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The Hong Kong Polytechnic University
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Resource-Constrained Project Evaluation and Review Technique
(PERT): Stochastic Simulation and Optimization

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

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Lam Hoi Ching

ABSTRACT

In the construction industry, the classic Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT) have been widely applied in modern project scheduling management systems since 1950s. The major limitation in conventional critical path analysis in handling practical construction project planning is identified as the potential confusions and misleading information associated with the constraints of resource availability and activity interruptions (such as multiple activity calendars, individual resource calendars, random resource breakdown or routine resource maintenance). In consequence, the determination of correct float values by using the industry norm software such as *Primavera Project Planner (P3)* and *Microsoft Project* is not guaranteed. The purpose of the research is to (1) develop a simulation tool for construction scheduling, named the *Simplified Simulation-based Scheduling* (short as *S3*), (2) apply an evolutionary optimization for resource-constrained construction scheduling analysis, (3) enable project cost analysis based on resource-constrained schedules and expose the implicit relationships between resources, project duration and cost, and (4) compare the functionality and special features of *S3* and *P3* in connection with the resource-constrained project scheduling.

S3 allows resource, time and cost-integrated project optimization analysis under both deterministic and uncertain scenarios, lending itself well to planning construction projects featuring complicated resource and technology constraints. In this research, a classic textbook example serves to illustrate the limitations of the popular *P3*, together with the application of *S3* developed from in-house research. In an effort to address *P3*'s shortfalls, a new total float (TF) determination algorithm is introduced to check the validity of TF and derive the accurate TF for those activities whose TF are overstated by *P3*. This thesis also presents the Particle Swarm Optimization (PSO) algorithm for the optimization of

resource-constrained scheduling problem and discusses the experimental results on case studies. *S3* is capable of rapidly formulating the best project plan with respect of achieving the shortest duration or the least cost. Finally, a real-world construction project is utilized to demonstrate the application of *S3* in practical settings. In conclusion, the methodology and prototype software of *S3* provide a complete and valid alternative solution to CPM-based project scheduling, subject to the constraints of resource limits and activity interruptions.

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CHAPTER 1

INTRODUCTION

1.1 Background

Project planning and scheduling is vital to the successful execution of construction site works. During project planning and scheduling stages, project managers need to determine when their own labor force and any sub-contractors need to be deployed, when materials need to be delivered to the construction sites, and when equipment and plants need to be rented. In practice, in an attempt to realize the time and cost objectives of a construction project, they need to arrange for activity sequence according to construction technology while also dealing with the allocation largely based on their intuition and experience.

Manual scheduling methods become inefficient, intractable and incapable as the size and complexity of construction projects ever increase. The large data storage and processing capacities make computers ideal tools for manipulating, keeping and updating schedule data.

In the construction industry, the classic Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT) have been widely applied in computer-based project scheduling management systems since 1950s. In particular, CPM analysis with the software packages of *Microsoft Project (MS Project)* and *Primavera Project Planner (P3)* are the analytical technique used most frequently by the construction managers (Galloway 2006b). Most large contracting firms are armed with *P3* and have invested heavily in training staff to know and apply *P3* in their work; while small subcontractors may opt for the inexpensive

MS Project.

Given the computer aid available to project managers, the resource management is still not an easy task due to the complexity of construction projects and the limitations of scheduling software. Practitioners particularly call for enhancement of the ability of existing software packages to provide near-optimal schedules under resource availability constraints (Liberatore et al. 2001), but most commercially available project scheduling software does not yet provide the capabilities for handling resource-scheduling optimization and time/cost trade-off problems. Generally, resource scheduling on CPM networks copes with the notorious “combinatorial explosion” problem. The consideration of uncertainties on construction projects, including high variability of activity durations plus random or prescheduled operational interruptions, further adds to the difficulty in attaining optimal solutions in resource scheduling. When adopting multiple calendar constraints, assigning different resources on each activity becomes much more complicated to tackle, and the underlying algorithms and theories of most scheduling software remain proprietary and unpublished (Kim and Garza 2005).

Moreover, the existing CPM or PERT scheduling software systems largely run on the precedence diagram method (PDM), which contains potential problems, confusions and faulty interpretations. The major limitation in conventional critical path analysis in handling practical construction project planning is identified as the potential confusions and misleading information associated with the constraints of resource availability and activity interruptions (i.e. multiple activity calendars, individual resource calendars, random resource breakdown or routine resource maintenance).

In recent years, the development of simulation and evolutionary optimization techniques, coupled with the enhancement of the power of computing hardware, has made it possible to explore the optimization for CPM resource scheduling on a realistic scale. Nevertheless, a

valid, cost efficient and computer-based methodology –which seamlessly integrates evolutionary optimization and stochastic simulation for practical resource scheduling– is desired by the construction industry and is yet to be developed. This thesis provides a complete framework for deterministic CPM analysis and stochastic simulation-optimization analysis of resource-constrained PERT models in a clear, general way to address both fundamental theories and application requirements.

1.2 Research Objectives

The study is focused on revealing the impact of (1) limited resource allocation, (2) activity-interruption constraints and (3) activity duration uncertainties upon CPM scheduling. A high-quality project schedule enables the client and the contractor to know in advance when to expect a certain action to take place and how to effectively allocate the limited resources. When it is inadequate for project managers to simply rely on their experience and intuition in making a construction schedule, the use of project scheduling tools is justified and the accurate predication of project duration and cost is desired.

In order to improve construction planning and resource management, a prototype project scheduling tool –named *Simplified Simulation-based Scheduling* (short as *S3*) – combines the simulation modeling with evolutionary optimization technique and has been customized in house as a result of the present thesis research. This thesis will also compare the functionality and special features of *S3* and *P3* in term of resource-constrained project scheduling.

1.3 Organization of Thesis

This thesis contains seven chapters. Chapter 1 introduces the background to present study, and the rest of the thesis is organized as follows. In Chapter 2, a review of the related research about project scheduling is given. The research methodology is described in Chapter 3. The *S3* simulation model is presented in the fourth chapter with a simple example that helps to explain how the model can be formed for project scheduling analysis. Chapter 5 describes the Particle Swarm Optimization (PSO) algorithm for the optimization of resource-constrained scheduling problems and discusses the experimental results. Chapter 6 uses a practical case to demonstrate the application of *S3*. Finally in Chapter 7, the summary and conclusion of this research are given.

CHAPTER 2

LITERATURE REVIEW

2.1 Construction Project Planning and Scheduling

Construction management includes the steps of planning, scheduling, controlling, and communicating during various phases of a construction project. In the project planning and scheduling stages, cost and time are areas of primary interest. Project planning is an essential task in which construction methods are selected, project scope and tasks are defined, tasks' durations are estimated, requirements and constraints of resources and costs are identified (Callahan et al. 1992).

Ahuja et al. (1994) stated that the most fundamental technique used for planning and managing a project is to break down the scope of work into manageable pieces. Work breakdown structure (WBS) is defined as “the progressive hierarchical breakdown of the project into smaller pieces to the lowest practical level to which cost is applied” (Daniel 2006). WBS is developed before dependencies are identified and activity durations are estimated, all serving as useful input to develop both cost and time plans.

Project scheduling, on the other hand, is to arrange project tasks and resources in an interrelated time-based sequence so as to meet the common goals of time, cost and quality under limited resources and budget constraints. Previous researchers have made contributions to the subject of project planning and scheduling, and some of these contributions are discussed below.

2.2 Overview of Project Scheduling

Analytical tools and graphical techniques of different types are available for planning and scheduling of construction operations. These tools are used to aid project managers in organizing their thoughts in plan formulation and communicating their thoughts to the people who will put their plan into action.

