion (EAC)	AC + ETC
Estimate To Completion (ETC)	EAC – AC
Variance At Completion (VAC)	BAC – EAC

Table 2.2: EVM forecasting formula

ETC Assumption	Formula
Work performed at Budget Rate	BAC – EV
Work performed at Present CPI	$\frac{BAC - EV}{CPI}$
Work considering both CPI and SPI	$\frac{BAC - EV}{CPI \times SPI}$

Table 2.3: ETC assumptions

Trend Indicator	Formula
To-Complete Performance Index based on EAC ($TCPI_{EAC}$)	$\frac{BAC - EV}{EAC - AC}$
To-Complete Performance Index based on BAC ($TCPI_{BAC}$)	$\frac{BAC - EV}{BAC - AC}$

Table 2.4: EVM trend formula

2.6 Improving Earned Value Management Framework

A major construction project usually spans for years, effective time and cost tracking is important to successful project delivery. Preventive and corrective actions are required to tackle any adverse situations in time. Though previous research pointed out that EVM could be successfully applied and beneficial to the industry (Christensen 1993, 1998), its effective applications in construction have been limited. Previous research (Eldin 1989; Vargas 2003; Solomon and Young 2007; Lukes 2008; Kim and Reinschmidt 2010) found that the EVM techniques fail to obtain accurate indicators to reflect project performance status, especially when the scope, schedule and cost estimates are imprecise or subjected to changes. Thus, EVM techniques are difficult to be applied to dynamic construction projects and do not add much value to project execution, especially when (1) the construction schedule is compounded by considering the resource constraints such as: resource availability limits and multiple calendars; and (2) activity and project delays encountered during project executions.

Anbari (2003) made an attempt to convert the EVM indicators in time-dimension, such as BAC, ETC in terms of time, not in cost-dimension as defined in the traditional EVM framework. He pointed out CPM and PERT does not consider the effect of past or current performances upon the future performance; in contrast, EVM does.

For case illustration, one 40-week project example was used. He evaluated *time variance* (TV), which is similar to *cost variance* (CV) but in terms of time, by using EVM approach based on the past project performances. The resulting TV was equal to 4 weeks. He emphasized that “CPM and PERT would estimate a completion of 44 week if the schedule slippage of four weeks estimated by EVM were on the critical path”. Hence, it can be deduced that EVM and CPM may not reach the same solution as they are two loosely coupled methodologies. Practitioners generally apply these two methodologies separately and independently. The value of TV, which is estimated by the EVM framework, may not be equivalent to the extension to project completion time calculated by the CPM framework. TV is only marginally connected with the critical path, which actually does not hold valid (or exist) under practical resource constraints.

The EVM techniques only consider a baseline schedule without schedule changes such as the changes on activity duration due to activity delays. It considers performance changes such as the past vs. the future CPI and SPI on an ongoing project. Note EVM is effective to indicate “as of date” and forecast future performances with well developed performance indicators. In contrast, CPM provides the systematic methodology to evaluate important parameters such as project completion time and TF, while EVM does not provide such vital information for project management. Therefore, a systematic method to bridge the gap between the two methods is lacking.

Nevertheless, there is no standard EVM implementation methodology for coping with changing scope definitions in connection with complicated activity-project delay scenarios. Though Anbari (2003) suggested “time estimate to complete” which is defined in EVM -to a certain extent- factors in delayed project time, the extended duration is roughly predicted without any quantitative scheduling analysis.

Therefore, the focus of Chapter 5 is to improve the EVM framework in order to better cope with delay scenarios, in connection with activity and project time extensions. To illustrate the improved EVM approach, a simple case study is taken from Ahuja et al. (1994). The details of this simple case study are described in Chapter 5. The results show that the proposed approach improves the EVM accuracy for a resource-constrained schedule, and this approach is cost-effective in tracking project time and cost performances under time extension scenarios. It is noteworthy that this established EVM approach can be readily applied to a complex construction project under practical constraints.

2.7 Concluding Remarks

In scheduling construction projects, critical path method (CPM) will continue to provide the backbone methodology for project and activity time analysis, supplemented by earned value management (EVM) to generate up-to-date indicators for project cost and time performances. The network diagramming techniques, namely, activity on node (AON) and precedence diagram method (PDM), are the predominant graphical modeling tools to represent all the activities of a project along with technology-constrained precedence relationships among activities. Both CPM and EVM have significantly contributed to project time planning and control on construction projects. The scope of this research study is limited to enhancing CPM and EVM to cater for more effective construction project management.

As emphasized in this chapter, activity total float (TF) represents the amount of time by which an activity can be delayed without extending the scheduled project time in the traditional CPM framework. This classic definition fails to take into account the complicated relationships between project and activity delays. On the other hand, the EVM, which assumes an ideal baseline schedule, is inadequate to tackle resource-constrained scheduling under delayed scenarios. The research efforts have been therefore narrowed down to refining the TF definition in the CPM framework and improving the EVM framework, by characterizing the relationships between activity time extension (ATE) and project time extension (PTE).

Effective time extension planning and control methodologies will be developed based on scheduling simulation to enhance CPM and EVM. The TF determination methodologies are proposed in Chapter 3 and 4, while the improved EVM framework is proposed in Chapter 5. Conclusions are drawn and contributions of this research study are recapitulated in Chapter 6.

CHAPTER 3

REVISITING TOTAL FLOAT IN CRITICAL PATH SCHEDULING

In this chapter, a new methodology is proposed for determining the TF for individual activities based on the relationships between activity time extension (ATE) and project time extension (PTE). Next, the linear and non-linear relationships between ATE and PTE are contrasted in the context of straightforward CPM analysis, and CPM analysis under resource limits and calendar constraints based on scheduling simulation. The applications of the proposed TF determination method are illustrated in a simple example project which is taken from Kraiem and Diekmann (1987). The proposed methodology is implemented in the two examples provided by Kim and de la Garza (2003). The results are compared and discussed. The highway widening project, introduced in Section 2.4 and detailed in Appendix A, is used to demonstrate how to determine TF in multiple project time delay scenarios being postulated.

3.1 Total Float Determination for Project Planning

The CPM under practical resource constraints entails TF determination for each activity so as to facilitate controlling ATE and PTE. The ATE and PTE are defined against (1)

This chapter is based on a paper entitled "*Revisiting total float for controlling project time extensions on resource-constrained construction schedules*", submitted to *Journal of Construction Engineering and Management, ASCE* for publication.

the original activity duration which is entered for CPM scheduling and (2) the scheduled project duration resulting from the forward pass scheduling analysis based on original activity duration, as Eq. (3.1) and Eq. (3.2) respectively.

$$\text{ATE} = \text{Delayed Activity Duration} - \text{Original Activity Duration} \tag{3.1}$$

$$\text{PTE} = \text{Delayed Project Completion Time} - \text{Scheduled Project Completion Time} \tag{3.2}$$

The classic TF definition can be expressed in Eq. (3.3). For a particular activity i, TF_i is the maximum amount of time by which the original duration on i can be extended while not extending the scheduled project completion time. The value is derived from the CPM forward pass analysis. TF_i is conditional on (1) ATE_k on all the other activities ($k \neq i$) being zero; (2) PTE on the scheduled project completion time being zero. The approach entails executing an iterative procedure for one activity at a time in order to derive TF based on changes to PTE, as shown in Fig. 3.1. The PTE (e) is firstly pre-set by users. The proposed methodology provides the flexibility in characterizing the relationships between project delay and activity delays for a specific scenario which is delineated by a specific PTE level of e. The pre-set PTE (e) is equal to zero, implying the project time extension is not desired. Then, selecting one activity i and increasing the ATE_i by a one-day increment, the effect of this activity delay on the PTE can be assessed by running *P3* resource leveling analysis. The iteration on one activity terminates once the PTE has exceeded the pre-set e. The TF on i is determined and can be cross-checked with the cumulative value in ATE_i. Note the ATE_i resets to zero prior to proceeding with processing the next activity. In other words, PTE, which is observed through simulation by increasing ATE_i, is used to compare against the pre-set e value that represents a threshold specified by the planner so as to evaluate TF.

$$TF_i \Big|_{\substack{ATE_k = 0, k \neq i \\ PTE = e}} \tag{3.3}$$

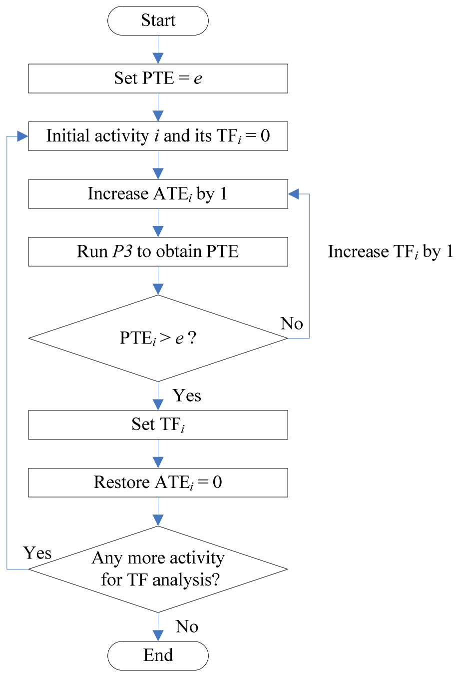


Fig. 3.1: TF determination algorithm flowchart given specific PTE

The classic TF definition is a non-negative activity attribute. The TF represents the maximum amount of activity delay time without extending the project completion time, as discussed in Section 2.2. The activities that own zero TF value are entitled as critical, and the longest path linking those critical activities in the project network is identified as the critical path. Mainstream scheduling application software Primavera® P3™ Project Planner (*P3*) allows for negative TF values. Note negative TF values yield when the pre-set project end date is earlier than the calculated project finish date from the forward pass scheduling simulation. Negative TF values are also indicative of date slippage when a critical activity is delayed to finish later than originally planned. The negative TF value, which implies the amount of time an activity has been delayed or can be delayed, can cause confusions in project planning and control. Generally, corrective measures should be taken to adjust the schedule until no negative TF exists (Harris 2006, 2008).

The present research requires non-negativity on TF, or the minimum value of activity TF is equal to zero. Thus, TF can be interpreted in a straightforward way as the maximum ATE that is allowable such that the PTE is kept as zero, which means the project completion time as determined from the CPM scheduling analysis will not be prolonged. Furthermore, for delay analysis and control on a construction schedule, the TF definition can be broadened by associating a specific delay time (*e*, being greater than zero) on the scheduled project completion date (i.e. PTE = *e*). As such, given a specific delay time *e*, TF is the maximum ATE that is allowable such that the PTE is kept as *e*.

The use of the term “simulation” provides a broadened definition of scheduling analysis. In the proposed flowchart (Fig. 3.1), it requires to manually run *P3* every time to extend the activity duration (ATE) and observe the project time extension (PTE). On the other hand, the term “simulation” is more applicable as the procedures are simulating the effect on PTE by increasing the ATE value. Once the concept is proven valid on small projects with certain manual procedures, the proposed methodologies will have to rely on computer automation in tackling problems of practical size and complexity in the near future.

P3 is a scheduling software tool which is suitable to facilitate the scheduling simulations conducted in this research study. In *P3*, the project network is defined by linking activity blocks according to activity precedence relationships. Combining resource leveling features under the settings of meeting-activity type and interruptible activity duration, *P3* is capable of accurately generating resource-constrained schedules from the forward pass scheduling simulation subject to availability limits and calendars being imposed on driving resources. Note the *P3*-based simulated schedule is deterministic as the activity duration can only be inputted as constants in *P3*. Valid resource-constrained schedules can readily turn into project evaluation and review technique (PERT) simulations (or Monte Carlo simulation on CPM) for stochastic analysis in the future research.

3.2 PTE-ATE Relationships of Single Activity Delay

The relationships between ATE and PTE can be revealed by plotting PTE against ATE for a particular project, for both non-resource-constrained and resource-constrained scheduling scenarios. The linear and non-linear relationships between ATE and PTE under different scheduling scenarios are elucidated as follows.

The linear relationships between ATE and PTE are in connection with a CPM schedule without posing resource limits and calendars constraints. The PTE remains to be zero when ATE_i is within the available TF_i (Fig. 3.2); and after TF_i is consumed, ATE_i is directly proportional to PTE with a constant slope value of one. This implies activity being delayed (D_i) by e days beyond TF_i ($ATE_i = TF_i + D_i$, $D_i = e$) results in the scheduled project time being extended by e days (PTE = e), as mentioned in Section 2.2.

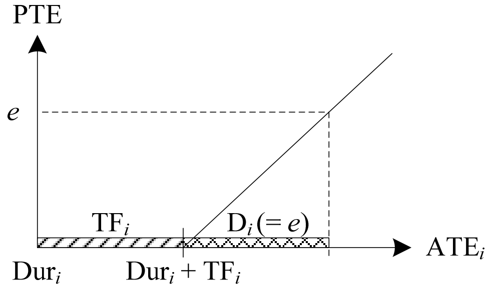


Fig. 3.2: PTE-ATE relationships in non-resource-constrained schedule

The non-linear relationships between ATE and PTE are in connection with a CPM schedule with resource limits and calendars constraints imposed (Fig. 3.3). The slope of PTE against ATE_i after consuming the TF_i is not a constant of one but exhibits highly non-linear characteristics. A single activity delay D_i beyond TF_i may or may not extend the project time: the resulting PTE can be equal to zero, or smaller than D_i, or equal to D_i, or larger than D_i. In other words, the PTE for e days ($\mathrm{PTE} = e$) may not result from an activity delay D_i of e days beyond TF_i. Note the ATE_i consists of TF_i and D_i, and D_i occurs beyond TF_i ($ATE_i = TF_i + D_i$ and $D_i > 0$). In short, the proposed TF determination method is effective to tackle the complicated non-linear relationships between ATE and PTE and evaluate accurate TF, subject to resource availability and calendar constraints. The proposed TF determination method is illustrated by the ensuing case study.

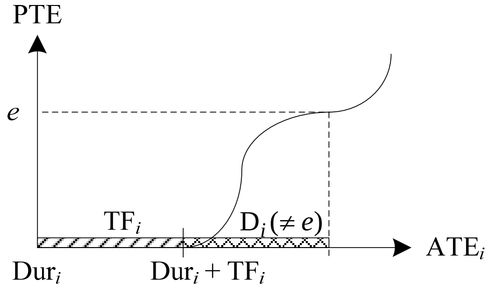


Fig. 3.3: PTE-ATE relationships in resource-constrained schedule

3.3 Illustrative Case

A case study is taken from Kraiem and Diekmann (1987). Note Alkass et al. (1996) used this schedule to illustrate the delay analysis techniques. The objectives are (1) applying the forward pass scheduling simulation method by using *P3*, (2) demonstrating linear and non-linear relationships between ATE and PTE in different scheduling scenarios, and (3) illustrating the proposed method for determining TF.

The schedule network and the activity duration requirements are shown in Fig. 3.4 and Table 3.1. The nodes "ST" and "EN" denote project start and end. This project consists of ten activities and there is no resource requirement in the base case scenario. In a resource-constrained scenario, resource work-time constraints (activity calendars) are added to this schedule. It is assumed that the project team runs on four-work-day weeks, taking Friday to Sunday off.

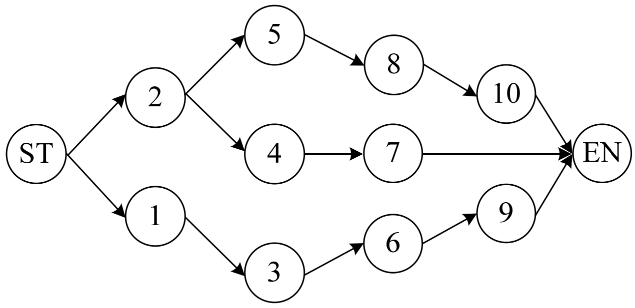


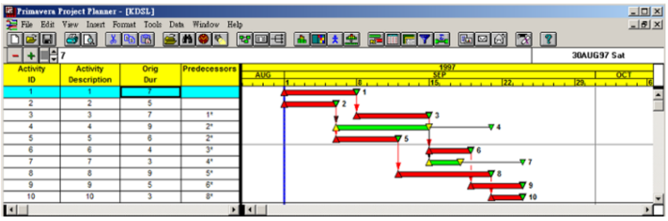
Fig. 3.4: Scheduling network diagram for simple case study which is taken from Kraiem and Diekmann (1987)

Activity	Duration (days)
1	7
2	5
3	7
4	9
5	6
6	4
7	3
8	9
9	5
10	3

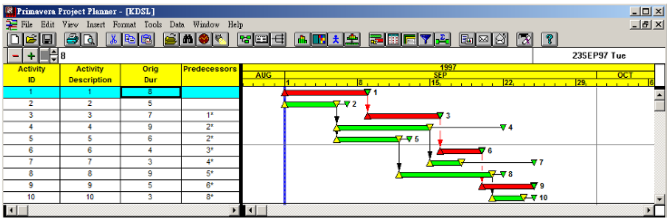
Table 3.1: Activity duration requirements for example project which is taken from Kraiem and Diekmann (1987)

To execute the iterative procedures, data of activity times, relationships and calendars are firstly entered in *P3*. The project completion time of the non-resource-constrained schedule is 23 days [Fig. 3.5(a)], while the resource-constrained schedule takes 38 days [Fig. 3.6(a)]. Activity 1 is selected to demonstrate the ATE and PTE relationships. The original activity duration is 7 days which is entered for CPM scheduling. Then, the ATE_1 increases by a one-day (by changing the activity duration to 8 days for *P3* inputs, according to Eq. (3.1)). The project completion time extends by 1 day from 23 days to 24 days [Fig. 3.5(b)]. Further, PTE is equal to 2 days when ATE_1 is 2 days [Fig. 3.5(c)]. Therefore, in the non-resource-constrained schedule, a unit ATE increment of one day results in one-day PTE. The activity TF is accumulated until the PTE exceeds the pre-set threshold (*e*) and the loop terminates.

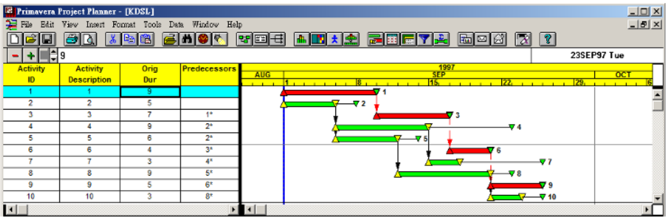
Similar iterative procedures are performed in the resource-constrained schedule. Note on the *P3* bar charts, the necking on an activity bar signifies a period of non-working days. The PTE is 1 day when the ATE_1 is 1 day [Fig. 3.6(b)]. However, PTE is equal to 5 days (the project completion time increases from 38 to 43 days) given ATE_1 is 2 days [Fig. 3.6(c)]. Thus, 5-day PTE is produced in contrast with 1-day PTE in the non-resource-constrained schedule. This implies *e*-day PTE may or may not results from *e*-day ATE increment in the resource-constrained schedule.



a) *P3* forward pass: ATE_1 = 0 day; PTE = 0 day

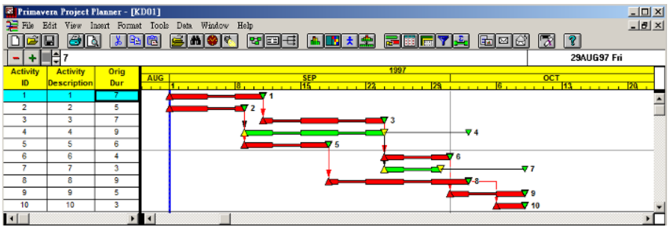


b) *P3* forward pass: ATE_1 = 1 day; PTE = 1 day

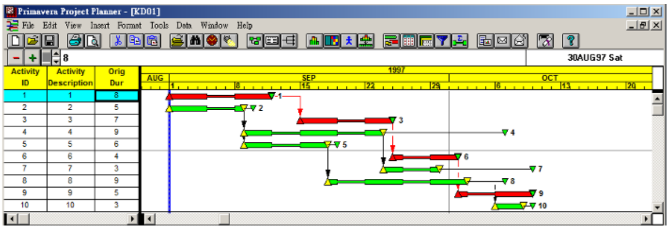


c) *P3* forward pass: ATE_1 = 2 days; PTE = 2 days

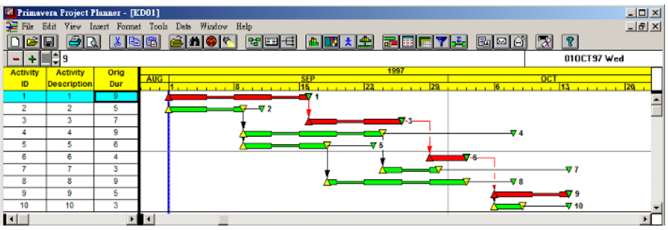
Fig. 3.5: *P3* forward pass scheduling simulation in non-resource-constrained schedule



a) *P3* forward pass: ATE_1 = 0 day; PTE = 0 day



b) *P3* forward pass: ATE_1 = 1 day; PTE = 1 day



c) *P3* forward pass: ATE_1 = 2 days; PTE = 5 days

Fig. 3.6: *P3* forward pass scheduling simulation in resource-constrained schedule

The PTE-ATE relationships are graphically described based on examining Activity 1 in the two scheduling scenarios. Table 3.2 summarizes the ATE_1 (from 0 to 14 days) and the corresponding PTE for the non-resource-constrained and resource-constrained schedules, respectively. In both scenarios, Activity 1 has zero TF and thus is deemed critical. In the schedule without imposing resource calendars, the PTE-ATE relationships are linear and ATE_1 is always equal to PTE. In contrast, the PTE is larger than or equal to ATE_i (PTE = e resulting from $0 < ATE_i \le e$ in this case) in the schedule subject to activity calendar constraints, revealing the non-linear effect on PTE as a result of ATE (PTE = e resulting from $ATE_i > 0$). The linear and non-linear relationships between ATE and PTE in the two scheduling scenarios are clearly contrasted in Fig. 3.7. The green (solid) and red (dashed) lines represent the PTE in non-resource-constrained and resource-constrained schedules respectively. The slope of the green line is equal to one while the slope of the red line is varying.