2.2.1 Bar Charts

Bar chart (or Gantt chart), which was developed in the early 1900s, has been widely accepted in construction scheduling. It graphically represents the activities involved in a project and the time taken for each activity. The activities in a bar chart are listed along the y-axis while horizontal bars against the time scale along the x-axis are shown to mark the start and finish times of the activities. Bar charts are the simplest form of scheduling tool to prepare and read. However, the lack of displaying logical interrelationship between activities is the major drawback (Moder 1983, Callahan et al. 1992). It is difficult to use it for forecasting, and it will be cumbersome if a lot of activities are involved as in a large project.

2.2.2 Progress Curve (S-curve)

Progress curve is also a graphical tool showing a measure of cumulative progress on the vertical y-axis against project time on the horizontal x-axis. The measured progress is generally in terms of money spent, man-hours used, and work-in-place, etc. The resulting cumulative curve will start at a flat slope, climb up steeply at the middle phase, and then flatten out at the final stage of the project forming the familiar S-shaped curve. By drawing the actual cumulative progress against the estimated progress on the same graph, it is easy for forecasting purpose and making decisions for any related corrective action (Callahan et

al. 1992). However, it is unable to display logical interrelationship between activities.

2.2.3 Linear Balance Charts

Linear Balance Chart is introduced for scheduling linear projects involving repetitive activities such as highways, tunnels, pipelines, and high-rise buildings. It is sometimes referred as Line-of-Balance (LOB) method because the planning strategy is to schedule the cumulative or rate progress (in vertical axis, and in terms of units or percentage completed) of activities delivered by a particular resource against time (in horizontal axis), such as crews of workers, in series of sloping lines –which are delineated with lines as parallel as possible to one another. The LOB technique is resource driven –meaning that it is more focused on resources in scheduling. It is good for projects which are composed of many identical units, but variations in individual units and floats allowed in the program might cause problems in the analysis (Mawdesley et al. 1997).

2.3 Network Techniques: CPM and PERT

Apart from the abovementioned scheduling methods, the network diagramming technique is the most popular method. There are two quite similar network modeling techniques that were developed independently, but almost concurrently in the late 1950s: Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT). The CPM grew out of a joint effort in late 1950s by the E. I. Du Pont de Nemours Company and Remington Rand while the PERT was developed to aid in producing the U.S. Polaris missile system in 1958 (Callahan et al. 1992). CPM is more important in construction industry as it determines how to reduce project expenditure by completing the project within minimum possible time. PERT is primarily used in research or undertakings where insufficient experience or historical data is available for estimating the durations of individual activities

in a project (Hinze 2004).

The classic CPM assumes that the construction project is performed under a deterministic situation and with the availability of unlimited resources. With CPM, estimates of activity durations are based on historical data and are assumed to be the mean or average time that the activity has required in the past. However, when a project contains a majority of activities for which no experience exists or no historical data is available, the estimating difficulty becomes significant. With no experience to serve as a guide, the only solution is to make the best possible guess, using whatever relevant experience available.

PERT, like CPM scheduling, uses network diagrams to analyze performance times, but the major difference of the two approaches is that CPM is focused on the calculation of deterministic event times but PERT assumes probabilistic events. Uncertainties associated with activity duration or cost are generally modeled using probability or fuzzy set theories for PERT analysis. Since the absence of historical cost or time data is common in the planning stage, PERT permits three time estimates (pessimistic, optimistic, most likely) for the duration of each activity to evaluate the likelihood of achieving a certain project completion time.

2.3.1 Graphical Tools

In the CPM and PERT network techniques, activity on arrow (AOA), activity on node (AON) and precedence diagram method (PDM) are three main graphical tools to show all the activities in the work breakdown structure of a project with the precedence relationships between them.

Dated back to 1960s, in applying the circle-and-connecting-line technique (later called

activity-on-node or AON) in a Navy Bureau of Yards and Docks study, Fondahl (1961) recognized that AON-based critical path analysis could not allow overlapping unless activities were further divided. As an extension of the original AON concept, the precedence diagram method (PDM) was introduced by H.B. Zachry in a 1964 IBM publication (the user's manual for the IBM 1440 program), using three relationships [finish-to-start (FS), start-to-start (SS), and finish-to-finish (FF)] and positive lags to depict the partially concurring or overlapped working procedures (Moder and Philips 1970). The start-to-finish (SF) relationship along with negative lags was later added to the PDM by Ponce-Campos (1970). This permits mutually dependent activities to be performed partially in parallel instead of in series. Paradoxically, PDM's usefulness and applicability backtracked in practice as its theoretical definitions became more complete and its scheduling features were further enriched (Lu 2006).

Since AOA will give rise to confusing and cumbersome network diagrams when dummies are introduced, it will be more awkward and inconvenient than AON or PDM in representing large projects. Therefore, the commonly used network diagrams to represent activities sequence and logical interdependencies are either in AON or PDM format.

2.3.2 *Comparative Studies of PDM and AON*

An AON network features finish-to-start (FS) relationships only and all preceding activities must be completed before a current activity can begin. In contrast, PDM eliminates the need for dummy activities and adds details (lag time and start-to-start, finish-to-finish, and start-to-finish relationships) to show activity overlapping, and hence offers a simpler way to indicate the complex logical relationships among construction activities. Some researchers maintain that PDM offers a more flexible network than conventional AON (Wiest 1981, Bullinger and Ammer 1984, Liu and Yuan 1996, Hinze 2004). In the market, most

commercially available project scheduling software programs are implementations of PDM, allowing for four possible logical relationships between activities.

PDM, however, still contains some potential problems, confusions and faulty interpretations such as complicated logic loops and anomalous effects on critical path continuity (Moder and Philips 1970, Wiest 1986, Oberlender 2000). The “smart” precedence relationships of PDM may render the float determination and interpretation much convoluted. Callahan et al. (1992) indicated that “it is not always clear what part of activity is related to another one through the use of relationships with lags,” because “the exact work represented by the lag may not be able to be determined by people other than the original scheduler”. PDM diagram users have to think harder to understand the logic depicted as compared with the simple AON format, and as a result, “PDM, in its sophistication, takes a step backward in communication capability” (O’Brien and Plotnick 1999). A recent industry-wide survey on CPM scheduling by Galloway (2006b) also recognized the complexity and difficulty of PDM and the possibility of CPM schedules being easily manipulated in terms of logic abuse.

2.3.3 *Implementation of Primavera Project Planner (P3)*

According to a recent industry survey (Galloway 2006a), *P3* has become a standard methodology for construction project management in both university curriculums and industry practices. Deeply rooted in construction, *P3* provides sophisticated scheduling features and functionalities (such as precedence diagram, resource loading, cost integration, and performance monitoring and reporting) that cater to the needs of managing construction projects. At present, a *P3*-generated construction schedule constitutes part of an eligible bid proposal for nearly every major project. Additionally, the *P3* schedules are also widely used to provide the legal effect for resolving disputes and justifying claims arising from the

project. Recent worldwide surveys on university CPM curriculums and CPM practices in the construction industry found that (1) the vast majority of US schools which offer a specific course on CPM scheduling use *P3* in the teaching of computerized scheduling; while (2) over 64% of the owners used *P3* as their specified software and nearly 65% of the contractors indicated their preference of applying the *P3* software (Galloway 2006a and 2006b).

Nonetheless, *P3* is associated with potential problems, confusions and faulty interpretations in dealing with resource availability or multiple calendar constraints, yielding incorrect dates in CPM's forward pass or backward pass calculations (Kim and Garza 2003; 2005). Kim and Garza also pointed out that *P3* generated incorrect dates for start-to-finish (SF) with zero lag and inconsistent results for negative lags on all relationship types and recommended "to avoid negative lags and the SF relationships with different calendars".

2.3.4 *Multiple Resource Calendars*

On the other hand, most scheduling tools provide the capability of handling interruptions on different activities and resources. For instance, three options on activity calendar type are available in *P3*, namely "Meeting", "Task", and "Independent", with respect to activity calendar settings. The "Meeting" option derives the activity calendar from combining the calendars of individual resources into common work time among all the resources involved when an activity requires matching multiple resources (e.g. concreting requires the use of the crew and a crane). As for "Independent", driving resources involved in an activity will run on their individual calendars independently. And the "Task" setting deals with calendar specification at the whole activity level, neglecting any individual resource calendars.

So far, research on CPM under calendar constraints has only dealt with the "Task" setting,

considering different activity calendar definitions at the predecessor and the successor respectively (Kim and Garza 2005). Research has yet to address how to incorporate the effects of multiple resource calendars on CPM scheduling in connection with assessing the activity calendar setting of “Meeting” of *P3* –which is more complicated yet more relevant to resource-driven construction planning.

2.4 Resource Scheduling Problems

In reality, the scheduling of multiple resources should be the main concern in project planning and controlling since labor and equipment resources are limited in availability and drive the progress on construction activities. Implementation of an optimal resource schedule will potentially decrease the project duration and total cost to clients and contractors. However, traditional CPM scheduling techniques have proven to be helpful only when the project deadline is not fixed and the resources are not constrained by either availability or time (Hegazy 1999). They have failed to clarify the “resource-critical” issue (Fondahl 1961): noncritical activities in the sense of having positive float can still be “resource-critical”, since project duration will be delayed if resource-critical activities fail to release resources that are required by critical activities on time.

Because computerized construction scheduling is an evolving process and the industry has no standard requirements as yet, computerized scheduling can become a challenge (Zafar and Rasmussen 2001). To deal with the unavailability of resources, project scheduling must include resource arrangement details, and the resource scheduling problems have been studied intensively in both construction industry and academic research for decades.

2.4.1 Optimization Aspects of Resource Management

An industry survey (Liberatore et al. 2001) pointed out that construction professionals are heavy users of critical path analysis for project planning, resource scheduling. Resource scheduling on CPM networks, which is traditionally categorized into (1) resource allocation, (2) resource leveling, and (3) time/cost trade-off, copes with the notorious “combinatorial explosion” problem. Each of these three categories has a different theme and objective. Resource allocation is an attempt to reschedule the project tasks so that a limited number of resources can be efficiently utilized while keeping the unavoidable extension of project to a minimum. In resource leveling studies, the aim is to reduce the sharp variations among the peaks and valleys in the resource demand histogram while maintaining the original project duration. Finding the most cost efficient option for carrying out activities so as to complete a project within an optimal time period and with the lowest total cost is the basic idea behind the time/cost trade-off analysis.

On the other hand, there are two commonly used methods for solving resource scheduling problem: the serial and parallel methods. In a serial method resources are freed from one activity and replenished to the resource pool for reallocation only when the activity is completed. In contrast, a parallel method frees and reallocates resources at the start of each time unit of scheduling (e.g. day) based on the updated priorities for each ready activity, thus it may cause activity interruptions from time to time. In most previous research, the resource-allocation algorithms maintain the resource work continuity in conducting each activity, and hence adopt essentially serial methods.

2.4.2 Traditional Optimization Techniques: Mathematical Methods

Studies on the optimization of resource scheduling have been in practice using various kinds of methods since the 1960s. Mathematical methods have received widespread

attention from academic research. Different mathematical approaches have been formulated to tackle deterministic resource-constrained scheduling problems. For examples, integer/linear programming, dynamic programming and branch-and-bound were proposed (Kelly 1961, Elmaghraby 1977, Talbot 1982). But these kinds of approaches explore too large search space for exhaustive enumeration in searching for the optimality. None is computationally tractable for any real-life problem size, thus rendering them impractical (Hegazy 1999).

2.4.3 Traditional Optimization Techniques: Heuristic Methods

In addition, analytical or heuristic techniques for resources allocation/leveling on classic CPM network plans have been developed since the early 1960. Almost all commercial scheduling software utilizes conventional heuristic rules or analytical methods to handle resource allocation problems. The general heuristic methods adopt priority rules among activities reflecting one or multiple factors such as activity's total float, duration and work content. Researchers have proposed various heuristic methods for resource leveling (Harris 1978), resource allocation (Lu and Li 2003), and time/cost tradeoff (Ahuja 1984). Theoretically, heuristic rules have the advantage of being simple to understand and easy to apply. Despite the techniques are able to find a feasible solution with far less computational effort, the performance is problem-dependent and the optimal or near optimal solution is not guaranteed. Their inconsistent solutions have contributed to large discrepancies among the resource scheduling features of commercial project management software (Hegazy and El-Zamamzay 1998).

2.4.4 Inadequacy of Traditional Resource Scheduling Methods

Little effort has been taken to achieve combined resource optimization because of the inherent complexity of projects and the difficulties associated with modeling all aspects

combined (Hegazy and Kassab 2003). Apart from the single objective optimization, project managers may simultaneously concern with resource allocation, day-to-day fluctuation problems on resource demand and time/cost tradeoff before the implementation of construction works. Thus, multicriteria optimized scheduling models are required to integrate the optimization objectives of recourse leveling, allocation of limited resources, and time-cost tradeoff. A multicriteria optimal model to search the optimal combination of construction durations, resource amounts, minimum direct project costs, and minimum project duration under the constraint of limited resources has been introduced (Leu and Yang 1999, Leu and Hung 2002).

The stochastic simulation and evolutionary optimization techniques could achieve multi-objective optimization for resource scheduling subject to limited resource availability and uncertain activity duration.

2.5 Simulation Modeling Analysis

In the literature, the traditional resource-constrained scheduling methods focused on deterministic situations. Compared with conventional mathematical programming techniques and heuristic methods, the simulation technology holds the potential to provide a useful decision-support tool in tackling the complicated and stochastic problem of project scheduling with resources constraints. During rapid development of computer technology, simulation modeling and analysis of construction processes have gained importance in recent years in light of an increase in the complexity of construction processes (Sawhney et al. 1999). Simulation is defined as “building a logical model of a system and experimenting with it on a computer” (Pritsker 1986). To achieve a better understanding of the problem, the application of modeling and simulation is a critical step in analyzing the construction

operation and improving its performance (Haplin 1977, Kartam and Ibbs 1996).

2.5.1 Handling Interruption Constraints

Simulation model analysis is able to handle not only the limited resource allocation but also the multiple interruptions constraints. Much research has focused on applying simulation for construction project scheduling with continuous working days. However, in a real construction project, activity interruptions always occur due to (1) the prescheduled events such as labor's holidays, periodic equipment maintenance; (2) the unexpected events such as unavailability of resources/materials, inclement weather, unforeseen site conditions, equipment breakdown.

Different calendars (different combinations of working and non-working shifts) applied for activities and resources should be considered in the simulation model. For the prescheduled events, operational interruptions can be modeled using either task or resource calendars, for example, work time and non-work time can be defined in the calendar utilities provided in most scheduling software. Operational interruptions due to the unexpected events can be modeled by probability distributions for productive hours/day, depending on weather patterns, etc (Naylor 1995).

2.5.2 Tackling PERT Limitations

Unlike deterministic CPM analysis, the classic PERT analysis adopts a probabilistic approach. Yet, PERT has its drawbacks in project scheduling since it only focuses upon a single critical path. The other parallel paths that are nearly critical might become critical due to random fluctuations. Ignoring these near-critical paths in determining project completion time probabilities causes a bias in the mean estimate, which is called the "merge event bias" (Ahuja et al. 1994). As a result, the mean project duration would be

underestimated or too optimistic.

Ahjuja et al. (1994) indicated that Monte Carlo simulation on PERT is a solution to tackle the merge event bias by using the true properties of the activity duration distributions in simulation. Previous studies have successfully demonstrated the use of Monte Carlo simulation for estimating the project duration or cost under uncertainty (Pristsker et al. 1989, Ahuja 1994, Sawhney and AbouRizk 1995, Lee 2005). A Monte Carlo-based sensitivity analysis could also be carried out to assess the impact of activity-time uncertainty upon the project duration.

Pristsker et al. (1989) presented an approach to PERT simulation and pointed out that “there is a large positive correlation between the ranking of critical activities based on the ratio of average slack (total float) to activity duration standard deviation and the criticality index”. The critical index (CI) for an activity in a percentage term is defined as the number of simulation runs in which the activity is critical, divided by the total number of simulation runs.