ATE_1 (days)	PTE (days)	
	Non-resource-constrained	Resource-constrained
0	0	0
1	1	1
2	2	5
3	3	6
4	4	7
5	5	8
6	6	12
7	7	13
8	8	14
9	9	15
10	10	19
11	11	20
12	12	21
13	13	22
14	14	26

Table 3.2: PTE results from ATE_1 for non-resource-constrained and resource-constrained scheduling scenarios

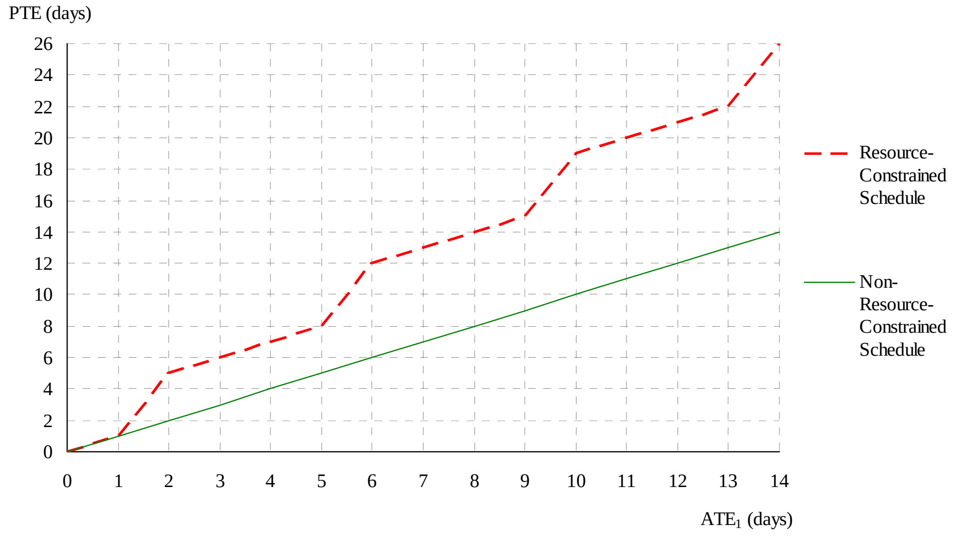


Fig. 3.7: A graphic representation of the PTE-ATE relationships based on ATE_1

The activity TF_i is generated by using the proposed TF determination method (Fig. 3.1). It is assumed that a maximum of two weeks PTE is granted on the project completion time for the current project. The PTE is set to zero and fourteen days for both non-resource-constrained and resource-constrained scheduling scenarios. Tables 3.3 and 3.4 summarize the TF values for each activity in the four cases under the two scheduling scenarios.

In Table 3.3, given activity i, TF_i increases by fourteen days when project completion time extends by two weeks, lending evidence to the PTE-ATE linear relationship. The resulting activity TF_i is interpreted as "the activity can be delayed within the TF_i without extending the scheduled project completion time by over fourteen days". The smaller the TF_i value, the more critical the activity. Thus, the proposed method for determining TF is instrumental in controlling activity delay and indicating activity criticality.

Regardless of the non-resource-constrained and resource-constrained schedules, the activity TF_i values are the same when the PTE is set at zero. Given the PTE is set at fourteen days, a comparison of the resulting TF_i values shows that larger TF_i values resulting from the non-resource-constrained schedule than from the resource-constrained schedule. In short, this case study clearly illustrates the PTE-ATE relationships turn non-linear (PTE = e results from $0 < \text{ATE}_i \leq e$) when the schedule is subjected to resource and calendar constraints.

Activity i	$\text{TF}_i \big\vert_{\substack{\text{ATE}_k = 0,\, k \neq i \\ \text{PTE} = 0\,\text{day}}}$	$\text{TF}_i \big\vert_{\substack{\text{ATE}_k = 0,\, k \neq i \\ \text{PTE} = 14\,\text{days}}}$
1	0	14
2	0	14
3	0	14
4	6	20
5	0	14
6	0	14
7	6	20
8	0	14
9	0	14
10	0	14

Table 3.3: Activity TF determined for non-resource-constrained schedule given zero and 14-day PTE

Activity i	$\mathrm{TF}_i \Big\vert \begin{matrix} \mathrm{ATE}_k = 0, k \neq i \\ \mathrm{PTE} = 0 \text{ day} \end{matrix}$	$\mathrm{TF}_i \Big\vert \begin{matrix} \mathrm{ATE}_k = 0, k \neq i \\ \mathrm{PTE} = 14 \text{ days} \end{matrix}$
1	0	8
2	0	8
3	0	8
4	6	14
5	0	8
6	0	8
7	6	14
8	0	8
9	0	8
10	0	8

Table 3.4: Activity TF determined for resource-constrained schedule given zero and 14-day PTE

3.4 Comparisons of "phantom float" examples

Two examples which are taken from "*phantom float*" authored by Kim and de la Garza (2003) are used to compare by using the proposed methodology. The schedule network diagram for first example is reproduced (Fig. 3.8). The activity and resource requirements for the original schedule (Fig. 7 in "*phantom float*" paper) and the alternative schedule (Fig. 8 in "*phantom float*" paper) are tabulated in Table 3.5 and 3.6, respectively. In order to impose activity sequences for resource allocation consistently (identical to those used in "*phantom float*" paper), activity priorities are introduced. The larger the code number, the higher the priority in activity execution. The TF results, which are evaluated by using the proposed method [PTE (e) is pre-set as 0-day], are exactly the same for the two methods. However, the proposed method does not spend any efforts in identifying resource links as suggested by Kim and de la Garza (2003), and provides the flexibility in setting *e* value.

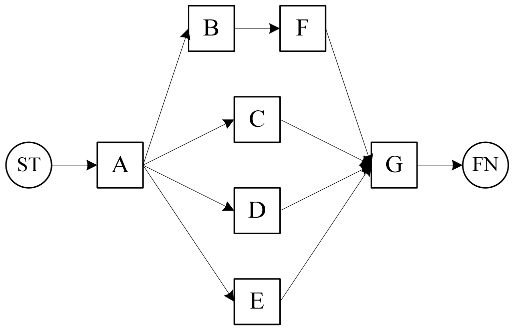


Fig. 3.8: Schedule network diagram for example one in "*phantom float*" paper

ID	Activity	Duration	Resource	Priority	TF
1	A	2	A[1]	7	0
2	B	4	A[1]	5	0
3	C	5	A[1]	3	0
4	D	6	B[1]	6	3
5	E	2	B[1]	4	4
6	F	3	B[1]	2	2
7	G	2	B[1]	1	0

Table 3.5: Scheduling analysis results which are comparable to original schedule in "*phantom float*" paper

ID	Activity	Duration	Resource	Priority	TF
1	A	2	A[1]	7	0
2	B	4	A[1]	6	0
3	C	5	A[1]	3	0
4	D	6	B[1]	5	3
5	E	2	B[1]	2	0
6	F	3	B[1]	4	0
7	G	2	B[1]	1	0

Table 3.6: Scheduling analysis results which are comparable to alternative schedule in "*phantom float*" paper

Thus, TF values are generated by using the proposed methodology subject to *x*-day PTE. Tables 3.7 and 3.8 summarize the TF results given *e* set from 0-day to 5-day, for the original and alternative schedules, respectively.

Activity	TF_i					
	PTE = 0	**PTE = 1**	**PTE = 2**	**PTE = 3**	**PTE = 4**	**PTE = 5**
A	0	1	2	3	4	5
B	0	1	2	3	4	5
C	0	1	2	3	4	5
D	3	4	5	6	7	8
E	0	1	2	3	4	5
F	0	1	2	3	4	5
G	0	1	2	3	4	5

Table 3.7: Activity TF determined for original schedule in "*phantom float*" paper

Activity	TF_i					
	PTE = 0	**PTE = 1**	**PTE = 2**	**PTE = 3**	**PTE = 4**	**PTE = 5**
A	0	1	2	3	4	5
B	0	1	4	5	6	7
C	0	1	2	3	4	5
D	3	4	5	6	7	8
E	4	5	6	7	8	9
F	2	3	4	5	6	7
G	0	1	2	3	4	5

Table 3.8: Activity TF determined for alternative schedule in "*phantom float*" paper

Further, the new developed method can also be applied to the schedule considering more complicated calendar constraints. The activity TF can be evaluated by characterizing the relationships between ATE and PTE, as demonstrated below. The case study is designed to impose resource calendar constraints on two resource types. Type A resource runs on four-work-day weeks, taking Friday to Sunday off; while type B resource runs on three-work-day weeks, taking Thursday to Sunday off. By employing the proposed simulation-based TF determination methodology, TF can be generated as tabulated in Table 3.9 and 3.10, for the original and alternative schedules.

Activity	TF_i				
	PTE = 0	**PTE = 5**	**PTE = 6**	**PTE = 7**	**PTE = 12**
A	0	5	6	7	12
B	0	2	3	4	6
C	2	3	5	6	7
D	5	6	8	9	10
E	0	1	2	3	4
F	0	1	2	3	4
G	0	1	2	3	4

Table 3.9: Activity TF determined for original schedule in "*phantom float*" paper considering resource calendar constraints (project completion time: 24 days)

Activity	TF_i				
	PTE = 0	**PTE = 1**	**PTE = 6**	**PTE = 7**	**PTE = 8**
A	1	5	6	8	12
B	1	3	4	6	7
C	1	2	3	5	6
D	4	5	6	8	9
E	2	3	4	5	6
F	1	2	3	4	5
G	0	1	2	3	4

Table 3.10: Activity TF determined for alternative schedule in "*phantom float*" paper considering resource calendar constraints (project completion time: 23 days)

The second example included in "*phantom float*" paper has also been redone by using the proposed simulation-based activity total float determination methodology. Fig. 3.9

shows the scheduling network diagram. The activity and resource requirements are tabulated in Table 3.11. Similarly, the activity priorities are specified. The resulting project completion time is 30-day. TF can be effectively evaluated according to the flowchart (Fig. 3.1). The TF values are evaluated based on the *e* value being pre-set as 0-day. The results are identical to TF values calculated by Kim and de la Garza (2003). This shows the proposed methodology is capable of generating the correct TF under resource availability constraints. The proposed algorithm essentially broadens the TF definition by providing flexibility for schedulers to specify the *e* value in analysis of construction schedules considering both resource limit availabilities and calendar constraints.

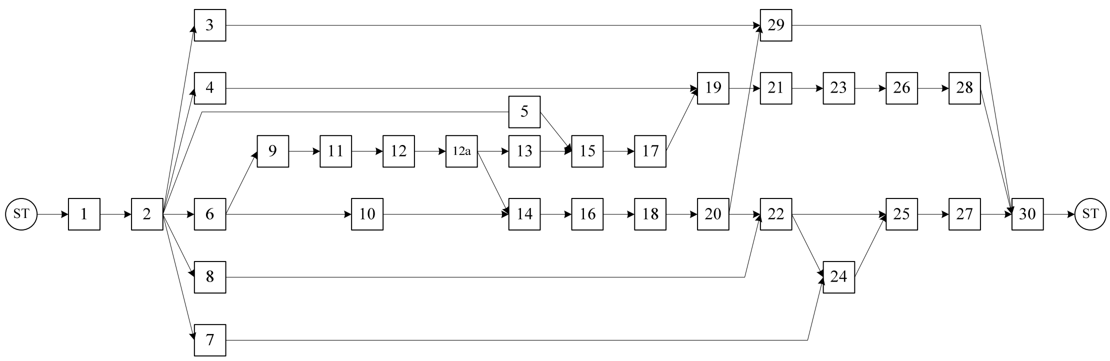


Fig. 3.9: Schedule network diagram for example two in "*phantom float*" paper

Act ID	Duration	Carpenters	Laborers	Iron Worker	**Act Priority**	**TF**
1	1	0	0	0	**31**	**0**
2	3	0	0	0	**30**	**0**
3	2	4	0	0	**5**	**0**
4	2	2	0	0	**25**	**0**
5	4	4	0	0	**22**	**0**
6	1	0	4	0	**29**	**0**
7	2	2	0	0	**11**	**1**
8	3	4	0	0	**13**	**1**
9	1	4	2	2	**28**	**0**
10	1	0	0	0	**27**	**5**
11	1	1	2	0	**26**	**0**
12	1	1	1	0	**24**	**0**
12a	3	0	0	0	**23**	**0**
13	1	0	0	4	**21**	**0**
14	2	0	2	0	**20**	**0**
15	1	0	0	4	**19**	**0**
16	1	2	0	2	**18**	**0**
17	1	2	0	2	**17**	**2**
18	1	1	2	0	**16**	**0**
19	1	0	0	4	**15**	**3**
20	6	0	0	0	**12**	**0**
21	1	0	0	4	**14**	**3**
22	2	4	0	0	**8**	**0**
23	2	2	0	0	**10**	**1**
24	1	2	0	0	**7**	**0**
25	1	0	2	0	**6**	**3**
26	1	0	2	0	**9**	**5**
27	2	0	0	0	**4**	**3**
28	2	2	0	0	**3**	**0**
29	1	4	0	0	**2**	**0**
30	1	0	4	0	**1**	**0**

Table 3.11: Scheduling analysis results for example two in “*phantom float*” paper

Noted that the proposed activity total float determination methodology does not provide an algorithm to find alternate schedules or identify the optimum schedule option as RCPM which is proposed by Kim and de la Garza (2003), but can be readily applied to any alternative, feasible schedules for a project under resource constraints. For example, the alternative schedule can be formulated by changing activity priorities. As demonstrated in Tables 3.5 and 3.6, the activity priorities of the original and alternative schedules are different. The optimum combination of activity priorities can be identified by using the optimization approach [such as particle swarm optimization (PSO) (Lu et al. 2008)]. The resulting activity priority can then fix the activity execution sequence to generate an alternate schedule. TF can be evaluated based on the alternate schedule.

3.5 Practical Application

The highway widening construction project, as detailed in appendix, has been adapted for demonstrating applications of the proposed TF determination method under practical constraints. After imposing all the practical constraints, the project time extends from 262 days to 606 days: the planned project start is on 26 April 1999 (Monday) and the project completion date is 22 December 2000 (Friday). It is assumed that a maximum of two-week time extension is granted on the scheduled project completion time. The project manager is required to control ATE and PTE, aided with activity TF derived by the newly proposed method in this case.

Given the two weeks of time window on PTE, the tentative completion date would fall anywhere between 22 December 2000 (Friday) and 05 January 2001 (Friday). As long as delay on activity *i* can be controlled within TF, the project time will not be prolonged by more than fourteen days.

$$\mathrm{TF}_i \left| \begin{array}{l} \mathrm{ATE}_k = 0,\ k \neq i \\ \mathrm{PTE} = x \text{ days},\ 0 \leq x \leq 14 \end{array} \right. \tag{3.4}$$

By setting all the activities as meeting-type in *P3*, TF_i on activity i is generated according to Eq. (3.4). Table 3.12 summarizes TF_i for all the activities in different scenarios (with PTE increasing from 0 to 14 days). Note the TF_i values -when evaluated on the condition of PTE being zero- are consistent with the classic TF definition. Across the columns, the activity criticality can be ranked by TF_i values. Accurate TF values are derived in this practical resource-constrained scheduling case as given in Table 3.5, which leads to the following observations:

Act ID	Name	TF_i						
		PTE = 0	**PTE = 5**	**PTE = 6**	**PTE = 7**	**PTE = 12**	**PTE = 13**	**PTE = 14**
2	2	1	1	1	7	10	10	10
3	3	4	4	4	12	14	14	14
4	4	1	1	1	6	9	9	9
5	5	2	3	3	7	10	10	10
6	6	17	19	19	22	26	26	26
7	7	1	1	1	6	9	9	9
8	8	1	1	1	6	9	9	9
9	9	1	1	1	7	9	9	9
10	10	1	1	1	7	9	9	9
11	11	3	3	3	8	10	10	10
12	12	3	3	3	8	10	10	10
13	13	3	3	3	8	10	10	10
14	14	3	3	3	8	10	10	10
15	15	4	6	6	9	10	10	11
16	16	38	40	40	43	44	44	45
17	17	31	33	34	35	36	37	38
18	18	**0**	2	3	4	5	7	8
19	19	89	90	90	95	98	98	98
20	20	343	345	346	349	350	351	352
21	21	21	22	22	27	30	30	30
22	22	1	2	2	5	8	8	8
23	23	8	10	10	13	17	17	17
24	24	1	1	1	6	9	9	9
25	25	3	3	3	8	10	10	10
26	26	1	2	2	5	8	8	8
27	27	1	3	3	6	10	10	10
28	28	**0**	2	2	3	5	5	5
29	29	**0**	3	3	5	7	7	8
30	30	**0**	2	2	5	6	6	7
31	31	**0**	2	3	5	6	7	8
32	32	15	17	17	20	21	21	22
33	33	**0**	2	2	5	6	6	7
34	34	**0**	2	2	5	6	6	7
35	35	42	44	44	47	48	48	49
36	36	79	84	84	84	88	89	89
37	37	64	69	69	69	73	74	74
38	38	64	69	69	69	73	74	74
39	39	1	1	1	4	6	6	6
40	40	1	1	1	5	7	7	7
41	41	1	1	1	5	6	6	6
42	42	2	2	2	6	8	8	8
43	43	26	29	29	29	31	32	32
44	44	35	38	38	39	41	42	42
45	45	26	28	28	29	30	31	31
46	46	23	25	25	26	27	28	28
47	47a	**0**	2	2	4	5	5	6
48	47b	**0**	2	2	4	5	5	6
49	48	**0**	2	2	4	5	5	6
50	49	**0**	2	2	4	5	5	6
51	50a	**0**	2	3	4	5	6	7
52	50b	**0**	2	3	4	5	6	7
53	51a	**0**	2	3	4	5	6	7
54	51b	**0**	2	3	4	5	6	7
55	52a	**0**	2	3	4	5	6	7
56	52b	**0**	2	3	4	5	6	7
57	53a	**0**	2	3	4	5	6	7
58	53b	**0**	1	2	3	4	5	6
59	54	**0**	1	2	3	4	5	6
60	55	**0**	1	2	3	4	5	6
61	56	**0**	1	2	3	4	5	6

Table 3.12: Activity TF determined for highway widening project with different PTE

- When PTE is set as zero, the derived TF values are consistent with the classic TF definition in CPM. In this case, for example, given zero PTE, Activity 3 has four-day TF, meaning that given duration of all the other activities are held at their original values, Activity 3 can be delayed for a maximum of four days without causing any extensions to the scheduled project completion time (606 days). In other words, in order to deliver the project right on schedule, the latest start on Activity 3 can be four days later than the scheduled earliest start date; or the latest finish on Activity 3 can be four days later than the scheduled earliest finish date.
- Under resource availability and calendar constraints, the conventional critical path does not exist in the form of a continuous path from project start to project end in the project network. When PTE is set as zero, all the activities with zero TF in Table 3.12 are identified as being critical (which are highlighted as bolded numbers); nonetheless, those critical activities, which are distinguished with thicker blocks in Fig. A.3, do not constitute a path in the project network.
- PTE cannot reach each pre-set increment value corresponding with all the postulated scheduling scenarios. In this case, when PTE is greater than zero as a result of ATE, the minimum value of PTE is five days. In other words, when an activity's finish time is one day later than the latest finish time, it is impossible to have one-day, two-day, three-day, or four-day PTE; instead, the resulting

extension to project completion time is at least five days. In fact, among all the optional values ranging from one to fourteen days, only PTE of five, six, seven, twelve, thirteen, and fourteen days are feasible factoring in all the practical resource and calendar constraints.

- As PTE reaches a higher level, TF on different activities would be lengthened to various degrees. In the current case, when PTE is at five days, Activity 36, 37 and 38 would have five days longer TF than the base case of zero PTE; while activities 29, 43 and 44 would have additional three days more TF.

In brief, this case study has demonstrated application of the proposed TF determination methodology based on resource-constrained scheduling simulation by *P3*. And the new method is effective for (1) generating accurate activity TF values so to keep project completion time and (2) gaining insight into the non-linear, complicated behavior of project time extension in connection with delay on individual activities of the project.