In order to overcome such difficulties, the concept of critical index and Monte Carlo simulation should be integrated with PERT to obtain more meaningful results.

2.5.3 Simulation Tools

Simulation modeling has proven beneficial in a large amount of applications in many industries, but many existing simulation tools require knowledge of computer programming and proprietary simulation languages, and lack integration with optimization algorithms. With the objective of simulating construction systems as easy as applying traditional CPM, SDESA (short for Simplified Discrete Event Simulation Approach) is a recent research

product developed at Hong Kong Polytechnic University (Lu 2003; Lu and Chan 2004; Lam and Lu 2006). Discrete-event simulation keeps track of the changes of the state of a system occurring at discrete points in time (Pidd 1992). On the SDESA platform, CPM/PERT models can be readily set up so as to enable the scheduling analysis by considering the effects of resource-constrained problems, multiple calendars constraints and activity-time uncertainties.

Based on the SDESA platform for modeling construction operations, a special-purpose simulation tool called *S3* is developed for rapidly building a simulation model for CPM scheduling. In this research study, *S3* is introduced to demonstrate a more efficient approach to conduct resource-constrained CPM/PERT simulation and optimization analysis under uncertainties. Also, what-if scenarios can be investigated to decide the desired resource amounts and activity sequence in planning and executing projects. *S3* delivers the optimum solution to the user-defined objective function (the corresponding project duration or cost). Therefore, *S3* can assist the managers in making informed decisions and enhancing the productivity and the resource utilization.

2.6 Evolutionary Optimization

As mentioned in previous sections, simulation modeling provides a meaningful representation of a construction project for analyzing the performance of the whole project (i.e. completion time, total cost) and resource utilization, but it does not enable optimization. In general, a trial-and-error approach such as adjusting various activity sequence or resource combinations might find a reasonable solution. During rapid development of computer technology and artificial intelligence, optimization methods have been proposed to solve complex project scheduling problem.

Compared with traditional optimization algorithm, evolutionary optimization is more appropriate to handle complicated large-scale project scheduling problems due to flexibility and adaptiveness of its stochastic search technique. Evolutionary algorithms refer to a class of algorithms based on probabilistic adaptation inspired by the principles of natural evolution. They follow a stochastic search strategy on a population of individuals, each representing a possible solution to the problem. Once all the members of the population are assigned fitness values, a selection process is carried out where better individuals (high fitness value) stand a greater chance to be selected for further evolution. The whole process is repeated with this new population until some termination criteria is satisfied. The average fitness of the population is expected to increase over generations, and finally converge at the point close to the global optimum.

2.6.1 Genetic Algorithm (GA)

One of the evolutionary optimization approaches, genetic algorithm (GA) conceptualized by John Holland in the 1970s, is a stochastic search technique based upon the mechanism of natural selection and genetics. In GAs, potential solutions to a problem are represented as a population of chromosomes, and each chromosome stands for a possible solution in each generation. In order to search optimal or near-optimal solutions, the chromosomes are evaluated on their performance with respect to the fitness functions (objective measures) during each generation/iteration. GAs have been proved to be efficient for identifying the optimal solution.

GA is the most popular evolutionary algorithm in research related to the optimization of construction scheduling (Hegazy 1999, Feng et al. 2000, Chan and Hu 2002). Many researchers used GAs to solve the problem of minimizing construction project duration in

deterministic conditions. In most research, the major task of resource allocation scheduling is to decide the priority of allocating resources to the activities. For instance, Chan et al. (1996) used GA to solve mathematic formulations for simultaneous resource allocation and leveling in scheduling construction project.

Hegazy (1999) proposed an optimization model using GA and heuristic rules (concepts of minimum total slack and minimum moment method) to find the best heuristic rules for prioritizing activities in allocating limited resources with the consideration of both resource allocation and leveling. However, it does not take into account project cost and time-cost relationship.

Apart from resource allocation, other models utilized GAs focused on time/cost tradeoff analysis. For instances, Feng et al. (1997) identified the pareto front in the project time-cost tradeoff analysis, Li et al. (Li and Love 1997; Li et al. 1999) facilitated the time-cost optimization to search the minimum project cost.

Leu and Yang (1999) developed a time-cost tradeoff and resource allocation unified GA-based optimization model. They used activity duration obtained from the time-cost tradeoff model as basic input data for the computation of minimum project duration under resource constraints. However, they stated that improvements in resource leveling need to be made because resource conflicts still occurred. The method produced suboptimal solutions and did not address total cost minimization.

The GA-RACPM (Genetic Algorithm enhanced Resource Activity Critical Path Method) software was developed to seamlessly integrate allocation of limited multitasking resources into resource-constrained CPM scheduling (Lu et al. 2002; Lu and Li 2003). In order to allocate multiple available resources to different activities to minimize the total project

duration, the GA-RACPM software is employed in developing the resource-constrained scheduling analysis by adjusting the priority values for activities.

Senouci and Eldin (2004) proposed a hybrid GA model to solve the nonlinear time/cost tradeoff problems. The model allows any linear or nonlinear function for the representation of cost-duration and resource-duration relationships. However, it failed to consider the effect of various combinations of resource limits.

As mentioned above, the proposed optimization models mostly focused on the deterministic problems. One common limitation noted in the above several GA-optimization models is that the input parameters (activity durations and costs) are simply represented with deterministic values instead of statistical distributions. In the literature, only a few probabilistic models have been developed that take resource constraints into account.

Leu et al. (1999) presented a fuzzy optimal model for resource-constrained construction scheduling. Although a GA-based technique was used to search for optimal fuzzy profiles of project duration and resource amounts under the constraint of limited resources, the method did not attempt to seek project total cost minimization.

Leu and Hung (2002) presented an approach, employing the GA and Monte Carlo simulation, to develop the resource-constrained scheduling model under uncertainty. Feng et al. (2000) developed a hybrid approach that combines simulation techniques and GAs to solve the time-cost trade-off problem under uncertainty. Their approaches provided more realistic solutions for project scheduling uncertainty, but they did not consider different combination of resource limits in optimization process or attempt to seek the optimal combination of resources.

2.6.2 Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is another evolutionary optimization technique proposed by Kennedy and Eberhart in 1995. The basic idea of PSO was inspired by natural flocking and swarm behavior of birds and insects. It is a powerful method to find the minimum of a numerical function, on a continuous definition domain.

Analogous to GA, PSO is also a population-based iterative algorithm, and starts with a population of randomly generated solutions (particles of PSO vs. chromosomes in GA). Both algorithms rely on fitness measures to evaluate and evolve over generations in approaching the optimum solution. In GA, the whole population of chromosomes moves toward the optimum by crossover and mutation operations. This random nature of GA requires a long process and becomes a main shortcoming. Unlike GA, PSO updates a population of particles with the internal velocity and position and benefits from the experiences of all particles. From one generation to the next, particles keep memory of their previous positions, which is a unique mechanism to the PSO algorithm and sets PSO apart from GA.

PSO shares the ability of the GA to optimize arbitrary nonlinear functions, but boasts a much simpler implementation mechanism. While PSO requires less computational bookkeeping and generally only a few lines of code, it clearly demonstrates good possibilities for widespread use in electromagnetic optimization (Boeringer and Werner 2004). In solving difficult combinatorial optimization problems, PSO has received a growing attention. One recent research is that Zhang et al. (2006a and 2006b) introduced PSO technique in solving resource-constrained project scheduling problems. Their hybrid particle-updating mechanism incorporated with a partially mapped crossover of the GA to minimize the project duration. However, the research is limited to deterministic cases and does not attempt to handle any project cost aspects.