3.6 Chapter Summary

In this chapter, a new total float determination methodology is proposed based on the relationships between activity time extension (ATE) and project time extension (PTE). With a simple example project network taken from Kraiem and Diekmann (1987), the linear and non-linear relationships between ATE and PTE are contrasted in the context of straightforward CPM analysis and CPM analysis under resource limits and calendars constraints. Combining resource leveling features with meeting-activity type and interruptible activity duration, *P3* is capable to accurately update the project completion time in the forward scheduling analysis, subject to different resource calendars being imposed on multiple diving resources. Precise activity TF value can be successfully determined by using scheduling simulation tool *P3* based on the new methodology proposed in the present research. Further, the proposed method does not spend any efforts in identifying resource links suggested by Kim and de la Garza (2003), and provides the flexibility in setting *e* value, in the context of resource-constrained schedule. In addition, the highway widening construction project serves as a practical case to demonstrate the application of the proposed TF determination method under resource constraints. TF for all the activities are successfully derived in multiple project time extension scenarios.

CHAPTER 4

CONTROLLING MULTIPLE ACTIVITY DELAYS ON A RESOURCE-CONSTRAINED SCHEDULE

As an extension to the TF determination problem defined in the Chapter 3 which concerns the delay on one activity at a time, the current chapter deals with a more complicated yet more realistic project scheduling setting that involves multiple activity delays on a resource-constrained schedule. If activity delays occur on a specific set of activities (*S*) on a project which result in a particular project time extension (*e*), how much float time (TF) is allowed on each activity involved such that the *e* will not be prolonged further? Similar to Chapter 3, the PTE-ATE relationships are firstly characterized through scheduling simulation based on the simple example project which is taken from Kraiem and Diekmann (1987), followed by proposing a procedure to define TF for an individual activity given a particular PTE level (*e*) and a particular set of delayed activities, each of which experiences a certain level of ATE. The proposed methodology is further applied on the highway widening project considering practical resource constraints.

This chapter is based on a paper entitled "*Characterization of project time extension effects resulting from multiple activity delays on resource-constrained construction schedules*", submitted to *Journal of Construction Engineering and Management, ASCE* for publication.

4.1 PTE-ATE Relationships of Multiple Activity Delays

As discussed in Chapter 3, the magnitude of TF essentially represents the amount of time by which the time duration of a particular activity can be delayed without extending the project time which is scheduled by the forward pass of CPM analysis, subject to the fact that time duration on all other activities on the project remain at their original values (ATE = zero).

TF can be interpreted in a straightforward way as the maximum ATE that is allowable such that the PTE is kept as zero, which means the project completion time as determined from the CPM scheduling analysis will not be prolonged. Furthermore, for delay analysis and control on a construction schedule, the TF definition can be broadened by associating a specific delay time (*e*, being greater than zero) on the scheduled project completion date (i.e. PTE = *e*). In other words, the TF is a non-negative activity attribute devised as a control measure in order to effectively keep ATE in check with the objective of avoiding or minimizing PTE. As such, given a specific delay time *e*, TF is the maximum ATE that is allowable on one individual activity such that the PTE is kept as *e*, while all the other activities hold their original duration (ATE = zero).

However, activity delays often involve two or more activities (i.e. ATE occurring on two or more activities), such as the concurrent delays (Kraiem and Diekmann 1987; Arditi and Robinson 1995; Holloway 2002), making it difficult to control PTE in practice. Multiple activity delays could complicate the determination of PTE on the scheduled project duration (denoted as *e*). If PTE is taken as the output of a project scheduling function with ATE on each activity as the input variables, then the TF relates the output with the input variables in a way analogous to taking the partial derivative of PTE along ATE for one particular activity. With resource constraints imposed to CPM scheduling including daily available limits and non-working time defined by resource calendars, the function relating PTE with ATE on each activity for a project network turns from a straightforward linear function into a convoluted non-linear one, as illustrated in the Figs. 4.1 and 4.2. On the same project network, two activities are potentially delayed with ATE of Activity A increasing from the zero day to ten days, while the ATE of Activity B increasing from zero days to thirteen days. By imposing resource constraints, the PTE-ATE function exhibits high non-linearity which changes from a slanted plane into a “wrinkled” surface.

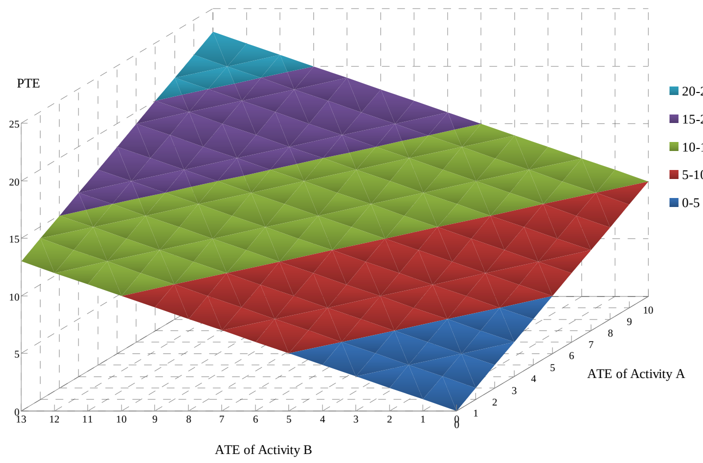


Fig. 4.1: PTE-ATE linear property

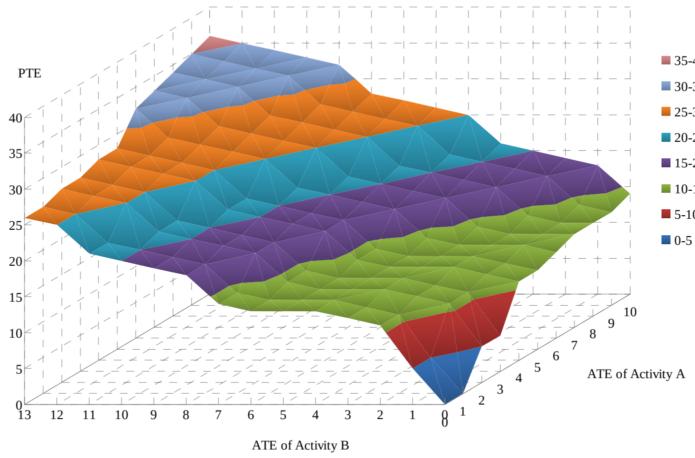


Fig. 4.2: PTE-ATE non-linear property

The present research is not intended to mathematically model the non-linear response surface of PTE given ATE occurring at multiple activities on a project, which is highly complicated and can vary depending on scenarios and projects. Instead, a scheduling simulation approach is adopted to simulate the PTE response surface in relation to known ATE on particular activities of a project. In other words, instead of formulating explicit mathematical equations, the PTE-ATE relationships are accurately modeled by a scheduling simulation model, which will make it possible for further analysis that is reminiscent of taking partial derivatives at a given point on the "wrinkled" surface, eventually resulting in the determination of TF associated with relevant activities. The TF will provide the control measure to be effectively taken at activity level in order to bring PTE in check.

4.2 Illustrative Case

The relationships between ATE and PTE in the context of multiple activity delays are elucidated by a simple project network which is taken from Kraiem and Diekmann (1987) identical to Section 3.3. The project network consists of three paths, namely, Path I being "ST-2-5-8-10-EN"; Path II being "ST-2-4-7-EN"; and Path III being "ST-1-3-6-9-EN". Based on the example project, two scheduling scenarios are contrasted and analyzed in order to characterize the PTE-ATE relationships, namely, (1) a base case scenario without any resource or calendar constraints, and (2) a resource-constrained scenario in which resource non-working time are specified as calendar constraints. Because a non-critical activity will not exert any effects on PTE unless the ATE reaches such a threshold that the non-critical activity actually turns into a critical one, the generalization of the PTE-ATE relationships was limited to multiple critical activities lying on one or two critical paths.

4.2.1 Base Case Scenario

The base case scenario is straightforward CPM analysis without any resource constraints (such as resource limits and calendars). The project completion time is 23 days with both Path I and III being identified as critical while Path II being non-critical. Only Activities 4 and 7 on Path II own six-day TF.

In general, if the two activities belong to one critical path, the PTE is equal to the summation of individual ATE on the two activities. For example, in the present case, Activities 5 and 10 belong to the same critical Path I. Given any combinations of ATE on the two activities, the resulting PTE is simply to add up individual ATE on the two activities. Table 4.1 shows the resulting PTE when ATE on Activity 5 and 10 are up to five days. Note the linear “addition” relationships hold valid on each ATE_5-ATE_{10} combination in Table 4.1. The number in each cell is the summation of associated values of ATE_5 and ATE_{10}. For instance, when ATE_5 = 3 days, ATE_{10} = 2 days, the PTE is 5 days; when ATE_5 = 0 day, ATE_{10} = 5 days, the PTE is 5 days.

If the two activities belong to different critical paths, then the PTE is equal to the maximum ATE value of the two activities. The “maximum” relationships exist on each ATE combinations. For example, when Activities 3 on Path III and Activities 5 on Path I are delayed simultaneously, the resulting PTE is equal to the maximum value of ATE of Activities 3 and 5. Table 4.2 shows the PTE value when ATE on Activities 3 and 5 are up to five days, respectively. The PTE consistently equates with the maximum value of the associated ATE_3 and ATE_5. For instance, when ATE_3 = 2 days, ATE_5 = 3 days, the PTE is 3 days; when ATE_3 = 0 days, ATE_5 = 5 days, the PTE is 5 days.

ATE_5 \ ATE_{10}	0	1	2	3	4	5
0	0	1	2	3	4	5
1	1	2	3	4	5	6
2	2	3	4	5	6	7
3	3	4	5	6	7	8
4	4	5	6	7	8	9
5	5	6	7	8	9	10

Table 4.1: PTE results from ATE_5 and ATE_{10} in non-resource-constrained schedule

ATE_5 \ ATE_3	0	1	2	3	4	5
0	0	1	2	3	4	5
1	1	1	2	3	4	5
2	2	2	2	3	4	5
3	3	3	3	3	4	5
4	4	4	4	4	4	5
5	5	5	5	5	5	5

Table 4.2: PTE results from ATE_3 and ATE_5 in non-resource-constrained schedule

4.2.2 Resource-Constrained Scenario

When resource constraints are imposed to a CPM schedule, the “addition” and “maximum” relationships between ATE and PTE on multiple activities of a project do not hold any more. Instead, the PTE is related with ATE in a highly non-linear fashion in the context of a resource-constrained schedule. Given the same combination on activity delays, the resulting PTE is generally greater than that obtained in the base case scenario having no resource constraints; the exact magnitude of PTE is dependent on the particular combination of activity delays and specific project constraints on precedence and resources; thus, it can be readily determined by scheduling simulation instead of analytical approach.

In the current case, resource work-time constraints in terms of activity calendars are imposed to the “base case” schedule. It is assumed that the project team runs on four-working-day weeks, taking Friday to Sunday off. As a result, the project completion time extends from 23 days to 38 days. The significant increase of project completion time is mainly due to activity interruptions in connection with the non-working time periods that are defined on activity calendars, as mentioned in Section 3.3.

Similarly, Activities 5 and 10 are selected to illustrate the PTE-ATE relationships given two activities residing on the same critical path. Table 4.3 shows the resulting PTE when ATE on Activity 5 and 10 are up to five days. Note the PTE is equal to the summation of ATE in three combinations only when ATE_5 is zero or one day and ATE_{10} is also zero or one day, which are bolded in Table 4.3. For the majority of combinations, the number in each cell is greater than the summation of the associated values of ATE_5 and ATE_{10}. For instance, when ATE_5 = 3 days, ATE_{10} = 2 days, the PTE is 8 days (instead of 5 days); when ATE_5 = 0 day, ATE_{10} = 5 days, the PTE is 8 days (instead of 5 days).

Activities 3 and 5 are selected to demonstrate the PTE-ATE relationships in connection with multiple activity delays occurring on two different critical paths in the resource-constrained scenario (Table 4.4). The PTE is no longer to take the maximum of ATE of the two activities in each combination of activity delays. As a result of the imposed resource calendar constraints, the PTE is generally greater than the maximum ATE. For instance, when ATE_3 = 2 days, ATE_5 = 3 days, the PTE is 6 days (instead of 3 days); when ATE_3 = 0 days, ATE_5 = 5 days, the PTE is 8 days (instead of 5 days).

ATE_5 \ ATE_{10}	0	1	2	3	4	5
0	**0**	**1**	5	6	7	8
1	**1**	5	6	7	8	12
2	5	6	7	8	12	13
3	6	7	8	12	13	14
4	7	8	12	13	14	15
5	8	12	13	14	15	19

Table 4.3: PTE results from ATE_5 and ATE_{10} in resource-constrained schedule

ATE_5 \ ATE_3	0	1	2	3	4	5
0	0	1	5	6	7	8
1	1	1	5	6	7	8
2	5	5	5	6	7	8
3	6	6	6	6	7	8
4	7	7	7	7	7	8
5	8	8	8	8	8	8

Table 4.4: PTE results from ATE_3 and ATE_5 in resource-constrained schedule

4.3 Total Float Determination for Project Control

Based on an in-depth understanding of the PTE-ATE relationships subject to multiple activity delays, the definition of TF is extended in order to enable effective control on PTE when activity delays occur on a specific set of activities in a project network.

As given in Eq. (4.1), the TF of Activity *k* on a particular set of activities (*S*) is defined, given that ATE on each activity in *S* and project time extension *e* are known. Note, all the other activities on the project that do not belong to *S* hold their original activity times without any delays (ATE = zero day).

$$\mathrm{TF}_{k\in S}\left|\begin{array}{l}\mathrm{ATE}_{k,\,k\in S}\\ \mathrm{PTE}=e\end{array}\right. \tag{4.1}$$

The TF implication is put simply as follows: If activity delays occur on a specific set of activities on a project which result in a particular PTE (*e*) to the original project completion time, how many days of further delay on those already delayed activities are allowable so as to keep the PTE at *e*? Note the classic TF definition is actually a particular instance of Eq. (4.1) when only one activity at a time is included in *S* while ATE on all the other activities are zero and the PTE are kept as zero. In order to determine the TF value based on the scheduling simulation, the algorithm is devised as shown in Fig. 4.3.

Similar to Section 3.1, PTE (*e*) is firstly pre-set by users according to Fig. 4.3. The proposed methodology provides the flexibility in characterizing the relationships between project delay and multiple activity delays for a specific scenario which is delineated by a specific PTE level of *e*. In other words, PTE, which is observed through simulation by increasing ATE, is used to compare against the pre-set *e* value that represents a threshold specified by the planner so as to evaluate TF.

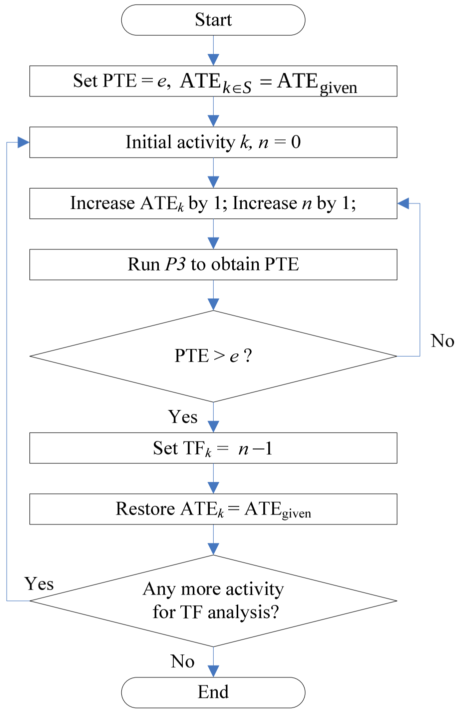


Fig. 4.3: TF determination algorithm flowchart given specific PTE with a set of delayed activities

The steps for determining TF based on the proposed algorithm are elaborated with the following example: The example project scheduled in the resource-constrained scenario (under activity calendar constraints) is considered. Given the project time extension is six days (e = 6 days), there is two-day delay on Activity 3 (ATE_3 = 2 days) and three-day delay on Activity 5 (ATE_5 = 3 days), as underlined in Table 4.4. In this case, the two activities are included in the delayed activity set S. All the other activities have zero delay, which implies their activity times are the original values as shown in Table 3.1.

Steps to evaluate TF_3:

- Set the *e* as 6 days, the delay on Activity 3 as 2 days (ATE_3 = 2 days) and the delay on Activity 5 as 3 days (ATE_5 = 3 days).
- Select current Activity 3 from set *S* and holding ATE_5 as 3 days; initialize *n* as zero;
- $ATE_3 = ATE_3 + 1$, so $ATE_3 = 2 + 1 = 3$ days; $n = 0 + 1 = 1$;
- Evaluate PTE by running forward pass in *P3* based on current ATE on all the activities of the project (ATE_3 = 3 days, ATE_5 = 3 days, all the others having zero ATE), resulting in 6 days PTE;
- Because 6 days PTE is not greater than *e* (6 days), then go to step 3;
- $ATE_3 = ATE_3 + 1$, so $ATE_3 = 3 + 1 = 4$ days; $n = 1 + 1 = 2$;
- Evaluate PTE by running forward pass *P3* based on current ATE on all the activities of the project (ATE_3 = 4 days, ATE_5 = 3 days and all the others having zero ATE), resulting in 7 days PTE;
- Because 7 days PTE is greater than *e* (6 days), then move to step 6;
- $TF_3 = 2 – 1 = 1$ day, and restore ATE_3 = 2 days.

Next, similar steps are followed to evaluate TF_5:

- Select current Activity 5 from set *S* (ATE_5 = 3 days) and holding ATE_3 as 2 days; initialize *n* as zero;

- $ATE_5 = ATE_5 + 1 = 3 + 1 = 4$ days; $n = 0 + 1 = 1$;
- Evaluate PTE by running forward pass *P3* based on current ATE on all the activities of the project ($ATE_5 = 4$ days, $ATE_3 = 2$ days and all the others having zero ATE), resulting in 7 days PTE;
- Because 7 days PTE is greater than *e* (6 days), then move to step 6;
- $TF_5 = n – 1 = 1 – 1 = 0$ day.

All the activities in the current set of delayed activities have been processed, the results are: when the project is resource-constrained, given project time extension is controlled at six days, and there is two-day delay occurring on Activity 3 and three-day delay on Activity 5, TF on Activities 3 and 5 are one day and zero day respectively.

It is noteworthy that the TF of all activities would change after the delays have been imposed. The proposed simulation-based activity total float determination methodology in indeed provides the flexibility of handling activities which have been classified as "already delayed" / "to be further delayed" / "non-delayed". Table 4.5 shows the TF evaluated based on two activities (including one "already delayed" activity, plus one non-delayed or "to be delayed" activity). The practitioners could evaluate all the activities concerned, which may include some or all the activities composing the project network, depending on the actual application needs on a practical project.

In the present case study, when the project time extension (*e*) is set as five days, the TF determination by the proposed algorithm is summarized in Table 4.5 for four examples. In the base case scenario, given ATE on activities 5 and 10 are zero and five days respectively, TF on both activities are determined as zero, meaning neither can be further delayed otherwise PTE will be greater than five days; Given Activities 3 and 5 are delayed by zero and five days respectively, TF_3 is determined as five days, meaning any further delays on Activity 3 under five days will not further extend the project completion time (*e* staying at five days), while TF_5 is zero, which implies any further delays on Activity 5 will cause PTE greater than the pre-set five days.

The last two examples in Table 4.5 are both associated with the resource-constrained scheduling scenario on the current case study. Still, the PTE is kept at five days, given delays on Activities 5 and 10 are two days and zero respectively. The resulting TF on both activities are zero. Given ATE on Activities 3 and 5 are zero and two days, Activity 3 has two-day TF while Activity 5 has zero TF.

Worth mentioning is that the classic definition of TF is an attribute of Activity *i* in order to control delay on Activity *i* (ATE_i) given the ATE_k ($k \neq i$) and PTE are all set as zero. The proposed TF determination methodology broadens the TF definition and provides the flexibility to characterize the relationships between project delay and multiple activity delays for a specific scenario which is delineated by a specific PTE level of *e* and a specific set of activities with known ATE on each.

Activity Delay Combinations	Project Extension	Scheduling Scenario	TF Determination
$ATE_5 = 0$ $ATE_{10} = 5$	PTE = 5	Base case	$TF_5 = 0$, $TF_{10} = 0$ | $ATE_5 = 0, ATE_{10} = 5$, $PTE = 5$
$ATE_3 = 0$ $ATE_5 = 5$	PTE = 5	Base case	$TF_3 = 5$, $TF_5 = 0$ | $ATE_3 = 0, ATE_5 = 5$, $PTE = 5$
$ATE_5 = 2$ $ATE_{10} = 0$	PTE = 5	Resource-constrained	$TF_5 = 0$, $TF_{10} = 0$ | $ATE_5 = 2, ATE_{10} = 0$, $PTE = 5$
$ATE_3 = 0$ $ATE_5 = 2$	PTE = 5	Resource-constrained	$TF_3 = 2$, $TF_5 = 0$ | $ATE_3 = 0, ATE_5 = 2$, $PTE = 5$

Table 4.5: TF determinations based on the TF algorithm

4.4 Practical Application

The highway widening construction project was used for this case study, similar to Section 3.4. The project completion time control that is enabled by TF determination based on activity delays is demonstrated in three scenarios being postulated, they are: (1) control on single activity time delay in delayed activity set *S*; (2) control on multiple delayed activities given a specified value project time extension; (3) control multiple delayed activities given a range of project time extension.

Activity 25 is selected in scenario one. The ATE_{25} and the corresponding PTE is tabulated (Table 4.6) by running forward pass in *P3*. The analysis is based on the assumption that ATE on all the activities of the project remain zero except for Activity 25, which incurs various ATE.

The PTE-ATE relationships are highly non-linear in the CPM schedule subject to constraints of resource availabilities and calendars. The discrete jump of the PTE (e.g. from zero to seven days) is attributable to the resource constraints being imposed on the schedule, as such, the PTE cannot reach each unit increment value on the likely range. In this case, when PTE is greater than zero as a result of ATE, the minimum value of PTE is seven days in connection with an ATE of four days on Activity 25. Note it is impossible to materialize one-day to six-day PTE from the scheduling analysis, similar to Section 3.4.

The TF_{25}, given a particular combination of ATE_{25} and PTE, are also determined in Table 4.6. It is noteworthy that the value of TF_{25} (TF_{25} = 3 days) is equivalent to classic TF definition when the PTE is zero and ATE_{25} is zero, which denotes the early finish time (EF) can be delayed up to three days so as not to extend the project completion time (606 days) resulting from the resource-constrained schedule simulated by *P3*.

In contrast, the TF is broadened to cope with PTE greater than zero. For instance, given that Activity 25 is delayed by four days (ATE_{25} = 4 days), the project completion time is delayed by seven days (PTE = 7 days), the value of TF_{25} is determined as four days, implying that as long as any further delays on Activity 25 is controlled under four days, the project completion time extension will be controlled under seven days.

ATE_{25}	PTE	TF_{25}
0	0	3
1	0	2
2	0	1
3	0	0
4	7	4
5	7	3
6	7	2
7	7	1
8	7	0
9	12	1
10	12	0

Table 4.6: TF_{25} with corresponding ATE_{25} and PTE

In the second scenario, three activities (Activities 18, 25 and 31) are delayed due to inclement weather and unexpected traffic and soil conditions, extending the project completion by two weeks (fourteen days). Thus, it is assumed that the contractor is entitled to a two-week time extension in this scenario. Thus, the *e* is pre-set to 14 days. Given the three activity delays, TF are evaluated by the proposed methodology. The project completion date is postponed to 05 January 2001 (Friday). Three settings are postulated to illustrate the practical uses of TF for project and activity delay analysis: (1) ATE_{18} = 1 day, ATE_{25} = 4 days, ATE_{31} = 2 days; (2) ATE_{18} = 4 days; ATE_{25} = 0 days; ATE_{31} = 4 days; (3) ATE_{18} = 5 days, ATE_{25} = 3 days, ATE_{31} = 3 days. By running *P3* scheduling analysis, all above settings result in increasing the project completion time to 620 days (PTE = 14 days).

There are many combinations and permutations of activities which could result in 14-day project time extension. In the case study, a great effort has been spent in testing all the combinations and permutations resulting *e*-day delay only in connection with the three activities predisposed to delays by trial and error. However, the purpose of including this illustrative case is to illustrate the TF applications, with particular emphasis on how to control the ATE in order to keep PTE under control, instead of providing a method for finding all the combinations and permutations on all the activities resulting in *e*-day project delay. Besides, it is important to calculate the TF of "already delayed", "to be further delayed" and "non-delayed" activities. The activity delays could change the amount of TF. The scenario settings are connected with the actual project management practices when additional project time is granted to the contractor because of excusable delays. The contractor is committed to completing the project without incurring any further project time extensions. Therefore, to keep the PTE as fourteen days, the project manager is required to control the delayed activities within their corresponding TF in this scenario. The TF are determined and tabulated in Table 4.7.

Setting 1: Given all three activities have been delayed by a certain amount of time, Activities 18 and 31 become critical with zero TF while Activity 25 has four-day TF. This means only Activity 25 can be further delayed up to a maximum of four days in order to keep the fourteen-day PTE from being prolonged.

Setting 2: Only two of the three activities have delayed: Activities 18 and 31 are delayed by 4 days each. There is zero delay on Activity 25 (ATE_{25} = 0 days). From the TF analysis, Activity 18 is critical with zero TF. Activities 25 and 31 have three-day and one-day TF, respectively. This implies that either Activity 25 could be delayed for a maximum of three days or Activity 31 delayed for one day only, as such, the project completion time will not be extended beyond fourteen days.

Setting 3: All the three activities are delayed (ATE_{18} = 5 days, ATE_{25} = 3 days, ATE_{31} = 3 days). The TF determination identifies all the three activities as being critical. This implies any activity delays will prolong the project completion time beyond fourteen days.

ATE_{18}	ATE_{25}	ATE_{31}	TF Determination
1	4	2	$TF_{18}=0$, $TF_{25}=4$, $TF_{31}=0$ | $ATE_{18}=1, ATE_{25}=4, ATE_{31}=2$; $PTE=14$
4	0	4	$TF_{18}=0$, $TF_{25}=3$, $TF_{31}=1$ | $ATE_{18}=4, ATE_{25}=0, ATE_{31}=4$; $PTE=14$
5	3	3	$TF_{18}=0$, $TF_{25}=0$, $TF_{31}=0$ | $ATE_{18}=5, ATE_{25}=3, ATE_{31}=3$; $PTE=14$

Table 4.7: Delay combinations of ATE_{18}, ATE_{25}, ATE_{31} and the corresponding PTE with TF expressions

The last scenario considers five activities (Activities 18, 25, 31, 39, 53b) which make up the delayed activity set *S*, as bolded in Fig. A.4, assuming that Activity 18 is delayed by five days, and both Activities 25 and 31 are delayed by three days, while there are not yet any delays on Activities 39 and 53b. Suppose that the three delayed activities (ATE_{18} = 5 days, ATE_{25} = 3 days, ATE_{31} = 3 days) are entitled to claiming fourteen days project time extension, as shown by the results for Setting 3 in Table 4.7. In addition, a maximum of seven days additional time extension to project completion time is granted for likely delays on Activity 39 and 53b. Totally, a maximum of twenty-one day of PTE is allowed to complete the current project. Note that delays on Activities 18, 25, and 31 may have already happened or expected to happen. TF is determined for each of the delayed activities within the set *S*. Thus, bound between fourteen-day PTE and twenty-one-day PTE, the project completion date must fall between 05 January 2001 (Friday) and 27 January 2001 (Friday).

To cope with this practical scenario, the TF determination methodology being proposed can be applied and TF evaluated based on the PTE ranging from fourteen days to twenty-one days. As a result, Activity 39 owns the smallest value of three-day TF and hence is the more critical than Activity 53b which has four-day TF. In order to verify the results, the following "what-if" scenarios were tested based on Activity 39: (1) if Activity 39 is delayed by three days, Activity 53b does not experience any delays, then, run *P3* to evaluate this current scenario in which ATE_{39} = 3 days, ATE_{53b} = 0 days are added to the other three activity delays (ATE_{18} = 5 days, ATE_{25} = 3 days, ATE_{31} = 3 days). This yields the project duration of 627 days, representing twenty-one-day of PTE against the original project completion time (606 days). (2) If Activity 39 is delayed by four days, i.e. one day beyond the available TF, the activity input scenario is updated to result in the project duration of 631 days, or twenty-five days of PTE which exceeds the allowable twenty-one days of PTE on the project. Thus, the new TF determination methodology provides a boarder perspective for project and activity time extension control in construction management.

4.5 Chapter Summary

In the previous chapter, the TF definition is revisited based on the relationships between activity time extension (ATE) on an individual activity and project time extension (PTE). Given a specific delay time *e*, TF is the maximum ATE that is allowable on one individual activity such that the PTE is kept as *e*, while all the other activities hold their original duration (ATE = zero). As an extension to the TF determination problem defined in the Chapter 3 which concerns the delay on one activity at a time, Chapter 4 deals with a more complicated yet more realistic project scheduling setting that involves multiple activity delays on a resource-constrained schedule. In this chapter, the TF are evaluated for a specific set of activities (*S*) such that the particular project time extension (*e*) will not be prolonged further, if activity delays for each activity involved occur on a project resulting in the time extension *e*. The present research is not intended to mathematically model the non-linear response surface of PTE given ATE occurring at multiple activities on a project, which is highly complicated and can vary depending on scenarios and projects. Instead, a scheduling simulation approach is adopted to simulate the PTE response surface in relation to known ATE on particular activities of a project. In other words, instead of formulating explicit mathematical equations, the PTE-ATE relationships are accurately modeled by a scheduling simulation model, which will make it possible for further analysis that is reminiscent of taking partial derivatives at a given point on the “wrinkled” surface, eventually resulting in the determination of TF associated with relevant activities. The mainstream scheduling software, Primavera® P3™ Project Planner (*P3*) is used in the current research for conducting forward pass scheduling simulations in order to model the PTE-ATE relationships. The resulting TF will provide the control measure to be effectively taken at activity level in order to bring PTE in check. Based on in-depth understandings and discussions of project and activity time extensions in Chapter 3 and 4, the following chapter improves the earned value management (EVM) framework, which is utilized for tracking the project schedule and cost performances under delay scenarios.

CHAPTER 5

IMPROVING EARNED VALUE MANAGEMENT

Based on the in-depth understanding of project and activity time extensions in the TF determination study, this chapter focuses on the associated cost implications in improving earned value management (EVM) for schedule and cost monitoring and control, under project time extension scenarios. As mentioned in Section 2.5, EVM is often employed to analytically track the project status. In order to truly reflect project performances, the availability of a precise resource-constrained schedule is the prerequisite to implementing EVM on a construction project. To tackle the complexity in generation of an accurate resource-constrained schedule, scheduling simulation provides the cost effective solution. However, the EVM techniques, which assume an ideal baseline schedule, are inadequate to tackle resource-constrained scheduling under delayed scenarios. Under activity delay scenarios, ATE contributes to the schedule change with a similar effect as changing scope on the project. On the other hand, the classic EVM approach lacks a standardized method to tackle this situation. For example, the PV of a delayed activity is questionable after the delay has occurred. Should the PV keep constant or increase? The rationale of EVM is to keep the activity budget cost as constant. The reason is that PV resembles the scheduled scope of work, and is used to

This chapter is based on a paper entitled "*Scheduling simulation-based techniques for earned value management on resource-constrained schedules under delayed scenarios*" to be published in *Proceedings of Winter Simulation Conference 2011, Phoenix, Arizona, The United States of America*.

compare with EV in evaluating schedule execution performances (i.e. to determine if the project is performing on / ahead of / behind schedule). However, the PV is usually defined based on the daily resource consumption during construction, similar to EV and AC parameters. Thus, keeping PV constant in EVM can be misleading. Thus, the framework is refined based on precise analyses of project time extension and project cost increment by taking advantages of both CPM and EVM frameworks which are discussed in Section 2.6, The EVM implementation is based on simulation of resource-constrained CPM schedules. A simple case example which is taken from Ahuja et al. (1994) is used to demonstrate the application of improved EVM techniques on a resource-constrained schedule under complicated activity-project delay scenarios, and revealing deficiencies of EVM indicators.

5.1 Improved EVM Approach for Project Monitoring and Control

The improved EVM approach is proposed to address delayed scenarios based on the simulated resource-constrained schedules, so as to enhancing the accuracy of EVM indicators. The traditional EVM approach mentioned in Section 2.5 is only applicable to a project with a steady scope. The PV defines the budget with a precise scope definition (without variations or project delays); the BAC is fixed given a fixed project scope. The indicators can be ambiguous in case of delays because project and activity delays may imply scope change has taken place on the project.

Given project and activity delays, EV may continue to increase during the delays according to the activity-resource requirements. An unrealistic SPI value would be produced if PV remains unchanged. Thus, PV/EV/AC must be updated accordingly as a result of the encountered delays. The refined approach modifies the EVM equations as (5.1) to (5.3). The delayed activity PV is updated, which takes into account the delayed time and the original PV per day. The PV of non-delayed activity remains unchanged according to the original planned schedule. EV is calculated according to the updated PV for the delayed activities. The percentage of work completed indicates the extra work has been completed during the delay. The increment of PV or EV reflects scope variation in terms of time and cost. On the other hand, the cost associated with project time extension (PTE) such as liquidated damage, denoted as “cost per day”, is included in the calculation of delayed activity’s AC. It is noteworthy that the calculated EVM indicators are compatible with the original EVM terminology, with particular emphasis on practical applications in the context of delayed scheduling scenarios.

The assumption of the proposed framework is: the baseline ideal schedule being used is equal to the planned resource-constrained CPM schedule. The established EVM approach is therefore triggered by revising the resource-constrained CPM schedule to obtain the associated delayed schedule. PTE (project time extension) can be obtained by comparing the project completion time of the as-planned and as-built schedules. Then, by using the modified PV/EV/AC equations (still retaining the original implications of all the performance indicators as defined in EVM) to recalculate all the essential EVM parameters, such as recalculating the PV of delayed activity according to daily resource requirements under delayed scenarios, the EVM indicators are updated based on all the adjusted parameters (PV/EV/AC) to reflect the changes in the resource-constrained CPM schedule.

However, all the EVM indicators only reflect project performances according to the delayed schedule (updated). In bridging both EVM and CPM frameworks, PV in EVM analysis is deliberated based on the early start time (ES) and early finish time (EF) from CPM analysis by *P3* forward pass scheduling simulations. The steps are illustrated in the ensuing case study.

$$\text{Delayed Activity PV} = (\text{PV / Day}) \times \text{Duration from Early Start to Data Date} \tag{5.1}$$

$$\text{Delayed Activity EV} = \text{Delayed Activity PV} \times \text{Percentage of Work Completed} \tag{5.2}$$

$$\text{Delayed Activity AC} = \text{AC} + (\text{PTE} \times \text{Cost / Day}) \tag{5.3}$$

5.2 Illustrative Case

The case study project network is taken from Ahuja et al. (1994) to demonstrate the improved EVM framework. The scheduling network (Fig. 5.1) plus activity time and resource requirements is shown (Table 5.1). The project consists of nine activities and two resource types. The resource availability limits are 6 laborers and 1 crane on a daily basis. Multiple calendar constraints are also imposed on driving resources. The laborers run on 6 work-day weeks, taking Sunday off; while the crane runs on 5 work-day weeks, taking both Saturday and Sunday off. The cost information is shown in Table 5.2, and liquidated damage per day is assumed at $5000/day.

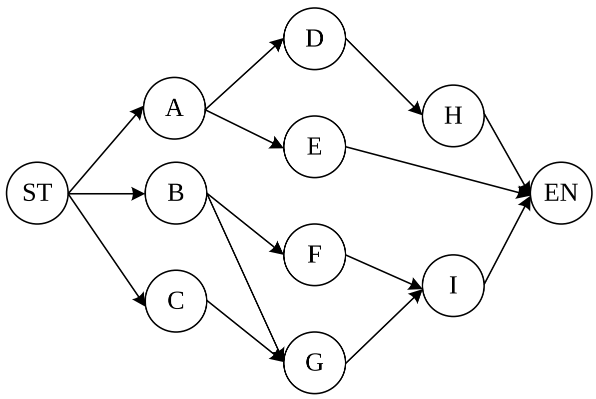


Fig. 5.1: Scheduling network diagram for example project which is taken from Ahuja et al. (1994)

Activity	Duration (days)	Resource Requirement		Priority
		Labor	Crane	
A	2	4	1	7
B	3	4	0	8
C	5	4	0	9
D	4	3	0	3
E	4	1	0	4
F	3	2	1	5
G	6	2	0	6
H	2	2	1	1
I	3	2	0	2

Table 5.1: Activity and resource requirements for example project which is taken from Ahuja et al. (1994)

Cost Types	PV ($ / Day)	AC ($ / Day)
Labor	500.00	700.00
Crane	2000.00	1800.00

Table 5.2: Cost requirements for example project which is taken from Ahuja et al. (1994)

Similar to Chapter 3 and 4, Primavera® P3™ Project Planner (*P3*) was firstly employed for forward pass scheduling simulation. The automatic leveling by built-in heuristic rules of *P3* generates activity execution sequence with activity priorities given in Table 5.1. The activity prioritization rule used is “late start, total float” which is set as default in *P3*. The specific details are not given in *P3* help files. These parameters are evaluated in *P3* as the criteria to define its built-in heuristic rules for resource allocation and leveling on a CPM schedule. *P3* produces the resource-constrained schedule with 23 days project completion time. Based on this resource-constrained schedule, the associated direct cost can be budgeted with respect to activities' early start and finish times (Table 5.3).

The activity daily costs are calculated by using Tables 5.1 and 5.2 (i.e. the resource requirements in Table 5.1 times the corresponding daily cost rates given in Table 5.2). The activity daily costs for as-planned and as-built schedules are different as the PV and AC of resources slightly differ in this assumed scenario, while the daily activity resource requirements remain unchanged. For instance, the planned daily cost of Activity C is \$2000.00 / Day (i.e. \$500.00 per day per laborer$\times$4 laborers). The actual daily cost changes to \$2800.00 / Day (i.e. \$700.00 per day per laborer$\times$4 laborers).

The cost budget for the total project without any activity and project delays is \$56000.00. Next, two delayed scenarios are postulated: (1) considering one activity delay, and (2) considering multiple activity delays.

Planned Resource-Constrained Schedule													
	1	2	3	4	5	6	**7**	8	9	10	11	12	13
A	0	0	0	0	0	0	**0**	0	0	4000	4000	0	0
B	0	0	0	0	0	2000	**0**	2000	2000	0	0	0	0
C	2000	2000	2000	2000	2000	0	**0**	0	0	0	0	0	0
D	0	0	0	0	0	0	**0**	0	0	0	0	0	0
E	0	0	0	0	0	0	**0**	0	0	0	0	500	500
F	0	0	0	0	0	0	**0**	0	0	0	0	3000	0
G	0	0	0	0	0	0	**0**	0	0	1000	1000	1000	1000
H	0	0	0	0	0	0	**0**	0	0	0	0	0	0
I	0	0	0	0	0	0	**0**	0	0	0	0	0	0
Daily Cost	2000	2000	2000	2000	2000	2000	**0**	2000	2000	5000	5000	4500	1500
Cumulative	2000	4000	6000	8000	10000	12000	**12000**	14000	16000	21000	26000	30500	32000
	14	15	16	17	18	19	20	**21**	22	23	-	-	-
A	**0**	0	0	0	0	0	0	**0**	0	0	-	-	-
B	**0**	0	0	0	0	0	0	**0**	0	0	-	-	-
C	**0**	0	0	0	0	0	0	**0**	0	0	-	-	-
D	**0**	0	0	1500	1500	1500	1500	**0**	0	0	-	-	-
E	**0**	500	500	0	0	0	0	**0**	0	0	-	-	-
F	**0**	3000	3000	0	0	0	0	**0**	0	0	-	-	-
G	**0**	1000	1000	0	0	0	0	**0**	0	0	-	-	-
H	**0**	0	0	0	0	0	0	**0**	3000	3000	-	-	-
I	**0**	0	0	1000	1000	1000	0	**0**	0	0	-	-	-
Daily Cost	**0**	4500	4500	2500	2500	2500	1500	**0**	3000	3000	-	-	-
Cumulative	**32000**	36500	41000	43500	46000	48500	50000	**50000**	53000	56000	-	-	-

Delayed Resource-Constrained Schedule													
	1	2	3	4	5	6	**7**	8	9	10	11	12	13
A	0	0	0	0	0	0	**0**	0	0	4600	4600	4600	0
B	0	0	0	0	0	2800	**0**	2800	2800	0	0	0	0
C	2800	2800	2800	2800	2800	0	**0**	0	0	0	0	0	0
D	0	0	0	0	0	0	**0**	0	0	0	0	0	0
E	0	0	0	0	0	0	**0**	0	0	0	0	0	0
F	0	0	0	0	0	0	**0**	0	0	0	0	0	0
G	0	0	0	0	0	0	**0**	0	0	1400	1400	1400	1400
H	0	0	0	0	0	0	**0**	0	0	0	0	0	0
I	0	0	0	0	0	0	**0**	0	0	0	0	0	0
Daily Cost	2800	2800	2800	2800	2800	2800	**0**	2800	2800	6000	6000	6000	1400
Cumulative	2800	5600	8400	11200	14000	16800	**16800**	19600	22400	28400	34400	40400	41800
	14	15	16	17	18	19	20	**21**	22	23	24	25	-
A	**0**	4600	4600	4600	0	0	0	**0**	0	0	0	0	-
B	**0**	0	0	0	0	0	0	**0**	0	0	0	0	-
C	**0**	0	0	0	0	0	0	**0**	0	0	0	0	-
D	**0**	0	0	0	2100	2100	2100	**0**	2100	0	0	0	-
E	**0**	0	0	0	700	700	700	**0**	700	0	0	0	-
F	**0**	0	0	0	3200	3200	0	**0**	3200	0	0	0	-
G	**0**	1400	1400	0	0	0	0	**0**	0	0	0	0	-
H	**0**	0	0	0	0	0	0	**0**	0	3200	3200	0	-
I	**0**	0	0	0	0	0	0	**0**	0	1400	1400	1400	-
Daily Cost	**0**	6000	6000	4600	6000	6000	2800	**0**	6000	4600	4600	1400	-
Cumulative	**41800**	47800	53800	58400	64400	70400	73200	**73200**	79200	83800	88400	89800	-

Table 5.3: Activity cost calculations for planned and delayed schedules

In the first delayed scenario, Activity A's duration is delayed from two days to six days, which ends at one day beyond its late finish time (LF). The resulting delayed schedule, which was also generated by *P3* based on the same activity priorities as in the original non-delay case, is shown in Table 5.3.