Based on the simulation platform of SDESA, Lu et al. (2003) developed a special-purpose simulation tool called HKCONSIM for rapidly building a simulation model for a typical one-plant-multisite system of concrete production and delivery. A follow-up attempt was to accelerate the optimization process of HKCONSIM by devising a PSO-based technique for coping with the optimization of stochastic system simulations (Lu et al. 2006). A comparison of PSO with GA was made in the context of optimizing an HKCONSIM model, showing the PSO-based approach could rapidly converge at the minimum level for a specific fitness measure while GA failed to converge or required long time (in order of hours) in search of the minimum (Lu et al. 2006). In brief, PSO was able to rapidly find the optimum on an output of a stochastic simulation model in the “non-steady, stochastic” setting. The improvement in terms of the order of optimum-searching time required is significant.

2.7 Conclusion of Literature Review

The above literature review leads to the following observation and conclusion.

In project scheduling, two network techniques (CPM and PERT) are the most popular scheduling methods. CPM network schedules considering deterministic activity durations facilitate tracking time and cost and so far have contributed significantly to the planning, control, and performance monitoring of construction projects. PERT network model considering probabilistic event times is actually more suitable to simulate the real construction project since the duration of activity could be represented by random variables (discrete or continuous distribution).

As to the network diagramming techniques, activity on node (AON) and precedence diagram method (PDM) become two main graphical tools to show all the activities of a project with the precedence relationships between them. A literature survey has been undertaken on the development of computerized scheduling tools. Most commercially available project scheduling software programs are implementations of PDM, allowing for four possible logical relationships between activities. A recent industry survey (Galloway 2006a) stated that *P3* has become a standard methodology for construction project management in both university curriculums and industry practices.

Kim and Garza (2005) addressed the issue of incorporating multiple calendars defined at activity level into PDM-based critical path scheduling and recommended to avoid negative lags and the PDM relationships with different calendars, particularly in applying *P3*. Given an existing PDM network, non-FS relationships with lags can be transformed into FS relationships prior to standard forward and backward pass calculations (Elmaghraby and Kamburowski 1992; Herroelen et al. 1998). Thus, the *P3*'s functionality dealing with resource constraints should be investigated first with AON instead of PDM (Lam and Lu 2006).

The project managers require accurate scheduling tools to deal with uncertainties, resource allocation and multiple interruption constraints. However, the main drawback of existing scheduling methods is that they fail to solve complex practical problems effectively and do not allow for real-world conditions and construction constraints (Jaskowski and Sobotka 2006). Stochastic simulation methods that combine PERT analysis and Monte Carlo simulation hold potential of dealing with the random nature in planning and analyzing project objectives, such as project completion time and costs (Ahuja and Nandakumar 1985, Diaz and Hadipriono 1993, Sawheny and AbouRizk 1995).

Recent advances in evolutionary optimization approaches make it possible to generate optimum resource schedules for project networks of practical size and complexity. Judging from the past research, it is necessary to develop a more efficient algorithm to obtain near optimal solutions of project scheduling problems. Compared with GA, PSO may provide a more effective and efficient solution to optimizing a stochastic system. A systematic and scientific approach to construction planning is desirable for accurately estimating project completion time and cost, efficiently utilizing limited resources, incorporating activity-time uncertainties, and finding minimum project time or cost solutions. Since little effort has been done to achieve combined resource scheduling simulation and optimization, the present research will deal with resource optimization and other aspects (resource allocation and time/cost trade-off) simultaneously.

Based on this study, simulation modeling and particle swarm optimization can be an effective combination with great potential for improving project resources scheduling and saving project duration and total cost. The computer system named *S3* can assist project managers in coping with the challenges of generating the best execution in resource allocation and time/cost tradeoff.

CHAPTER 3

RESEARCH METHODOLOGY

In order to conceptualize the resource management and multi-criteria optimization framework for critical path method (CPM) or project evaluation and review technique (PERT) simulation models, the details of the latest project scheduling and evolutionary optimization techniques were reviewed. Apart from elaborating on the underlying algorithms and theories, the research is intended to address practical project scheduling problems such as resource-availability and multiple interruption constraints. Based on the characteristics and special requirements of construction projects, both CPM-based and PERT-based network analyses were dealt with.

3.1 Development of CPM/PERT Simulation Software

To achieve accurate and valid project scheduling, the schedule model should simultaneously handle several constraints such as resources availabilities, multiple resource interruptions and resource transit given a certain construction site layout. This has resulted in the development of in-house special-purpose simulation tool called the *Simplified Simulation-based Scheduling* (short as *S3*) system for rapidly building a simulation model for a typical CPM/PERT analysis. The *S3* software package is customized in the simulation platform of SDESA (simplified discrete-event simulation approach). In order to eliminate errors and redundancy when forming a *S3* model, the research has developed theories and guidelines for CPM/PERT model construction, resulting in clear setup procedures of resource-constrained CPM/PERT network simulation models with *S3*.

A typical activity-on-node (AON) network problem was studied to work out a general guide for the model setup procedures in *S3*. In this second part of the studies, two kinds of resource-constrained network models (CPM and PERT) were investigated in order to embed practical project scheduling constraints. The research also compared the functionality and special features of *S3* and *P3* in connection with the resource-constrained project scheduling. In deterministic CPM scenario, we resorted to a case study to illustrate the limitations of *P3* alongside with applying *S3*. The detailed algorithm of the *S3*'s CPM network simulation analysis was presented. A sample application of stochastic PERT analysis with *S3* was then carried out on the same AON network.

3.2 Evolutionary Optimization

Another contribution of the thesis research is to apply an effective optimization methodology to CPM/PERT simulation modeling aimed at minimizing an objective function factoring in one or multiple criteria. Recent advances in evolutionary optimization approaches can effectively generate optimal or near-optimal resource schedule for project networks of practical size and complexity. The *S3* computer simulation system is powered by a Particle Swarm Optimization (PSO) engine, delivering both optimization performance and computing efficiency in searching the best operation strategy in resource scheduling.

In particular, strategies were proposed to handle two common types of resource scheduling problems: (1) in resource allocation, the combination of resources and sequence of activities would be optimized, thus minimizing the simulation-produced project duration; and (2) by entering cost data (i.e. daily wages of labour, rental rates of equipment) to the *S3* model, the sum-product of resource amount, task duration and daily costs of associated resources would be defined as an objective function for total project cost minimization.

3.3 Case Study based on a Real-World Project

The research has entailed conducting a case study on a real construction project to test the validity and cost-effectiveness of the new construction planning method. The case study spanned (1) input data preparation, (2) simulation model analysis, (3) determination of total project cost and duration, and (4) further optimization analysis under different “what-if” scenarios postulated with practical implications. In addition, the case study also included the application of *P3* and compared *P3*’s performance against *S3*, under the application of resource-availability and multiple interruption constraints.

CHAPTER 4

RESOURCE-CONSTRAINED PROJECT SCHEDULING

4.1 Simulation Concept and Algorithms in S3

The *Simplified Simulation-based Scheduling* (short as *S3*) software is customized in the streamlined construction simulation platform of SDESA (simplified discrete-event simulation approach) in order to implement critical path method (CPM) analysis under deterministic or stochastic simulation settings.

In practice, project managers prepare most initial project schedules in activity-on-node (AON) in order to keep the diagram easy to communicate and analyze. To simulate the real situation, resource constraints –such as resource limits and resource calendars– are added to AON for incorporating resource availability constraints in construction processes. To make construction simulations more realistic, interruptions models are embedded to accurately account for the effects of operational interruptions upon the system performance. With the increased use of computers, simulation is one of the advanced techniques for examining the effect of changing resource allocation and enhancing resource utilization.

A simulation model consists of discrete entities. An entity is an object that is created at the start of simulation, processed in the simulation model, and terminated at the end of simulation. The simulation system keeps track of the changes of the state or behaviors of each entity occurring at discrete points in time. In SDESA, resource availability constraints and precedence relationships between activities can be readily modeled by use of reusable and disposable resource entities, thus allowing the specification of a resource-constrained

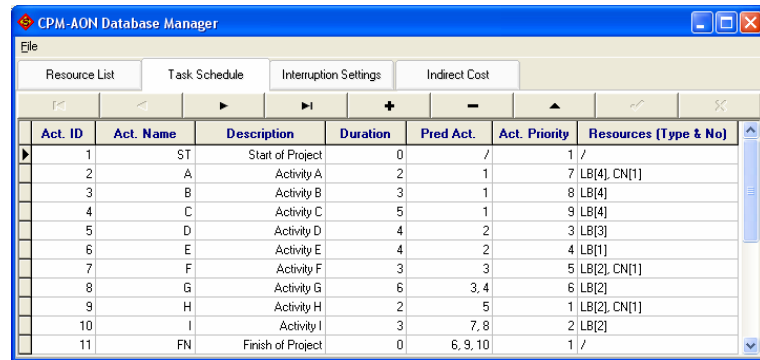
CPM network model based on AON. By manipulating two dynamic queues (activity entity queue and resource entity queue), all events can be processed according to their event times, activity sequence and resource availability (Lu 2003).

Also, interruption algorithms have been embedded in SDESA (Lu and Chan 2004). An activity interruption is a time period in which normal work on an activity is halted, and is defined by its start and end times. The activity interruptions can be further extended to include those due to individual resources' breakdown or interruption. Scheduling a simple activity interruption entails processing a series of events by an event-based methodology from (1) schedule the "interruption start" event time (place the activity back in the queue and calculate the remaining activity duration), (2) cancel the prescheduled "activity end" event time in the event list, (3) schedule the "activity interruption end" event time, to (4) re-schedule the "activity end" event time according to the remainder of activity duration.

Thus, a resource-constrained project scheduling model is required to simultaneously accommodate precedence relationships, resource limits and associated resource/activity calendar constraints. Based on user's model input, a "what-if" scenario analysis can be performed with S3. The "what-if" scenario analysis is executed by running simulation to assess and compare the different scenarios, such as extending specific activity duration, employing more resources, or introducing different interruptions.

4.2 User Interface

S3 is developed to allow users to enter activity details through a simple activity schedule form (as shown in Figure 1). An input screen of S3 is designed for user to specify the details of activities and resources requirement as well as the resource availability and interruption constraints.

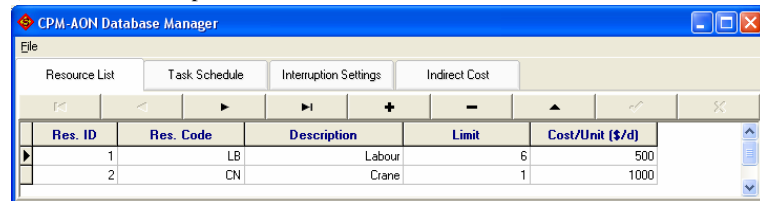


CPM-AON Database Manager

File | Resource List | Task Schedule | Interruption Settings | Indirect Cost

Act. ID	Act. Name	Description	Duration	Pred Act.	Act. Priority	Resources (Type & No)
1	ST	Start of Project	0	/	/	1 /
2	A	Activity A	2	1	7	LB[4], CN[1]
3	B	Activity B	3	1	8	LB[4]
4	C	Activity C	5	1	9	LB[4]
5	D	Activity D	4	2	3	LB[3]
6	E	Activity E	4	2	4	LB[1]
7	F	Activity F	3	3	5	LB[2], CN[1]
8	G	Activity G	6	3, 4	6	LB[2]
9	H	Activity H	2	5	1	LB[2], CN[1]
10	I	Activity I	3	7, 8	2	LB[2]
11	FN	Finish of Project	0	6, 9, 10	1	/

a) Task schedule input screen

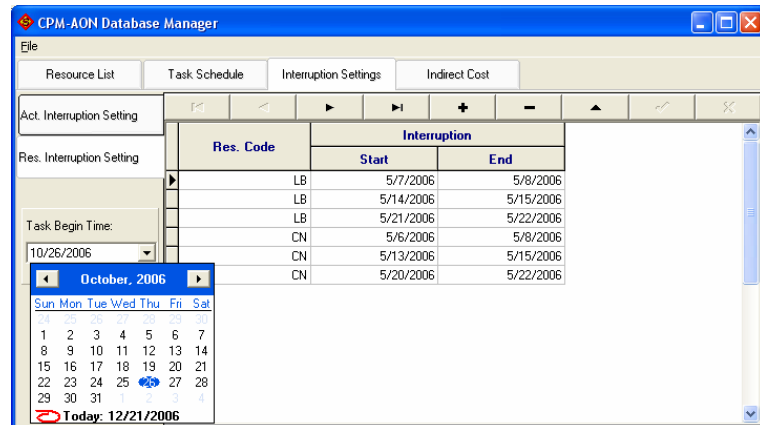


CPM-AON Database Manager

File | Resource List | Task Schedule | Interruption Settings | Indirect Cost

Res. ID	Res. Code	Description	Limit	Cost/Unit (\$/d)
1	LB	Labour	6	500
2	CN	Crane	1	1000

b) Resource detail input screen



CPM-AON Database Manager

File | Resource List | Task Schedule | Interruption Settings | Indirect Cost

Act. Interruption Setting

Res. Interruption Setting

Res. Code	Interruption	
	Start	End
LB	5/7/2006	5/8/2006
LB	5/14/2006	5/15/2006
LB	5/21/2006	5/22/2006
CN	5/6/2006	5/8/2006
CN	5/13/2006	5/15/2006
CN	5/20/2006	5/22/2006

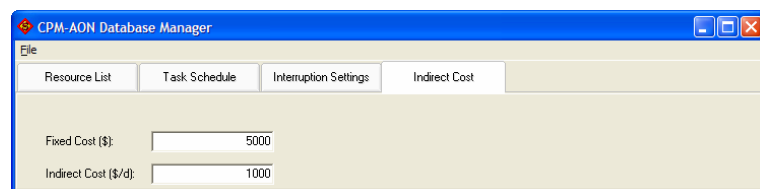
Task Begin Time: 10/26/2006

October, 2006

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

Today: 12/21/2006

c) Activity/Resource interruption input screen



CPM-AON Database Manager

File | Resource List | Task Schedule | Interruption Settings | Indirect Cost

Fixed Cost (\$): 5000

Indirect Cost (\$/d): 1000

d) Cost detail input screen

Figure 1. Activity details input form

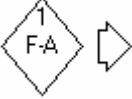

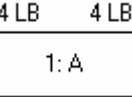

The resource calendar defines the work/non-work dates when the resource is available or unavailable for utilization. The simulation model for the whole project is automatically generated after taking detailed inputs. As such, through simulation and optimization, the project planner can readily and analytically determine the amount of resources along with the activity sequence, resulting in full utilization of resources and shortest project duration

or lowest project cost possible. Software use guideline can be found in APPENDIX A – S3 User Guide.

4.3 Formation of Simulation Model in SDESA

The S3 system is customized on top of the simulation platform of SDESA. The basic modeling elements of SDESA are list in Table 1. According to the input data defining the AON network, the simulation model will be created in the SDESA platform as follows.

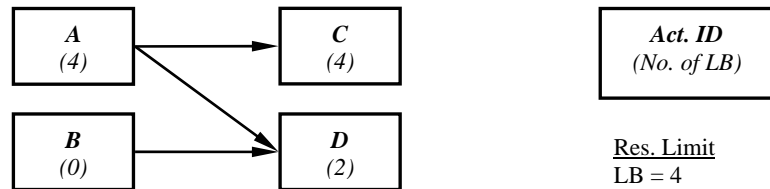
Table 1. Modeling elements description of SDESA

Name	Symbol	Description
Flow Entity		A flow entity diamond is the head of a flow of activities. One flow entity ensures each activity is executed once only.
Activity		Activity is a task that consumes time and resources in processing a flow entity.
Reusable Resource (RR) Entity		Reusable resources are defined as Resource Entities, limited in availability. They are required to perform an activity, and upon finishing, are released to the resource pool. RR Required are shown in Top Left Corner; RR Released in Top Right Corner.
Disposable Resource (DR) Entity		Disposable resources entities are either intermediate products or command units generated by one activity and required by another; they are used establish the interdependent relationships between various activities/processes, and can be utilized once only. DR Required of an activity is shown in the Top Left Corner and DR Generated in bottom right corner.