The intention of fixing the activity priorities is to facilitate the comparison of cost and time changes on the project as a result of activity delays in earned value analysis (the variable of activity sequencing for resource-allocation is removed). This is also to be in line with current construction management practice. The delays are often developed during the project execution, and generally unforeseeable during the planning stage. If the delays occur, the contractor usually directly imposes the activity delays to the planned schedule using delay analysis techniques while keeping the as-planned activity sequencing in resource allocation.

Note the schedule will change if re-scheduling is done by using *P3*, different activity sequences and schedules will result. Thus, the activity priorities has fixed according to the planned schedule in this case study. The delayed schedule is manually done based on the planned schedule with identical activity priorities. Note that the enhanced EVM approach can also be applied if any re-scheduling is needed. Then, the EVM indicators can be evaluated based on the updated schedule with different activity priorities.

After imposing the delays of Activity A on the planned schedule, the project completion time increases from twenty-three days to twenty-five days. According to Eqs. (3.1) and (3.2), ATE is 4 days and PTE is 2 days. The result shows the PTE-ATE relationships exhibit non-linearity. Table 5.3 also tabulates the actual cost for this delayed schedule. Days 7, 14 and 21 are assumed to incur zero direct cost (as bolded) as they are non-working days. The project cost increases from $56000.00 (according to the originally planned schedule) to $89800.00 (according to the updated schedule) due to additional activity expenses.

Because Activity A owns 3-day TF, its completion time can be delayed from Day 12 to 15 without extending the project completion time (PTE = 0 day). However, PV and EV on the delayed Activity A are updated according to Eqs. (5.1) and (5.2) respectively. For instance, on Day 11, PV is (4000.00×2) = $8000.00; EV is $(8000.00 \times 2/6)$ = $2666.67; AC is (4600.00×2) = $9200.00. On Day 12, PV increases to (4000.00×3) = $12000.00, EV is $(12000.00 \times 3/6)$ = $6000.00, AC is (4600.00×3) = $13800.00. The EVM indicators on Activity A remain unchanged in the following two non-working days. Similar procedures are taken to calculate the EVM indicators from Day 15 to Day 17. Note that the PV values of non-delayed activities remain unchanged, such as the Activity E and F are assessed with the PV value of $500.00 and $3000.00 on Day 12 respectively, according to the planned schedule (Table 5.3). However, as the Activity E and F have not been started owing to the delay of Activity A, the associated value of EV and AC is $0.00. By using the formulae in Table 2.1, the values of SPI and CPI from Day 11 to 17 are calculated and given in Table 5.4.

The cost associated with time extensions such as liquidated damage should be considered on Day 17. Note Eq. (5.3) can be applied whenever the contractor intends to factor in the cost associated with PTE. On activity level, the AC of Activity A is increased by ($27600.00 + 2$\times$5000.00) = $37600.00, according to Eq. (5.3). In other words, the total amount of AC is modified to (58400.00 + 2$\times$5000.00) = $68400.00 on project level. The CPI immediately decreases from 0.79 to 0.67. The sudden drop reflects the cost overspend resulting from project delays (PTE).

This improved EVM framework was successfully applied to this single activity delay (Activity A) scenario. Next, the EVM is applied in multiple activity-delay (Activities A and G) scenario.

End of Day 11			
Activity	PV	EV	AC
A	8000.00	2666.67	9200.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	0.00	0.00	0.00
F	0.00	0.00	0.00
G	2000.00	2000.00	2800.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	26000.00	20666.67	34400.00
SPI:	0.79	CPI:	0.60

End of Day 12			
Activity	PV	EV	AC
A	12000.00	6000.00	13800.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	500.00	0.00	0.00
F	3000.00	0.00	0.00
G	3000.00	3000.00	4200.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	34500.00	25000.00	40400.00
SPI:	0.72	CPI:	0.62

End of Day 13			
Activity	PV	EV	AC
A	12000.00	6000.00	13800.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	1000.00	0.00	0.00
F	3000.00	0.00	0.00
G	4000.00	4000.00	5600.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	36000.00	26000.00	41800.00
SPI:	0.72	CPI:	0.62

End of Day 15			
Activity	PV	EV	AC
A	16000.00	10666.67	18400.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	1500.00	0.00	0.00
F	6000.00	0.00	0.00
G	5000.00	5000.00	7000.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	44500.00	31666.67	47800.00
SPI:	0.71	CPI:	0.66

End of Day 16			
Activity	PV	EV	AC
A	20000.00	16666.67	23000.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	0.00	0.00	0.00
E	2000.00	0.00	0.00
F	9000.00	0.00	0.00
G	6000.00	6000.00	8400.00
H	0.00	0.00	0.00
I	0.00	0.00	0.00
Total	53000.00	38666.67	53800.00
SPI:	0.73	CPI:	0.72

End of Day 17			
Activity	PV	EV	AC
A	24000.00	24000.00	27600.00
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	1500.00	0.00	0.00
E	2000.00	0.00	0.00
F	9000.00	0.00	0.00
G	6000.00	6000.00	8400.00
H	0.00	0.00	0.00
I	1000.00	0.00	0.00
Total	59500.00	46000.00	68400.00
SPI:	0.77	CPI:	0.67

Table 5.4: EVM calculations from Day 11 to Day 17 in single-activity delay scenario

In a multiple-activity-delay scenario, delays on Activities A and G are considered. ATE on Activity A are 4 days, which is identical to the previous scenario, additionally, 1-day

ATE occurs on Activity G. After imposing the delays to the resource-constrained project schedule, the project completion time is lengthened for two days (2-day PTE), showing ATE and PTE are related in a highly non-linear fashion subject to multiple activity delays, according to Chapter 3 and 4. Similarly, the EVM indicators on Activities A and G are updated according to Eqs. (5.1) to (5.3) in consideration of activity delays. Table 5.5 gives EVM calculations on Day 17, where the underlined values are updated costs on the two delayed activities.

End of Day 17			
Activity	PV	EV	AC
A	<u>24000.00</u>	<u>24000.00</u>	<u>27600.00</u>
B	6000.00	6000.00	8400.00
C	10000.00	10000.00	14000.00
D	1500.00	0.00	0.00
E	2000.00	0.00	0.00
F	9000.00	0.00	0.00
G	<u>7000.00</u>	<u>7000.00</u>	<u>9800.00</u>
H	0.00	0.00	0.00
I	1000.00	0.00	0.00
Total	60500.00	47000.00	79800.00
SPI:	0.78	CPI:	0.59

Table 5.5: EVM calculations in multiple activity delays scenario

The SPI and CPI values, which are smaller than one, imply underperformances in project time and cost control. Considering both current cost and schedule performances (see formulas given in Tables 2.2 to 2.4), EAC is calculated as $99356.71 by Eq. (5.4), and therefore VAC is –$33356.71. $TCPI_{EAC}$ is calculated as 0.46 by Eq. (5.5), indicating productivity loss on the project in the remainder of the project execution. In short, this improved approach can be applied to complex delayed scenarios, on resource-constrained schedules.

$$\text{EAC} = 79800.00 + \frac{56000.00 - 47000.00}{0.78 \times 0.59} \tag{5.4}$$

$$\text{TCPI}_{\text{EAC}} = \frac{56000.00 - 47000.00}{99356.71 - 79800.00} \tag{5.5}$$

The case study proves the improved EVM approach is capable to generate accurate project performance indicators for single and multiple activity-delay scenarios. By using the simple case study taken from Ahuja et al. (1994), the steps in demonstrating the improved EVM framework implementations are included. As emphasized in Section 2.6, there is no standardized EVM approach available to account for resource-constrained scheduling under delay situations. Thus, three basic equations [Eqs. (5.1) to (5.3)] for calculating EVM parameters (PV, EV and AC) are adjusted in connection with activity delays and the associated project time extensions. The research makes an effort in bridging the gap between EVM and CPM frameworks. Further, the improved EVM methodology can be applied in single and multiple activity-delay scenarios. The limitations of established techniques have also been included in order to guide project managers in applying EVM more effectively. The refined EVM techniques can be readily applied to complex construction projects under practical constraints. The proposed EVM framework can be further enhanced so as to (1) quantitatively assess the project performance by tracking scope change, work done and actual expenses on a continuous basis; (2) seamlessly connect EVM indicators with TF determined from CPM. Those limitations present further research opportunities. In short, planners are capable of using this proposed EVM approach to cope with complicated activity-project delay scenarios in resource-constrained schedules, which is supported by *P3* forward pass scheduling simulations.

5.3 Chapter Summary

This chapter addresses the cost implications in improving the schedule and cost management integrated earned value management (EVM) framework in connection with activity and project time extensions. The traditional EVM approach is mainly intended for ideal scheduling scenarios without practical resource constraints or time delays. The EVM indicators fail to accurately quantify project time and cost performances, given resource constraints or activity delays are considered on a planned schedule. This chapter has addressed the cost implications in connection with activity and project time extensions, which are determined from the TF analysis based on precise resource-constrained schedules. A simple project example, which is taken from Ahuja et al. (1994), is used for concept proving and illustrations in a case study. Both single and multiple activity-delay scenarios are investigated. In-depth discussions on how to implement the new approach under delayed scenarios are given.

This research provides an enhanced methodology to implement EVM techniques based on resource-constrained CPM scheduling under delay scenarios by seamlessly bridging the gap between EVM and CPM. Three basic EVM parameters, namely, *planned value* (PV), *earned value* (EV) and *actual cost* (AC), have been adjusted in connection with time delays occurring on multiple activities and the whole project. Without changing original implications, all the EVM performance indicators can be evaluated and interpreted more accurately by factoring in these refined parameters. The case study proves that this approach lends a feasible solution for project managers to cope with changing project scope definitions resulting from activity delays, while the traditional EVM approach fails to address such practical needs. The improved EVM framework will add to the body of knowledge in project management and construction planning.

The proposed EVM framework can be further enhanced in terms of (1) quantitatively assessing the project performance by tracking scope change, work done and actual expenses on a continuous basis, and (2) seamlessly connecting the EVM indicators with total float (TF) determined from the TF determination methodologies proposed in Chapter 3 and 4. In short, the refined EVM approach provides a cost-effective project control methodology to track project time and cost performances on resource-constrained schedules under complicated activity-project delayed scenarios.

CHAPTER 6

CONCLUSIONS

With enhanced methodologies for project scheduling and control being proposed in this research study, the objectives set in Chapter 1 have been successfully achieved. The methodologies developed in this research along with insightful findings will benefit construction practitioners in the planning and control of challenging construction projects. As a result, construction managers can develop an integral view of scheduling development, from past to future, deeply understand the project and activity time extensions, and the cost implications, and effectively plan and control the time extensions in construction project scheduling under technology and resource constraints.

Project time extension and the associated cost overspend are generally indicative of a degree of failure in project management. Effective time control is vital during project planning, monitoring and control. Critical path method (CPM) will continue to provide the backbone methodology for project and activity time analysis, supplemented by earned value management (EVM) which produces indicators for project cost and time performances, in scheduling construction projects, as mentioned in Chapter 2. Both CPM and EVM have significantly contributed to time-cost planning and control on construction projects. For instance, the activity start times, activity finish times, activity total float and project completion time can be determined by CPM analysis, while the activity and project schedule and cost performances such as over-budget and ahead-of-schedule can be revealed at a particular control date by using EVM.

In the CPM framework, the activity total float (TF) has been devised as an effective instrument for identifying critical paths and controlling project time extension. The TF, which is a non-negative activity attribute of each individual activity is devised as a control measure in order to effectively keep activity time extension (ATE) in check with the objective of avoiding project time extension (PTE) at the project level. However, the classic TF definition fails to cope with the time extension effects resulting from complicated relationships between project and activity delays, and hence is often not a reliable time control measure. The occurrence of multiple activity delays which result in a complicated combinatorial effect of project time extension further limits the role of the classic TF definition in project time control. On the other hand, the earned value management (EVM), which assumes an ideal baseline schedule, is inadequate to tackle resource-constrained scheduling under delayed scenarios. Thus, this research study has focused on revisiting and refining the TF definitions in the CPM framework and improving the EVM framework in order to better cope with delay scenarios in connection with activity and project time extensions. As research deliverables, effective time extension planning and control methodologies are developed as enhancements to CPM and EVM based on applying scheduling simulations. The scheduling simulation tool Primavera® P3™ Project Planner (*P3*) has been selected for precisely generating resource-constrained schedules and determining TF based on the relationships between ATE and PTE, as detailed in Chapter 2.

The linear and non-linear relationships between ATE and PTE have been characterized and contrasted in a simple example project network which is taken from Kraiem and Diekmann (1987). Straightforward CPM analysis with and without consideration of the resource constraints are conducted for scenarios having single or multiple activity delays. The results have shown that the PTE-ATE relationships are characteristic of complicated non-linearity after imposing resource constraints. Based on the in-depth understanding of PTE-ATE relationships, activity total float determination methodologies have been developed. The refined TF is closely related with the classic definition of TF, which is a single activity attribute to control activity delay, given the ATE and PTE on other activities, are all set as zero. The algorithms are proposed to determine TF, for one individual activity in the project given a particular PTE level (Chapter 3) or for a set of delayed activities, each of which experiences a certain level of ATE (Chapter 4). The proposed TF determination methodologies provide the flexibility to characterize the relationships between project delay and multiple activity delays. For example, the refined TF determination method has been successfully applied on a highway widening construction project to control an individual activity delay given a range of PTE (illustrated in Section 3.4), and to control multiple activity delays given a range of PTE with a set of delayed activity (demonstrated in Section 4.4.). The proposed method proved to be effective in tracking the resource dependency identification problems in the context of resource-constrained schedule, comparisons and discussions are included by using the two examples taken from Kim and de la Garza (2003).

Project cost increase is generally a significant by-product of activity and project time extensions. The EVM fails to indicate changes to a project baseline schedule due to activity and project time extensions, resulting in mislead project performance tracking information. This research study has found that the EVM can only be applied to ideal scheduling scenarios without practical resource constraints and time extensions. Based on the in-depth understanding of complicated relationships between project and activity time extensions obtained in the TF determination study, the EVM framework for schedule and cost monitoring under both activity and project time extension scenarios has been improved in Chapter 5. A case study, which is taken from Ahuja et al. (1994), is used to illustrate the refined EVM framework. In-depth discussions on how to apply this improved approach for resource constrained scheduling under both single and multiple activity-delay scenarios are investigated. The results have shown that the proposed approach addresses delayed scenarios based on the simulated resource-constrained schedules, so as to enhance the accuracy of EVM indicators. This refined approach is cost-effective to track the project time and cost performances for resource-constrained schedules in complicated activity-project delay scenarios.

The simulation-based activity total float determination methodologies and the improved earned value management approach for project time extension planning, tracking and control have been developed in this research. The proposed methodologies, the observations and findings generalized from this research will add to the body of knowledge in project management and benefit construction practitioners in planning and control of challenging resource-constrained construction projects. The thesis research provides a boarder view of project extension control and activity delay analysis in construction project management.

APPENDIX A

HIGHWAY WIDENING CONSTRUCTION PROJECT UNDER PRACTICAL CONSTRAINTS

A highway widening construction project, which is included in the Primavera® P3™ Project Planner (*P3*) software installation, serves as the test bed for demonstrating applications of newly proposed activity total float determination methodologies under practical constraints. The project consists of fifty-five activities and twenty-four types of resources along with daily maximum resource limits and non-working days defined on the nearly two-year project duration.

The original project network is composed by the precedence diagram method (PDM) and contains a small quantity of non-finish-to-start relationships (Fig. A.1). The non-finish-to-start relationships can be firstly transformed into finish-to-start in order to simplify the ensuing resource-constrained scheduling analysis (Lu and Lam 2009).

By using the transformation technique (Fig. A.2), the resulting scheduling network is shown in Fig. A.3. Note that without imposing any resource constraints, the identical project completion time (262 days) can be obtained by *P3* by analyzing the two equivalent networks, namely, the original PDM network with non-finish-to-start relationships and the transformed activity-on-node network with only finish-to-start relationships.

Next, the project scheduling problem definition is enhanced by adding practical constraints so as to enable resource-constrained scheduling analysis. Activity and resource requirements are summarized in Table A.1 and A.2 respectively. The project consists of fifty-five activities and twenty-four types of resources with respective daily maximum resource limits imposed as resource availability constraints. Activity calendar constraints (Table A.3) and resource calendar constraints (Table A.4), which are based on non-working-days of Hong Kong calendars of the years 1999, 2000 and 2001, are taken into account in the resource-constrained scheduling simulations.

It is noteworthy that *P3* provides two options for forward resource leveling: (1) automatic leveling by built-in heuristic rules; and (2) user-specified activity priority settings. In the case study, activity priorities used are manually specified as given in Table A.1. The larger the code number, the higher the priority in activity execution. After imposing all the practical constraints, the project time extends from 262 days to 606 days: the planned project start time is on 26 April 1999 (Monday) and the project completion date is 22 December 2000 (Friday).

Act ID	Name	Description	Duration (Day)	Resource [Unit/Day]	Priority
Start Up					
1	1	Begin Project	0	-	1
2	2	Mobilization	4	-	61
3	3	General conditions	13	-	57
4	4	Clear site	4	DOZE[1], FORE[2], LB-G[6]	60
Traffic Control					
5	5	Remove temp. const. barrier	1	CRN[1], FORE[2], LB-G[8], OPER[8]	41
6	6	Place time. striping & divert traffic	1	LB-G[16]	40
7	7	Place temp. marking tape	1	FORE[2], LB-G[16]	56
8	8	Place temp. const. barrier	1	CRN[1], FORE[2], LB-G[8], OPER[16]	55
9	9	Construct temp. bent #1 & #2	20	DOZE[1], FORE[2], LB-G[16], OPER[8]	52
10	10	Remove temp. const. barrier	1	CRN[1], FORE[2], LB-G[16], OPER[8]	51
11	11	Divert traffic onto temp. road	1	LB-G[16]	49
12	12	Remove temp. marking tape	1	FORE[2], LB-G[16]	48
13	13	Place const. barrier & temp. stringing ramp	4	CRN[1], FORE[2], LB-G[8], OPER[8]	47
14	14	Place const. barrier	12	CRN[1], FORE[2], LB-G[8], OPER[8]	45
15	15	Place temp. const. barrier	6	CRN[1], FORE[2], LB-G[8], OPER[8]	29
16	16	Remove temp. const. barrier	5	CRN[1], FORE[2], LB-G[8], OPER[8]	27
17	17	Strip roadway	9	DRVR[8]. FORE[2], LB-H[32], OPER[8], STRI[1], TRK[1]	9
18	18	Remove temp. barrier	4	CRN[1], FORE[2], LB-G[8], OPER[8]	6
Signage					
19	19	Procurement of sign structure	10	-	58
20	20	Procurement of noise barrier post & panels	19	-	59
21	21	Procurement of ESW/SL signs	10	-	44
22	22	Install sign support structure	8	DRVR[8]. FORE[2], LB-G[8], OP-L[8], PTDR[1], TRK[1]	39
23	23	Erect signs	3	CRN[1], FORE[2], LB-G[16], OPER[8]	37
Earthwork					
24	24	Excavate	5	FORE[2], LB-G[16], LOAD[1]	54
25	25	Excavate ramp & install 15"RCP pipe with inlets	10	DOZE[1]. FORE[2], LB-S[16]	46
26	26	Grub & strip topsoil	8	DOZE[1], DRVR[24], FORE[4], LOAD[1], TK-D[1]	38
27	27	Install erosion control devices	15	FORE[2], LB-G[16]	36
28	28	Install temp. sheeting	12	CARP[16], COMP[1], FORE[2], LB-G[24], SHT[1]	35
29	29	Excavate retaining wall	12	FORE[2], LB-G[8], LOAD[1], OPER[8]	34
30	30	Place porous fill behind wall	9	DOZE[1], FORE[2], LB-G[16], OPER[8]	21
31	31	Backfill retaining wall	7	DOZE[1], FORE[2], LB-G[8], OPER[8]	19
32	32	Remove guide rail	4	FORE[2], LB-H[16], LOAD[1], OPER[8]	32
33	33	Excavate for electrical	10	FORE[2], LB-G[8], LOAD[1], OP-L[8]	30
34	34	Remove temp. pavement	9	FORE[2], LB-G[16], LOAD[1], OPER[8]	28
35	35	Regrade area	7	DOZE[1], FORE[2], OPER[8]	23
Electric and power elements					
36	36	Install temp. electrics	15	ELEC[24], FORE[2]	31
37	37	Install electric conduits & structures	19	CRN[1], ELEC[24], FORE[2], LB-S[16]	24
38	38	Install power & lighting	15	ELEC[24], FORE[2], LB-S[16]	22
Sub-surface and paving work					
39	39	Place 2" surface course	3	FORE[2], LB-H[32], OPER[16], PAVE[1], ROL2[2]	42
40	40	Place aggregate & asphalt base course	6	DOZE[1], FORE[2], LB-H[8], ROL1[1], SPRE[1]	53
41	41	Place 2" surface course	3	FORE[2], LB-H[24], OPER[24], PAVE[1], ROL2[1]	50
42	42	Place aggregate & asphalt base course	4	DOZE[1], FORE[2], LB-G[16], OPER[24], ROL1[1], SPRE[1]	43
43	43	Sub-grade preparation	14	FORE[2], LB-H[8], OPER[8], ROL2[1]	18
44	44	Place aggregate & asphalt base course	10	DOZE[1], FORE[2], LB-H[16], OPER[24], ROL1[1], SPRE[1]	16
45	45	Place asphalt stabilized course	12	FORE[2], LB-H[18], OPER[8], PAVE[1], ROL2[1]	13
46	46	Place 2" surface course	10	FORE[2], LB-H[8], OPER[8], PAVE[1], ROL2[1]	10
Concrete					
47	47a	Construct footing	15	FINI[24], FORE[2], LB-G[24], VIBR[2]	33
48	47b	Construct footing	12	FINI[24], FORE[2], LB-G[24], VIBR[2]	25
49	48	Construct retaining wall	27	FINI[24], FORE[2], LB-G[24], VIBR[2]	26
50	49	Construct concrete barrier against wall	8	FINI[24], FORE[2], LB-G[24], VIBR[2]	20
51	50a	Construct concrete barrier against wall	15	FINI[24], FORE[2], LB-G[24], VIBR[2]	17
52	50b	Construct concrete barrier against wall	5	FINI[24], FORE[2], LB-G[24], VIBR[2]	14
53	51a	Construct concrete barrier against wall	15	FINI[24], FORE[2], LB-G[24], VIBR[2]	15
54	51b	Construct concrete barrier against wall	9	FINI[24], FORE[2], LB-G[24], VIBR[2]	11
55	52a	Construct concrete barrier against wall	15	FINI[24], FORE[2], LB-G[24], VIBR[2]	12
56	52b	Construct concrete barrier against wall	10	FINI[24], FORE[2], LB-G[24], VIBR[2]	7
57	53a	Construct concrete barrier against wall	15	FINI[24], FORE[2], LB-G[24], VIBR[2]	8
58	53b	Construct concrete barrier against wall	9	FINI[24], FORE[2], LB-G[24], VIBR[2]	4
59	54	Construct concrete barrier against wall	20	FINI[24], FORE[2], LB-G[24], VIBR[2]	5
60	55	Construct concrete barrier against wall	6	FINI[24], FORE[2], LB-G[24], VIBR[2]	3
61	56	Construct concrete barrier against wall	6	FINI[24], FORE[2], LB-G[24], VIBR[2]	2
Closeout					
62	57	Project complete	0		1

Table A.1: Activity requirements for highway widening project

Res ID	Res Code	Resource Description	Daily Res Limit (Unit)
1	CARP	Carpenter	16
2	COMP	Air compressor	3
3	CRN	Crane	1
4	DOZE	Dozer	1
5	DRVR	Truck driver	24
6	ELEC	Electrician	24
7	FINI	Cememt finisher	24
8	FORE	Foreman	8
9	LB-G	General laborer	24
10	LB-H	Highway laborer	32
11	LB-S	Skilled laborer	16
12	LOAD	Loader	1
13	OPER	Equipment operator	24
14	OP-L	Equipment operator - Light	8
15	PAVE	Asphalt paver	2
16	PTDR	Post driver	1
17	ROL1	Roller, Tandem	2
18	ROL2	Roller, Steel Wheel	2
19	SHT	Sheeting driver	1
20	SPRE	Aggregate spreader	1
21	STRI	Paint stripper	1
22	TRK	Truck - Flatbed	2
23	TK-D	Dump truck	3
24	VIBR	Gas engine vibrator	2

Table A.2: Resources employed with the daily provision limits for highway widening project

1999		2000		2001	
1-Jan	New Year's Day	1-Jan	New Year's Day	1-Jan	New Year's Day
16-Feb	Chinese Lunar New Year's Day	5-Feb	Chinese Lunar New Year's Day	24-Jan	Chinese Lunar New Year's Day
17-Feb	Second day of Chinese Lunar New Year	7-Feb	Second day of Chinese Lunar New Year	25-Jan	Second day of Chinese Lunar New Year
18-Feb	Third day of Chinese Lunar New Year	7-Feb	Third day of Chinese Lunar New Year	26-Jan	Third day of Chinese Lunar New Year
2-Apr	Good Friday	4-Apr	Ching Ming Festival	5-Apr	Ching Ming Festival
5-Apr	Ching Ming Festival	21-Apr	Good Friday	13-Apr	Good Friday
5-Apr	Easter Monday	24-Apr	Easter Monday	14-Apr	Holy Saturday
1-May	Labor Day	1-May	Labor Day	16-Apr	Easter Monday
18-Jun	Dragon Boat Festival	6-Jun	Dragon Boat Festival	30-Apr	Buddha's Birthday
1-Jul	HKSAR Establishment Day	1-Jul	HKSAR Establishment Day	1-May	Labor Day
25-Sep	Day after Mid-Autumn Festival	13-Sep	Day after Mid-Autumn Festival	25-Jun	Dragon Boat Festival
1-Oct	National Day of the PRC	1-Oct	National Day of the PRC	1-Jul	HKSAR Establishment Day
18-Oct	Chung Yeung Festival	2-Oct	'National Day of the PRC ' observed	2-Jul	' HKSAR Establishment Day' observed
25-Dec	Christmas Day	6-Oct	Chung Yeung Festival	1-Oct	National Day of the PRC
		25-Dec	Christmas Day	2-Oct	Day after Mid-Autumn Festival
				25-Oct	Chung Yeung Festival
				25-Dec	Christmas Day
				26-Dec	Boxing Day
All activities normally work from Monday to Saturday					

Table A.3: Activity calendars imposed on highway widening project scheduling

Res ID	Res Code	Resource Description	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	CARP	Carpenter	1	1	1	1	1	0	0
2	COMP	Air compressor	1	1	1	0	0	1	1
3	CRN	Crane	1	1	1	1	1	1	1
4	DOZE	Dozer	1	1	1	1	1	1	1
5	DRVR	Truck driver	1	1	1	1	1	0	0
6	ELEC	Electrician	1	1	1	1	1	0	0
7	FINI	Cememt finisher	1	1	1	1	1	0	0
8	FORE	Foreman	1	1	1	1	1	0	0
9	LB-G	General laborer	1	1	1	1	1	0	0
10	LB-H	Highway laborer	1	1	1	1	1	0	0
11	LB-S	Skilled laborer	1	1	1	1	1	0	0
12	LOAD	Loader	1	1	1	1	1	1	1
13	OPER	Equipment operator	1	1	1	1	1	0	0
14	OP-L	Equipment operator - Light	1	1	1	1	1	0	0
15	PAVE	Asphalt paver	1	1	1	1	0	0	1
16	PTDR	Post driver	1	1	1	1	1	0	0
17	ROL1	Roller, Tandem	1	1	1	1	0	1	1
18	ROL2	Roller, Steel Wheel	1	1	1	0	0	1	1
19	SHT	Sheeting driver	1	1	1	1	1	0	0
20	SPRE	Aggregate spreader	1	1	1	1	1	1	1
21	STRI	Paint stripper	1	1	1	1	1	1	1
22	TRK	Truck - Flatbed	1	1	1	1	0	0	1
23	TK-D	Dump truck	1	1	1	1	0	1	1
24	VIBR	Gas engine vibrator	1	1	1	1	0	0	1
0=Not Available; 1=Available									

Table A.4: Resource calendars imposed on highway widening project scheduling

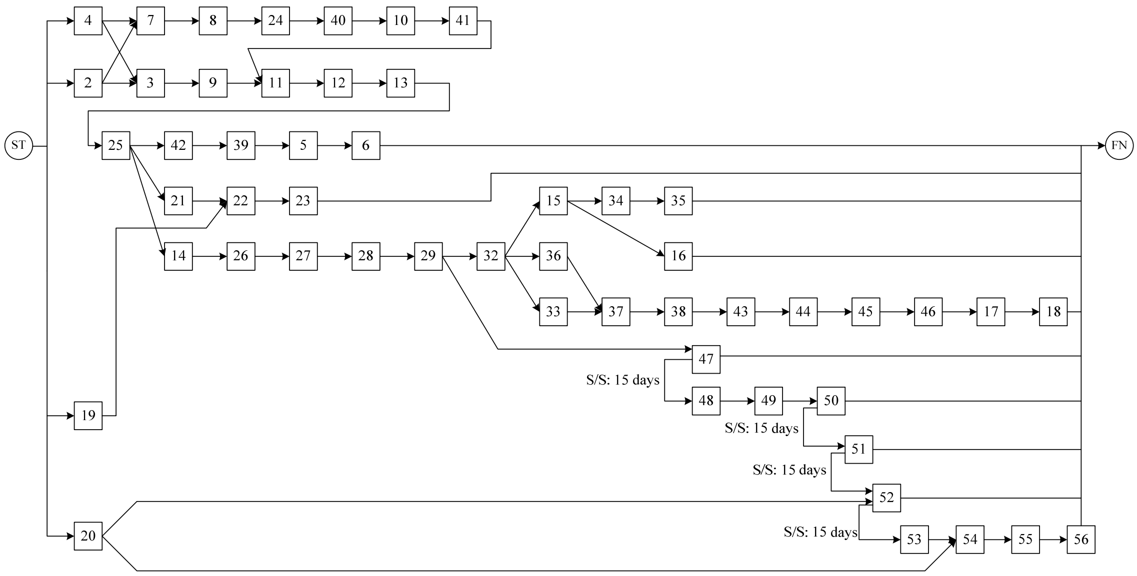


Fig. A.1: Original scheduling network for highway widening project

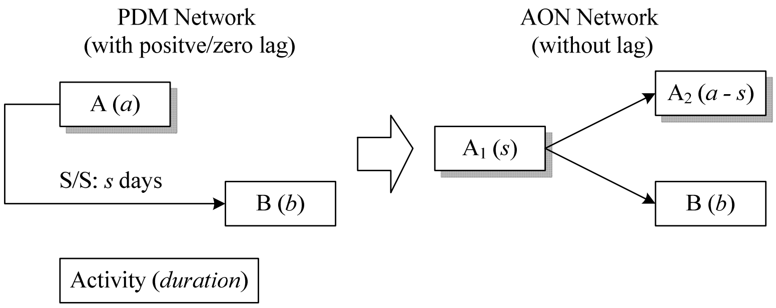


Fig. A.2: PDM-AON transformation scheme for start-to-start relationships

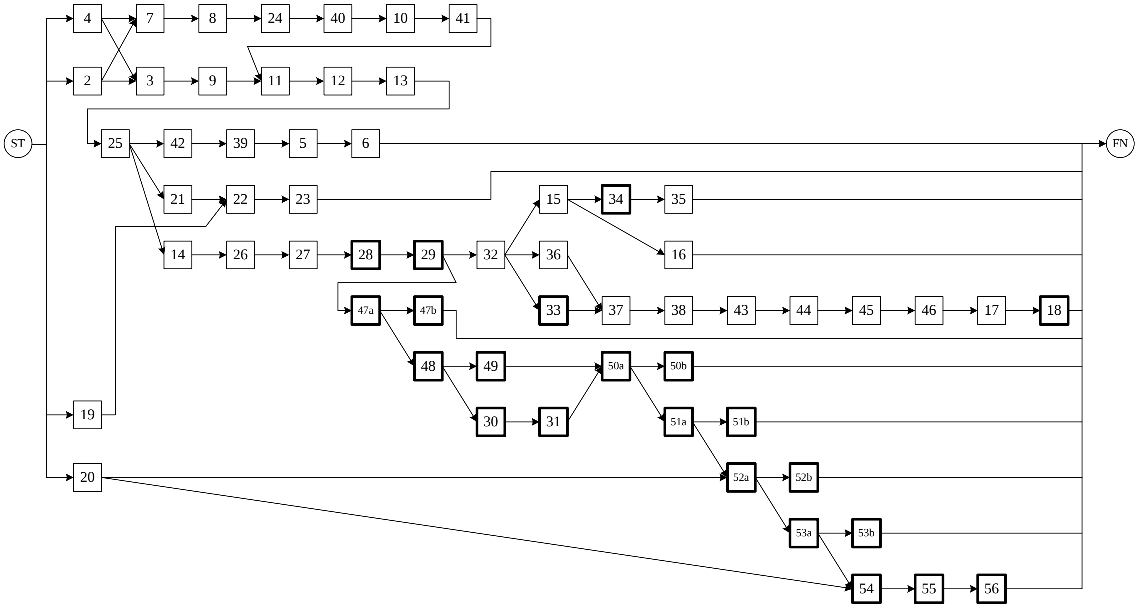


Fig. A.3: Transformed scheduling network for highway widening project; critical activities are highlighted with thicker blocks when PTE is at zero

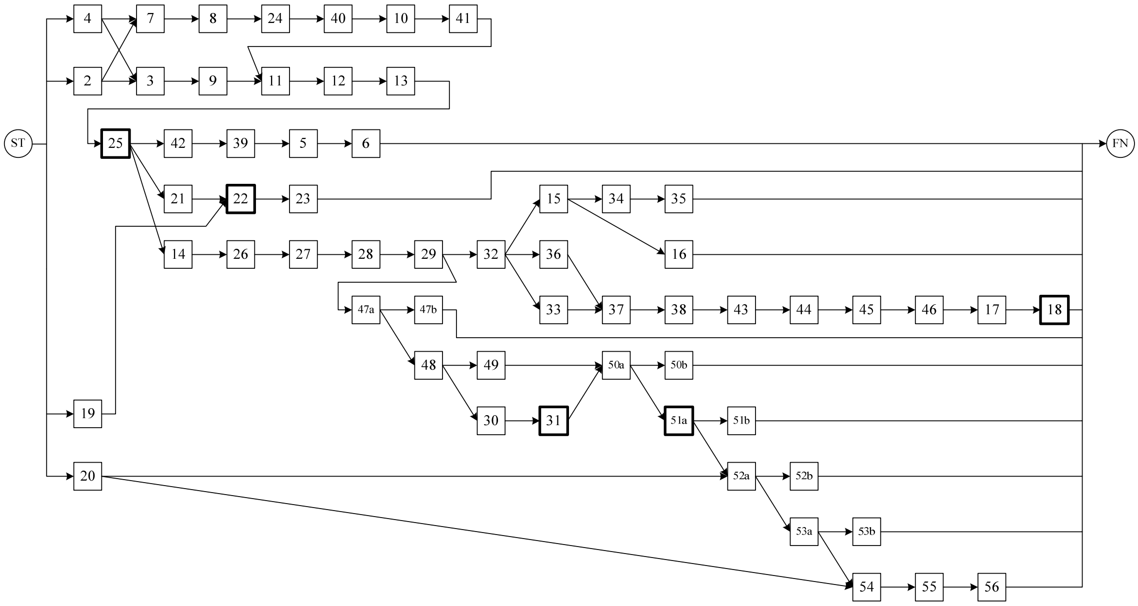


Fig. A.4: Transformed scheduling network for highway widening project; delayed activities are highlighted with thicker blocks

APPENDIX B

FEATURES AND INTERFACES OF PRIMAVERA® P3™ PROJECT PLANNER (*P3*) AND PRIMAVERA® P6™ PROJECT MANAGEMENT (*P6*)

This appendix provides the features and interfaces of two commonly used scheduling simulation tools, namely: Primavera® P3™ Project Planner (*P3*) copyright © 1999 by Primavera Systems, Inc. All rights reserved (Section B.1), and Primavera® P6™ Project Management (*P6*) copyright © 1998, 2009 Oracle and/or its affiliates. All rights reserved (Section B.2). Screen shots with simple explanations are included so as to introduce the advanced resource-constrained scheduling functions provided by *P3* and *P6*.

B.1 Primavera® P3™ Project Planner (*P3*)

B.1.1 Navigating *P3* interface

P3 has a Windows menu system similar to typical Windows applications. Menu bar is used to perform functions in *P3*. Activity table displays activities associated with the opened project, with activity and resource requirements. Activity relationships are created in the activity form, and Gantt chart is generated in the bar area.

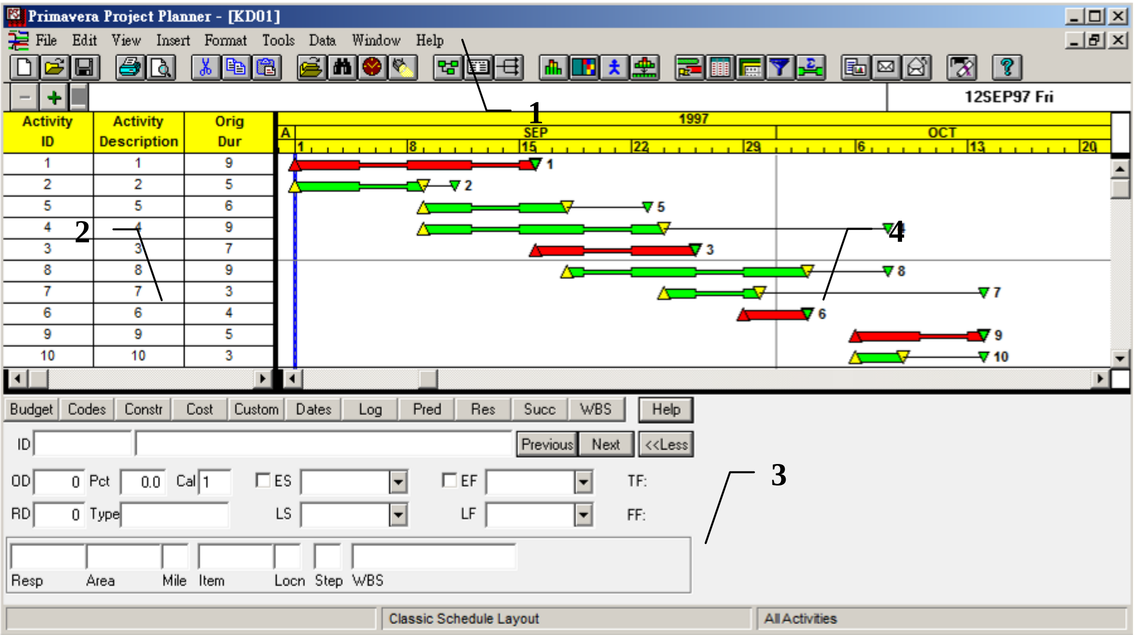


Fig. B.1: Introductions of *P3* interface

(1: Menu bar; 2: Activity table; 3: Activity form; 4: Bar area)

B.1.2 Adding activities and creating activity relationships

Activity is added and inputted in the activity table, with its duration and descriptions. The activity relationships are created by identifying its predecessors and successors. The predecessors and successors are added in predecessors and successors dialog boxes, which are opened by clicking the predecessors and successors tabs, respectively.

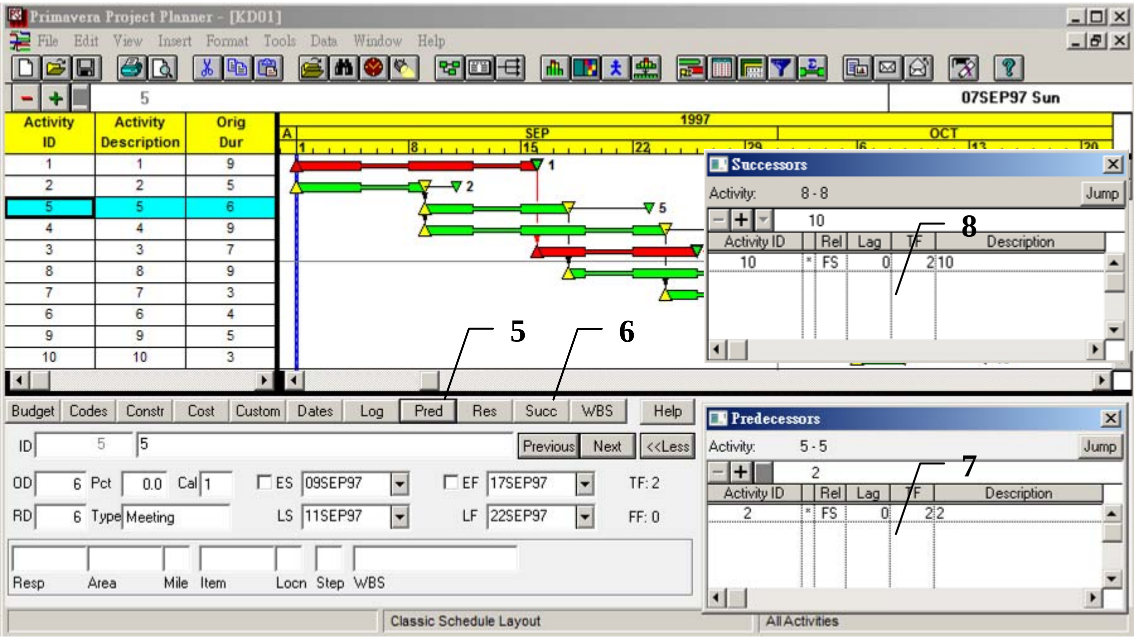


Fig. B.2: Adding activity and creating activity relationships in *P3*

(5: Predecessors tab; 6: Successors tab; 7: Predecessors dialog box; 8: Successors dialog box)

B.1.3 Assigning activity types

Activity types are assigned to an activity by choosing from the activity type drop-down list. “Task”, “Independent” and “Meeting” activity types are commonly defined in *P3*.