Firstly, each activity in the AON network is represented with an *Activity Block*, which is symbolized with rectangle and denotes a task that consumes time and requires resource. A *Flow Entity* is initialized within a diamond, which is linked with one *Activity Block* in the SDESA model in Figure 2. As such, each activity will be executed once only to process the one flow entity in simulation. Secondly, the *Disposable Resource Entity* in SDESA substitutes for the arrows in the AON network for expressing inter-activity logical relationships, as shown in Figure 2. Note, an activity generates N *Disposable Resource Entities* (marked on the bottom right corner of the activity rectangle), which are requested to

initiate its N successors. When all its preceding activities are finished, as a result, all the required *Disposable Resource Entities* would become available to trigger the start of the current activity (marked on the top left corner of the activity rectangle). Thirdly, we can specify the resource requirements for each activity. The *Reusable Resource Entities* requested by each activity, such as manpower and equipment, are marked -along with Disposable ones- on the top left corner of the activity rectangle, while the *Reusable Resource Entities* to be released at the end of the activity are marked on the top right corner (in Figure 2). Note in Figure 2, in the resource pool of the SDESA model, four laborers are defined as the maximum daily limit for the labor resource while the quantities of disposable resource entities “+A-Finish(A-F)” and “+B-Finish(B-F)” are initially set as zero and will change on the fly as simulation advances: For instance, two “+A-F” resource entities will be generated and placed in the resource pool at the end of executing Activity A; one “+A-F” will be seized by activity C and the other one by activity D in follow-up simulation transactions.

a) **AON Diagram**



b) **S3 Model Diagram**

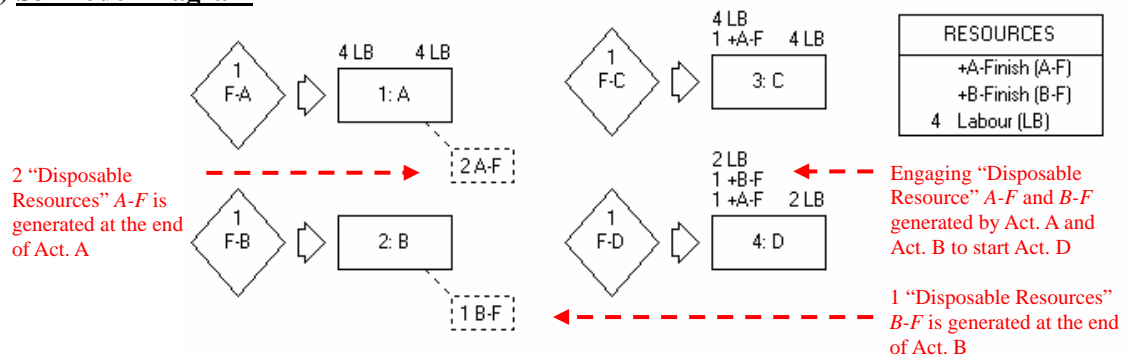


Figure 2. Methodology of S3 model setup by SDESA

Once the *S3* model is defined, the forward-pass calculations of CPM can be performed by executing the simulation, which accounts for both technological and resource constraints. The assumptions made in the *S3* model are: (1) all predecessors must be finished before an activity can start; (2) no splitting of activity; and (3) resource allocation strategy is first in first serve. The objective of the following analysis is to assess the effects of different calendar constraints on the total project duration and activity criticality. We will show how to perform CPM/PERT analysis using the *S3* software, and apply the CPM/PERT analysis using *S3* on an example network.

4.4 Deterministic Analysis: CPM Simulation

In this case study, a deterministic CPM analysis will be presented to elucidate the *S3* application procedures ranging from (1) generating a simulation model in SDESA, (2) assessing the “criticality” of activities and resources under resource-availability and activity-interruption constraints, (3) running *S3* simulations to conduct project scheduling analysis subject to the resource-availability and calendar constraints, to (4) total float determination and analysis.

To test the functionality of *S3* and verify the performance of *S3* simulation, a construction project was chosen from the text of Ahuja et al. (1994) – consisting of nine activities (Fig. 1) and involving limited resources, with the maximum quantities of laborers and crane available daily being assumed to be six and one respectively. Note that activity times and resource requirements are given in Table 2; resources are matched and allocated in the serial mode (no activity splitting is allowed); and all predecessors must be finished before an activity can start.

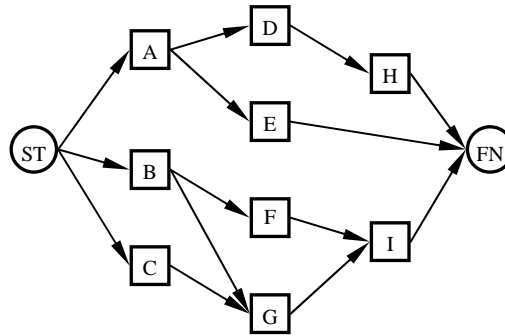


Figure 3. AON diagram of case study 1

Table 2. Activity data for example network of case study 1

Activity	Duration (days)	Resource Requirement		Preceding Activity
		Labor	Crane	
A	2	4	1	ST
B	3	4	0	ST
C	5	4	0	ST
D	4	3	0	A
E	4	1	0	A
F	3	2	1	B
G	6	2	0	B, C
H	2	2	1	D
I	3	2	0	F, G

Figure 4 shows the complete *S3* model for the case study with 6 laborers and 1 crane (Reusable Resource Entities) which are listed in the resource pool together with all the disposable resources. While all activity data and resource information are compiled into the schedule model, the *S3* simulation can be executed to perform schedule network analysis to generate the CPM schedule. The output screens of *S3* are given in Figure 5.