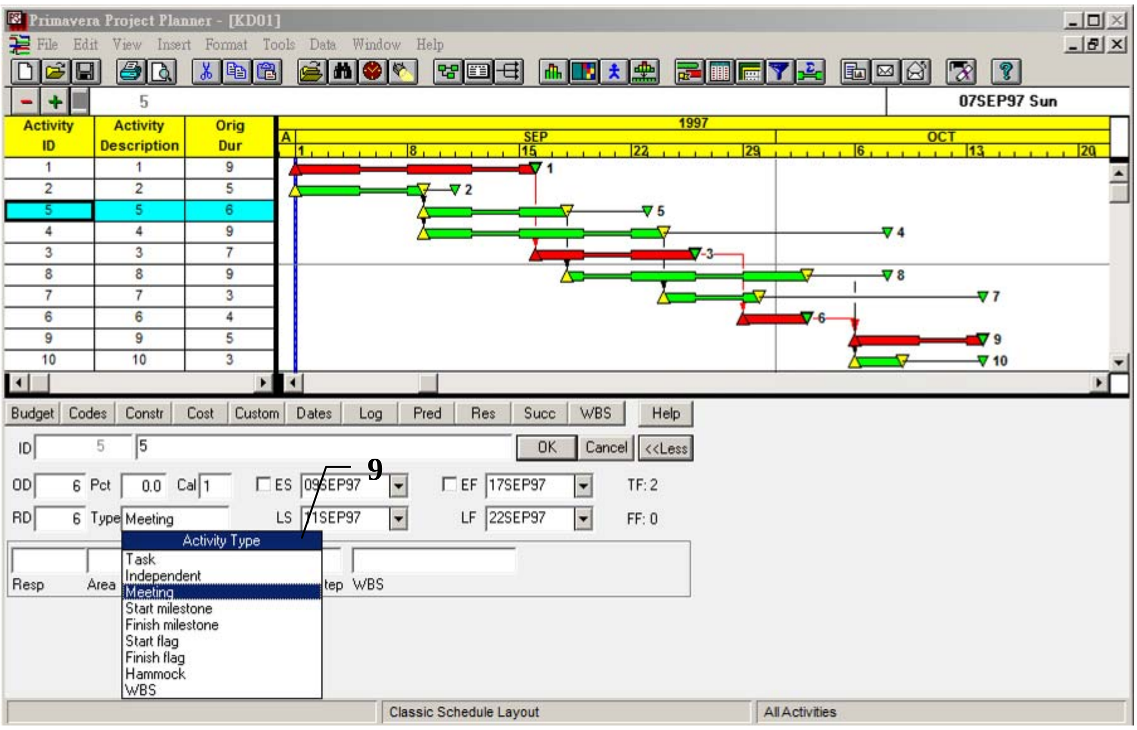


Fig. B.3: *P3* activity types

(9: Activity type drop-down list)

B.1.4 Creating calendars

Calendars are created and modified in calendars dialog box by assessing “Data, Calendars”. A unique calendar ID is assigned to each calendar.

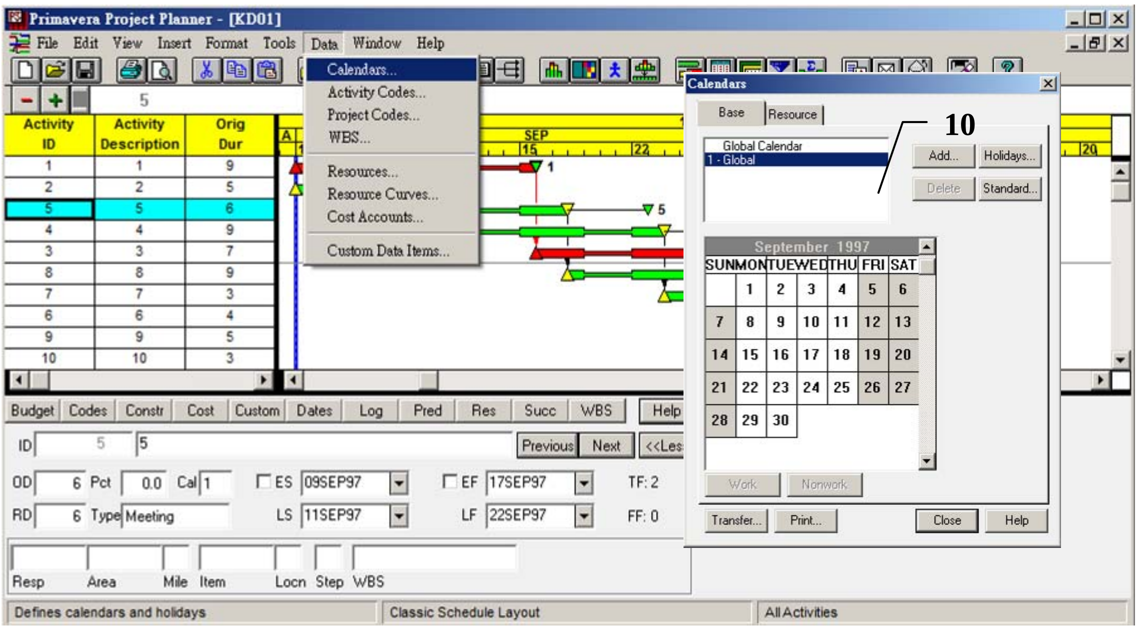


Fig. B.4: Creating calendars in *P3*

(10: Calendars dialog box)

B.1.5 Loading activity calendars

The created calendars with unique IDs are automatically displayed in calendar ID drop-down list. Activity calendar constraint is imposed by assigning the calendar to the highlighted activity in activity table.

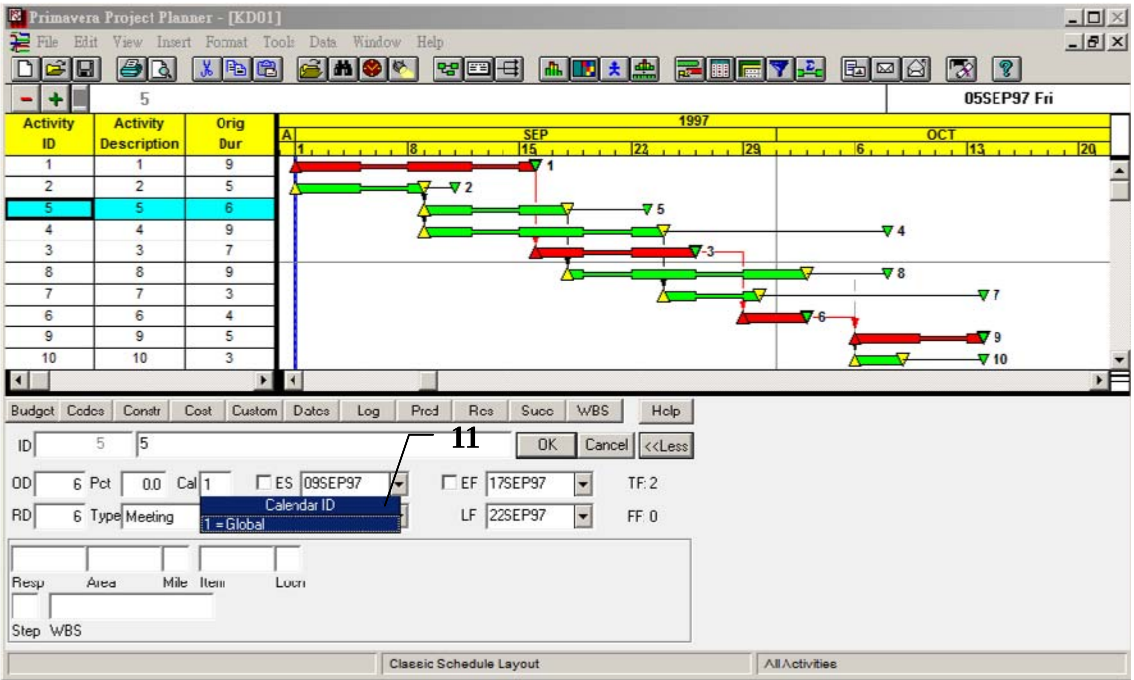


Fig. B.5: Imposing activity calendars in *P3*

(11: Calendar ID drop-down list)

B.1.6. Creating resources, setting resource availability limits and loading resource calendars

Resources are created in resource dialog box by entering "Data, Resource" menu command. Resource field in resource dialog box shows the details of all available project resources. Resource calendar constraints are imposed by selecting calendar ID in base column. Resource availability limits are set in normal and max columns.

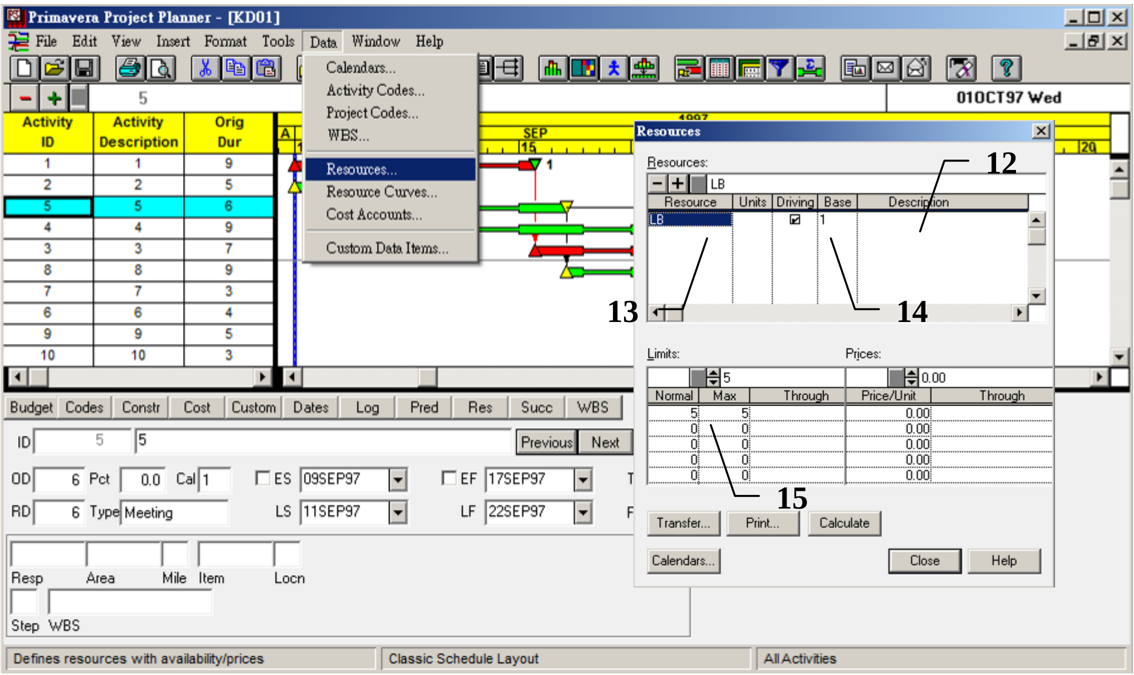


Fig. B.6: Creating resource, resource availability limits and resource calendars in *P3* (12: Resource dialog box; 13: Resource field; 14: Base column; 15: Normal and Max columns)

B.1.7. Loading resource

Resources are assigned to highlighted activity by adding created resources in resources dialog box. The dialog box is opened by clicking resource tab in activity form.

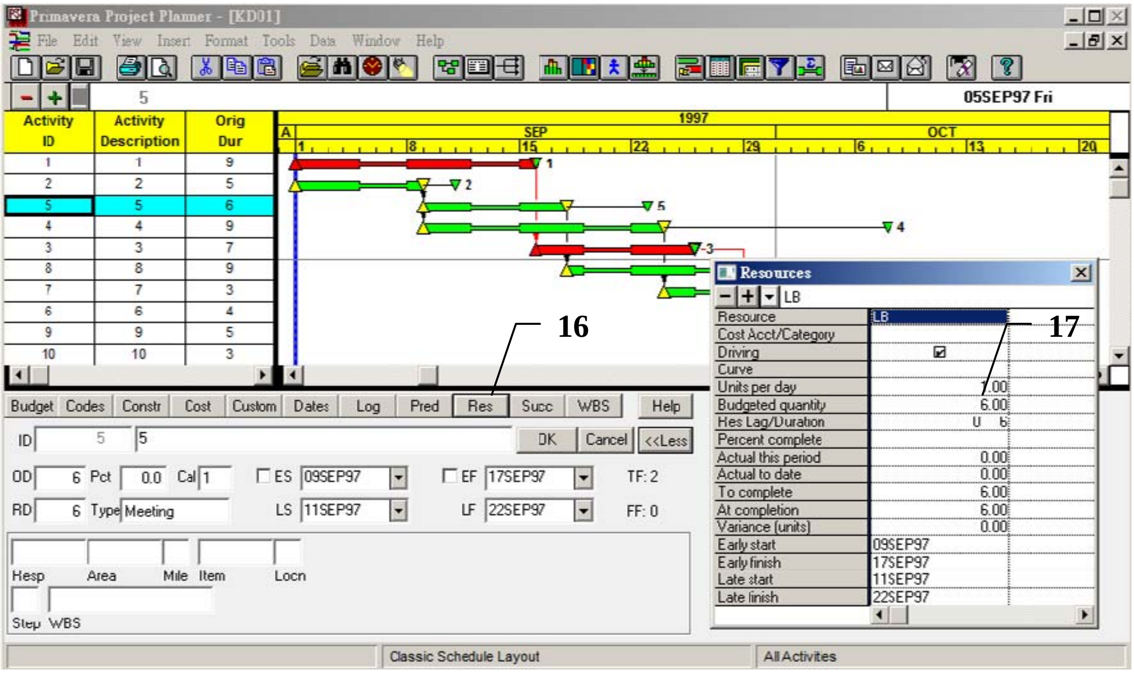


Fig. B.7: Loading resource in *P3*

(16: Resource tab; 17: Resources dialog box)

B.1.8. Scheduling by resource leveling

Schedule analysis by resource leveling function is presented in level dialog box, by invoking “Tools, Level”. The prioritization field is available to specify activity priority rules to define its built-in heuristic. The activity prioritization rule used is “late start, total float” which is set as default in *P3*. By clicking “level now” button, the resources are automatically allocated and leveled according to the defined prioritization parameters.

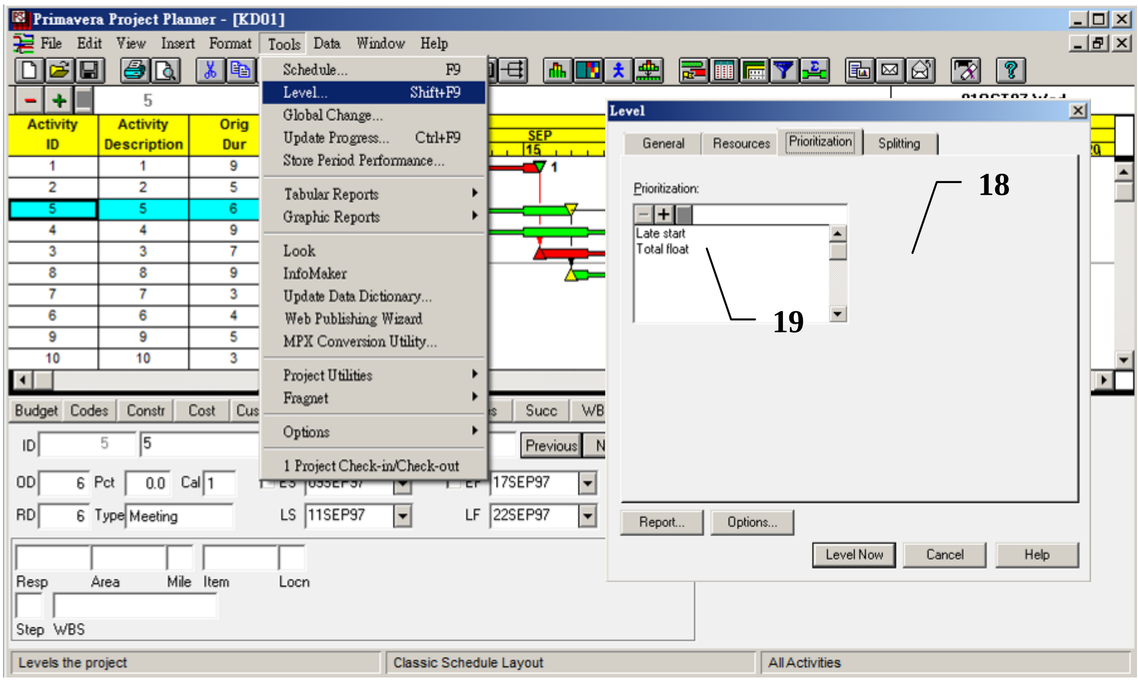


Fig. B.8: *P3* scheduling by resource leveling

(18: Level dialog box; 19: Prioritization field)

B.2 Primavera® P6™ Project Management (*P6*)

B.2.1 Navigating *P6* interface

“Home” window provides quick access to enterprise data and project data when starting *P6* application. Menu bar is used to perform *P6* functions. Navigation bar is used to move between open windows, toggle the directory bar, and open help. Additional workspaces such as “Project”, “Activities” and “Resource” windows are opened by clicking corresponding buttons in directory bar.

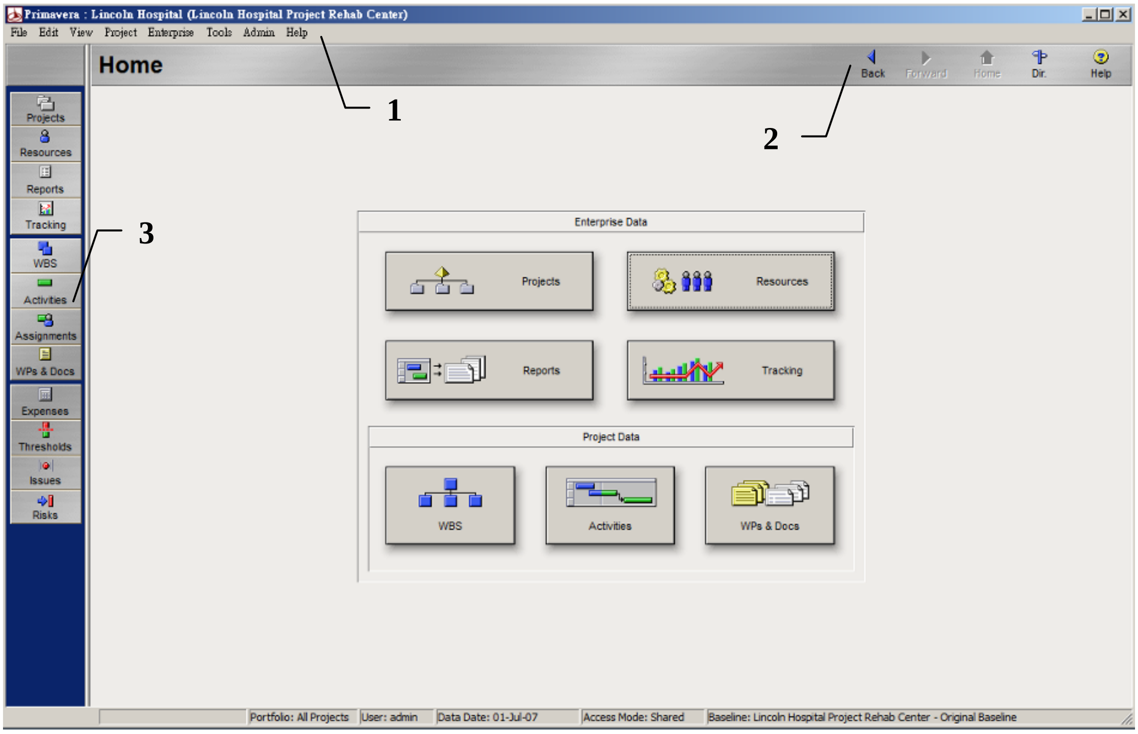


Fig. B.9: Introductions of *P6* interface

(1: Menu bar; 2: Navigation bar; 3: Directory bar)

B.2.2 Adding activities and creating activity relationships

"Activity" window is used to create, view, and edit activities for opened projects. The activity relationships are defined in relationships tab. The predecessors and successors are assigned by clicking the "assign" button in predecessors and successors panes, respectively. The resulting Gantt chart is automatically shown in the bar area.

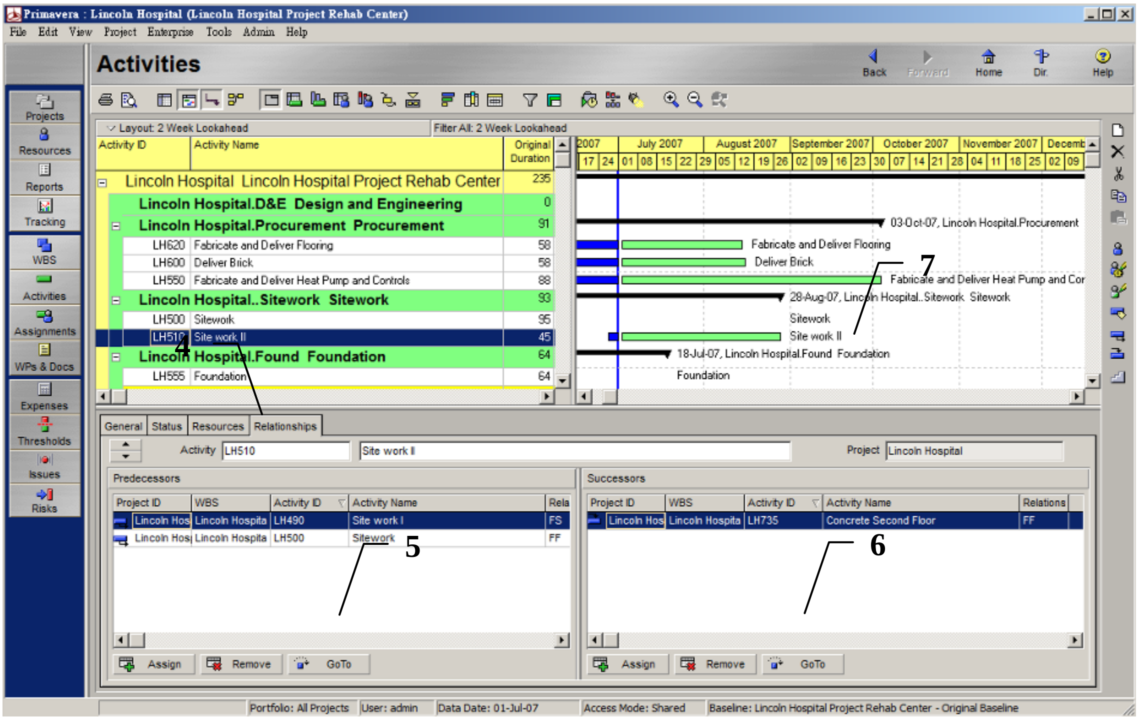


Fig. B.10: Adding activities and creating activity relationships in *P6*

(4: Relationships tab; 5: Predecessors pane; 6: Successors pane; 7: Bar area)

B.2.3 Assigning activity types

Activity types are assigned to an activity by choosing from the activity type drop-down list. “Task dependent” and “Resource dependent” activity type are available in *P6*. Note that the meeting-type activity, which is available in *P3*, is missing in *P6*.

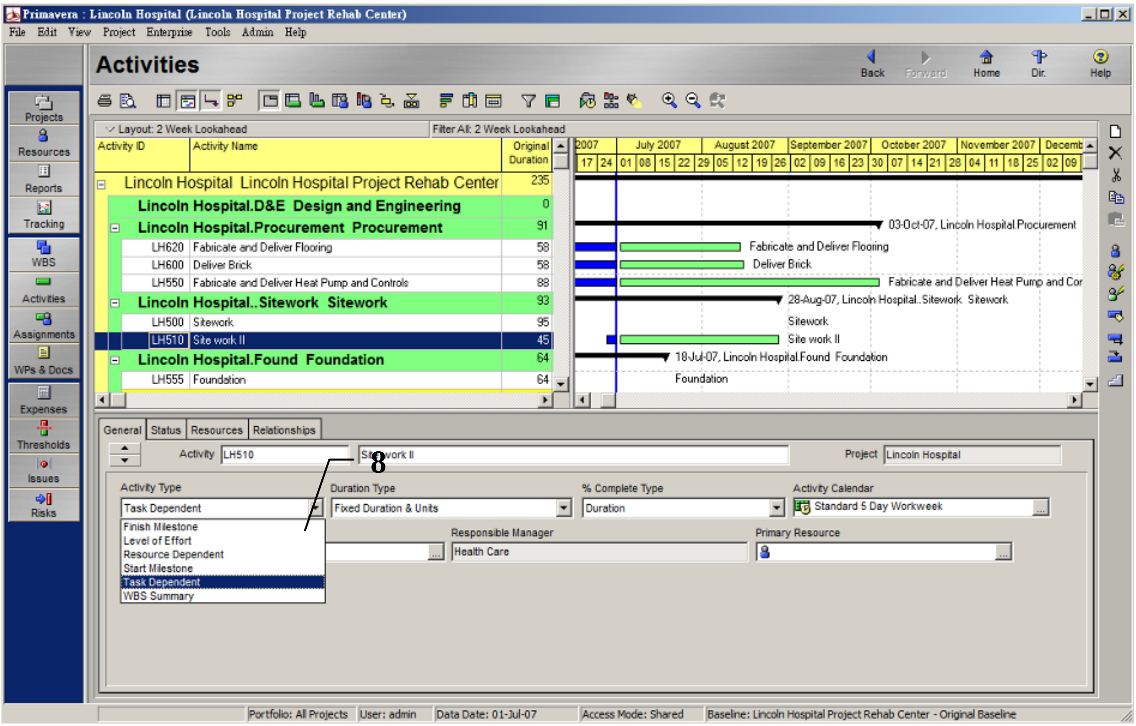


Fig. B.11: *P6* activity types

(8: Activity type drop-down list)

B.2.4 Creating calendars

Calendars can be created, copied and modified by selecting “Enterprise, Calendars”. In calendars dialog box, work time and non-working time are edited. The created calendars are specified by calendar name.

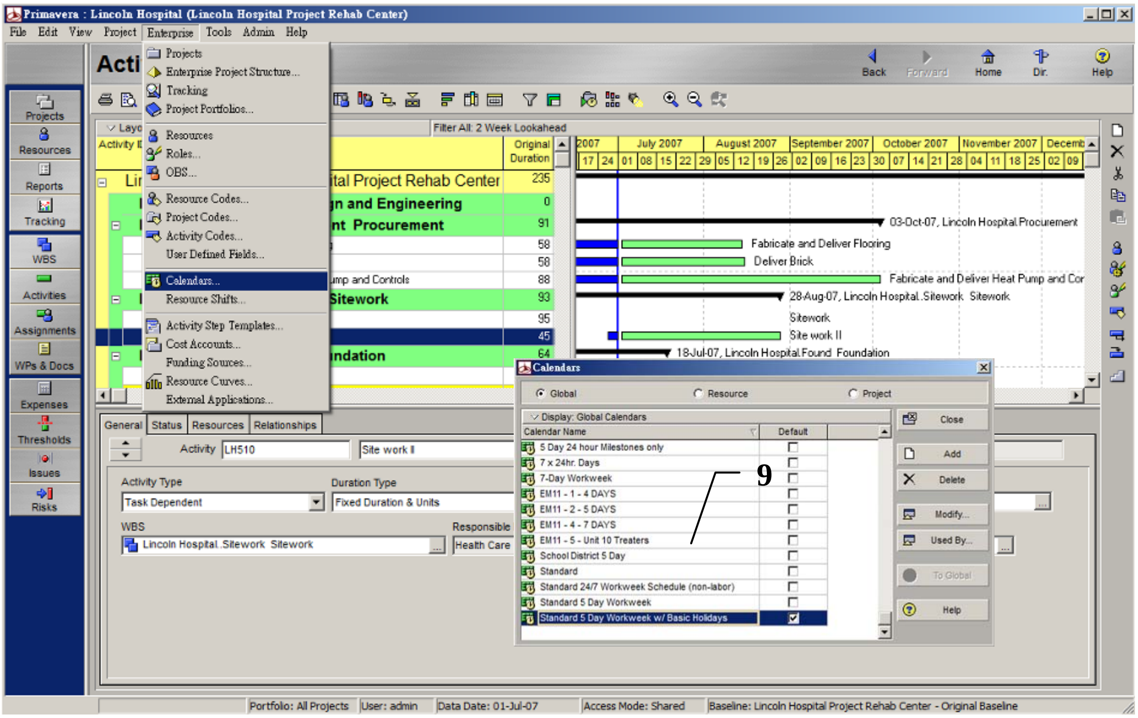


Fig. B.12: Creating calendars in *P6*

(9: Calendars dialog box)

B.2.5 Loading activity calendars

By clicking “” in activity calendar field, activity calendar constraint is imposed by choosing the calendar shown in the select activity calendar dialog box.

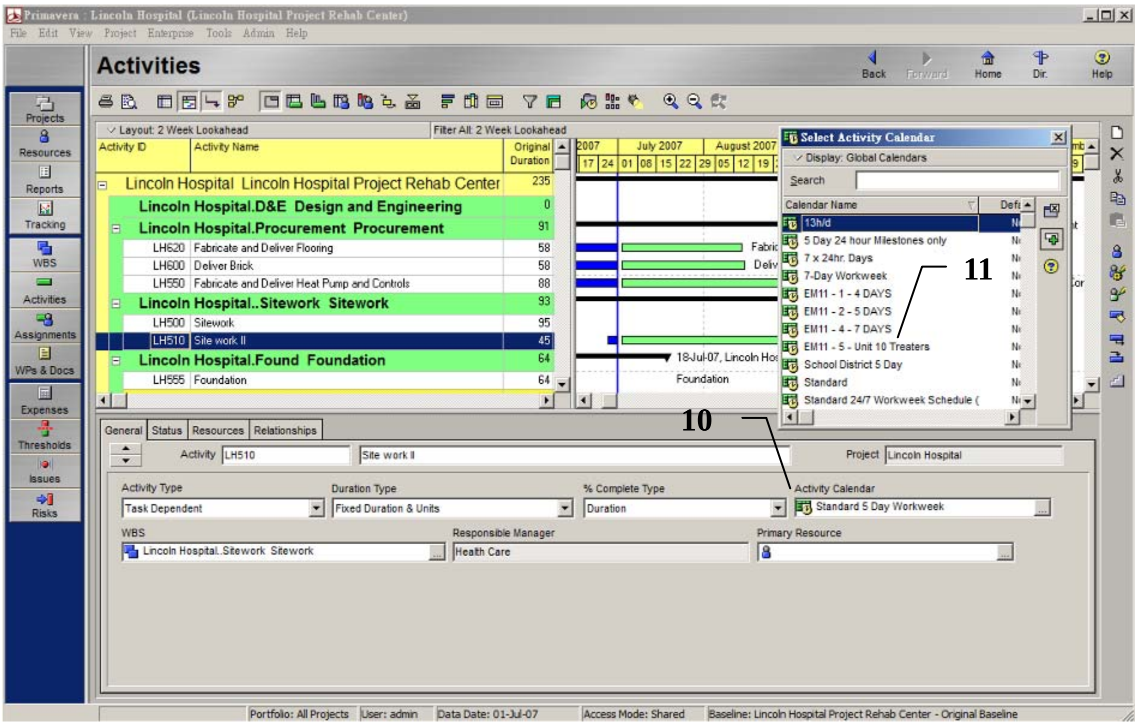


Fig. B.13: Imposing activity calendars in *P6*

(10: Activity calendar field; 11: Select activity calendar dialog box)

B.2.6 Creating resources, setting resource availability limits and loading resource calendars

“Resources” window displays information on all available resources across an organization in *P6*. Resources are added, viewed, and edited in resource workspace. Resource calendar is displayed in calendar field for highlighted resource. By clicking “”, calendar is changed by choosing others displayed in select resource calendar dialog box. Note that the resource availability limits are set in max units/time column.

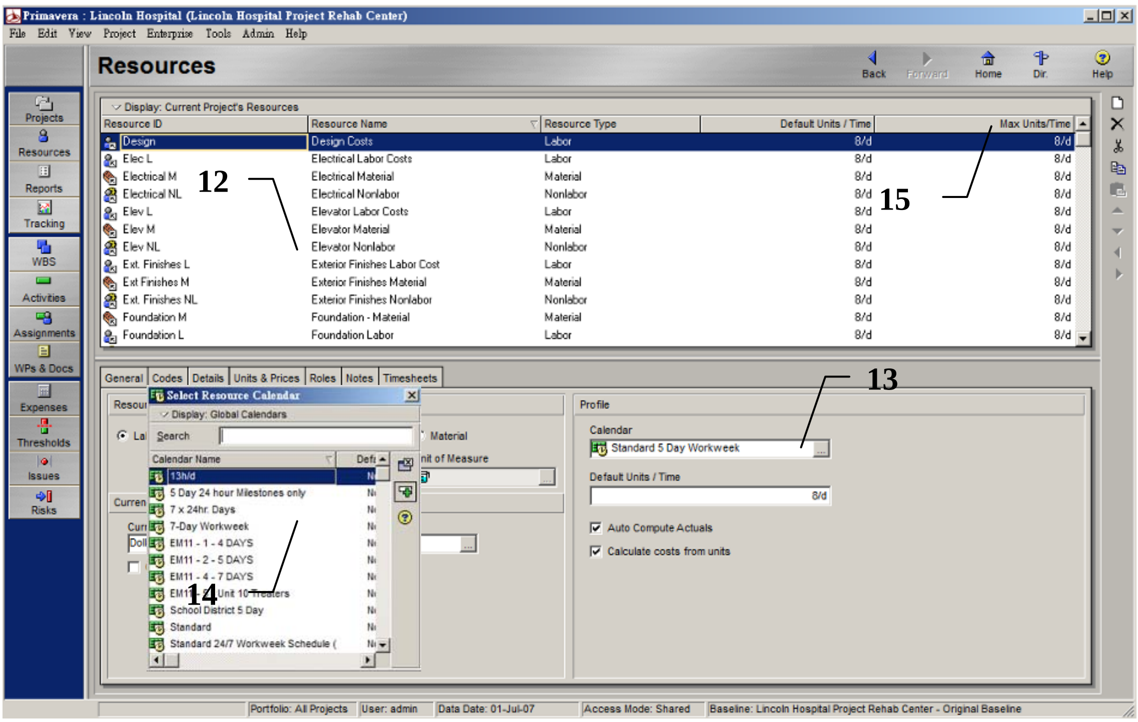


Fig. B.14: Creating resources, resource availability limits and resource calendars in *P6*

(12: Resource workspace; 13: Calendar field; 14: Select resource calendar dialog box; 15: Max units/time column)

B.2.7 Loading resources

Resources are assigned to the activity by clicking resources tab located in activity window. Resources are loaded to highlighted activity by selecting available resources in the assign resources dialog box, which is opened by clicking “add resource” button.

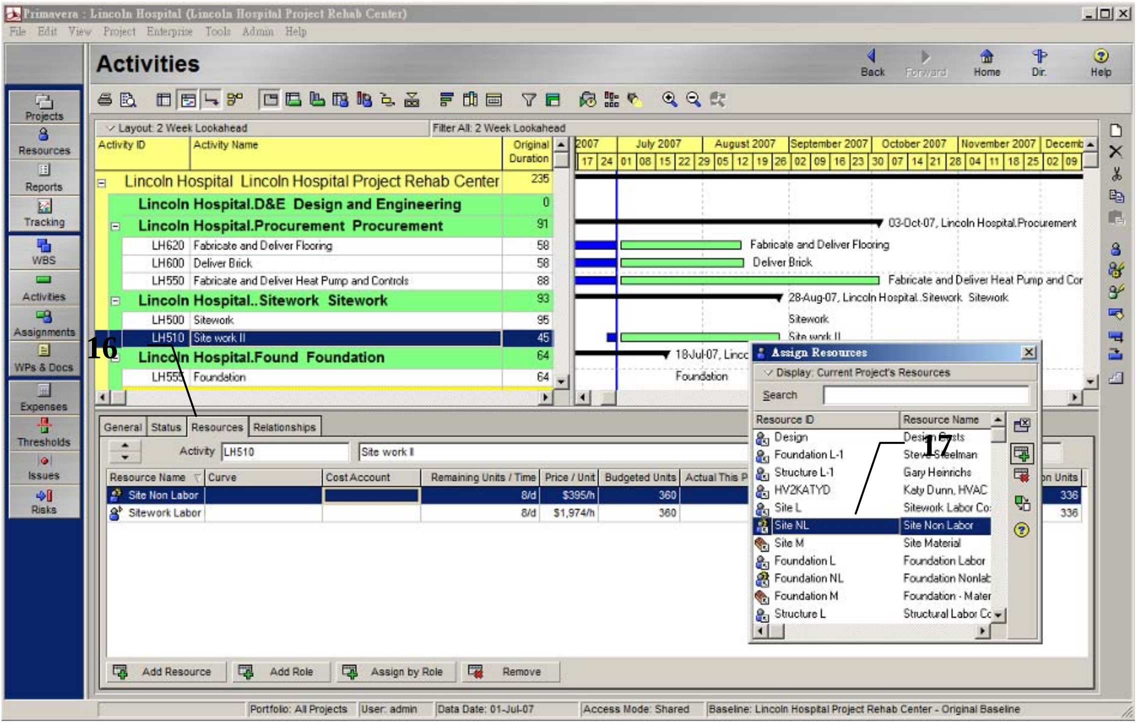


Fig. B.15: Loading resource in *P6*

(16: Resources tab; 17: Assign resources dialog box)

B.2.8 Scheduling by resource leveling

Schedule analysis by resource leveling option is available in level resources dialog box, which is opened by invoking "Tools, Level resources". The leveling priorities field is available to specify activity priority rules to define its built-in heuristic rules for resource allocation and leveling. By clicking "level" button, the resources are automatically allocated and leveled according to the defined prioritization parameters.

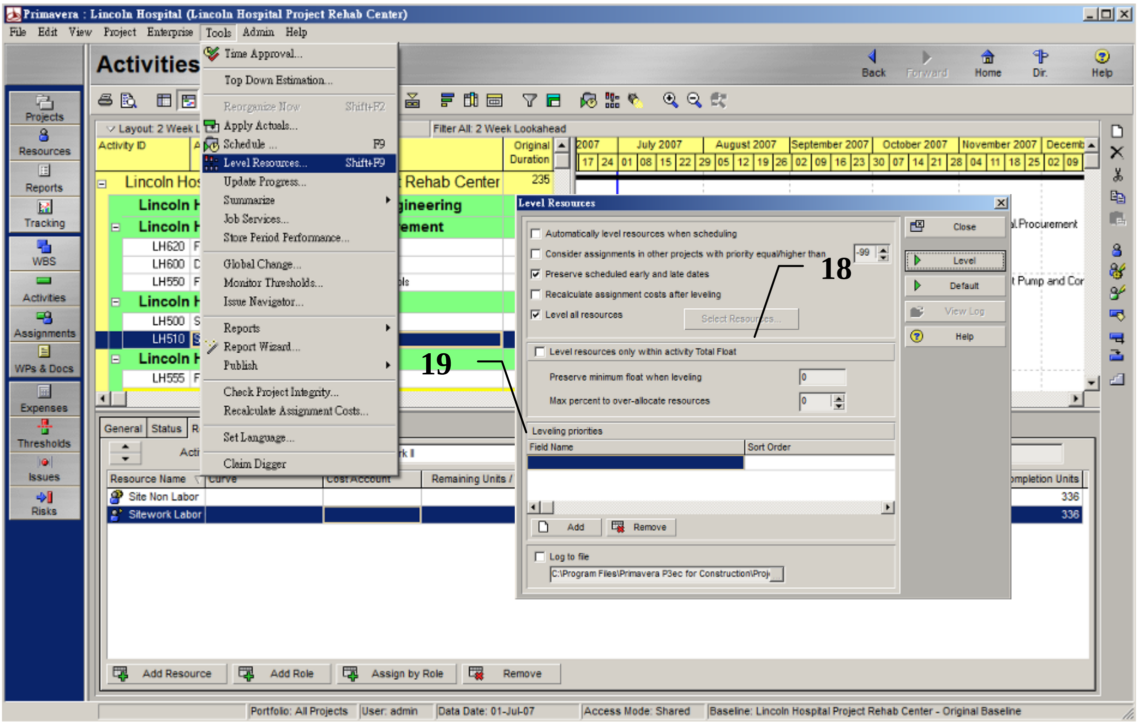


Fig. B.16: *P6* scheduling by resource leveling

(18: Level resources dialog box; 19: Leveling priorities field)

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