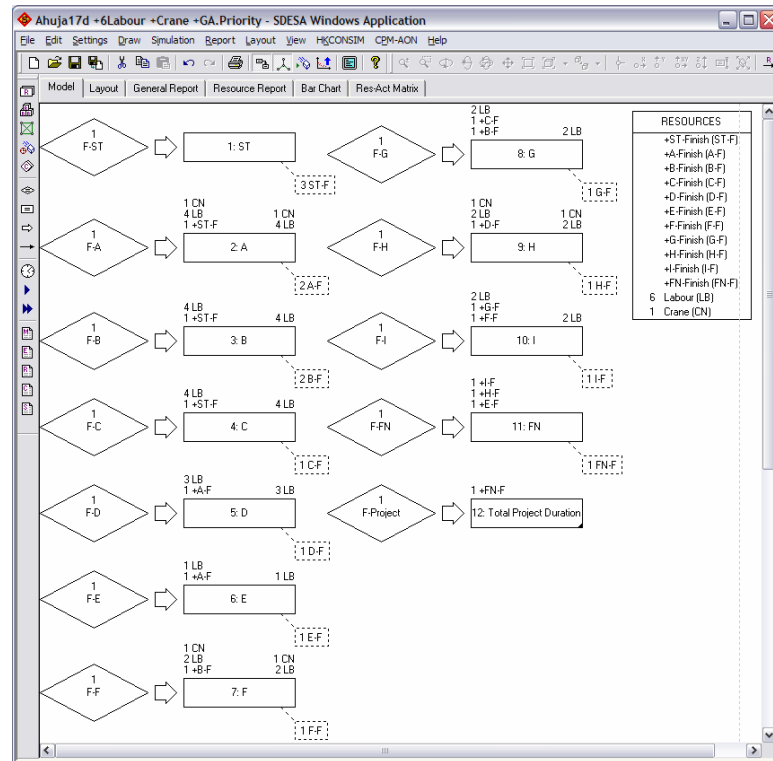


Figure 4. S3's network model for case study 1

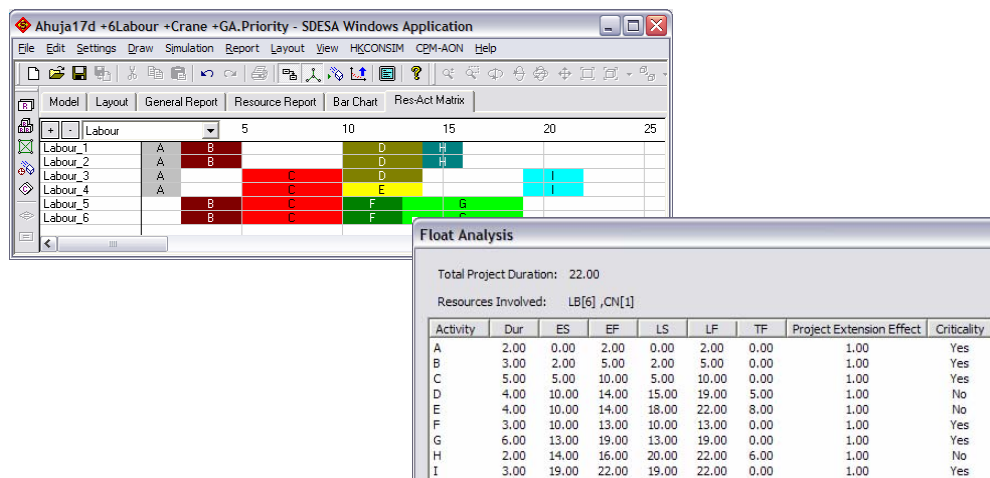


Figure 5. S3's resulting resource bar chart and activity float times summary

4.4.1 Scheduling Results Comparison between P3 and S3

As mentioned in the literature review, the total float determination by *P3* is associated with confusions and faulty interpretations under resource availability or multiple calendar constraints. Thus, we also evaluated *P3* along with the application of *S3* in this section. The

P3 version 3.1 (education version) is adopted in this study. P3 can perform CPM analysis under resource-availability and multiple calendars constraints to identify multiple critical paths together with all total and free slack calculations. The project start date is set as 1st May, 2006. Based on the example network, three scenarios are designed to allow for three various combinations of resource constraints.

The base case scenario is the straightforward CPM analysis ignoring any resource limit and resource calendar constraints. Scenario 1 considers the constraints of maximum six laborers and one crane available on any given day. In Scenario 2, both resource limits and resource calendar constraints are considered in scheduling analysis. Each individual resource can have its own unique work vs. non-work day arrangement on a weekly basis (i.e. laborers run on six work-day weeks, taking Sunday off; crane is available on five work-day weeks from Monday to Friday). The calendar dates in connection with resource unavailability periods are defined for *P3* and *S3* analysis. In the following sections, we will check the validity of total project duration and activity float times in the base case scenario, observe the total float and activity-resource criticality in the first scenario and examine the project extension effect due to prolonged activity duration in the last scenario.

4.4.2 Base Case Scenario: CPM without Resource Constraints

In the base case scenario, without resource and interruption constraints, both *P3* and *S3* arrived at the total project duration of 14 days with identical TF determined for each activity. It is observed that the *S3* model is capable of accurately working out the CPM analysis, deriving the total project duration and float times (i.e. start times, finish times and total floats) identical to the results from the classic CPM as shown in Figure 6. *S3*'s scheduling results can be easily validated by applying it to any simple CPM network.

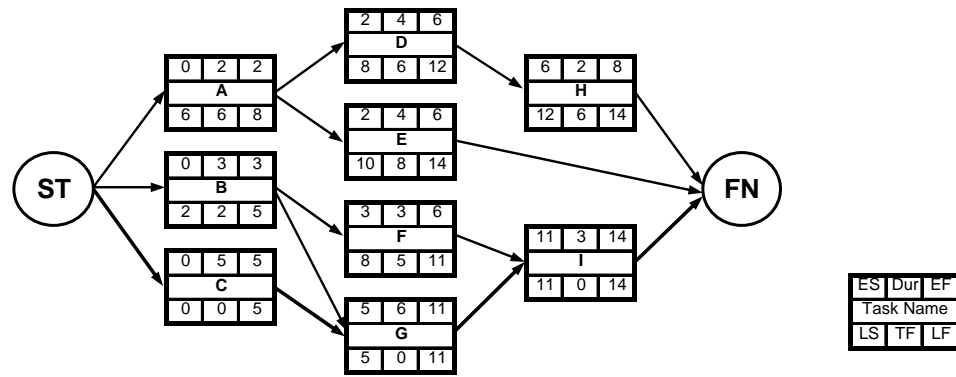


Figure 6. Classic CPM network analysis

4.4.3 Scenario 1: Considering Resource-Availability Constraints

Moreover, resource-availability constraints were applied on both scheduling tools to compare the scheduling performance of *P3* and *S3* in Scenario 1. Note *P3* provides an option of automatic forward resource leveling following its built-in heuristic rules (i.e. “late start” and “total float”). In order to compare *P3* and *S3* in total float determination, the same activity execution sequence in resource allocation –as followed by *P3*– applies to *S3*. The activity which starts earlier in *P3* is assigned with a higher activity priority in the *S3* model.

1. Scheduling Results Validation

According to activity sequence suggested by *P3* (Figure 7), the corresponding priority settings are defined in *S3* model shown the last column of Table 3, with a priority code 9 standing for the highest priority, and 1 for the lowest in resource allocation. As a result, both scheduling tools extend the total project duration from 14 days of the base case scenario to 19 days of Scenario 1. However, compared with *S3* schedule results (Figure 8), *P3* generates different total float values, as summarized in Table 3, for Activities A, B, C and F.

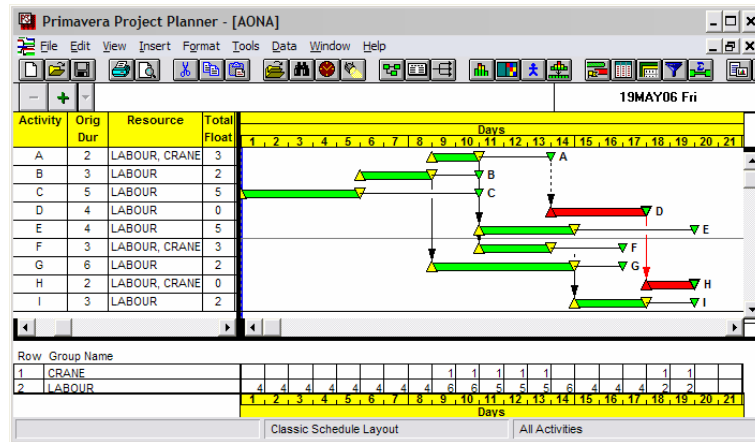
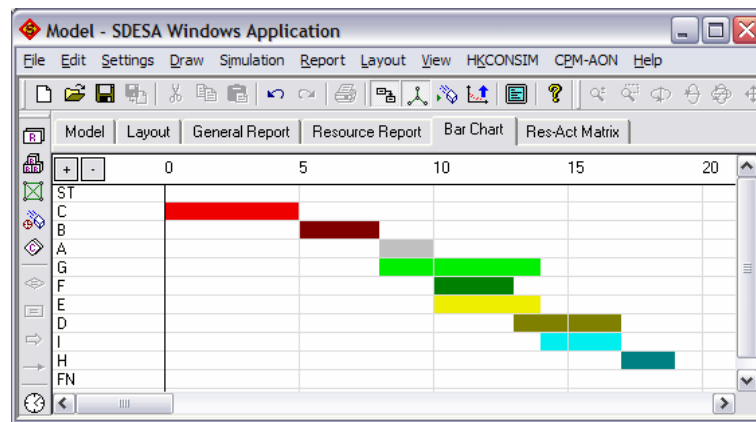
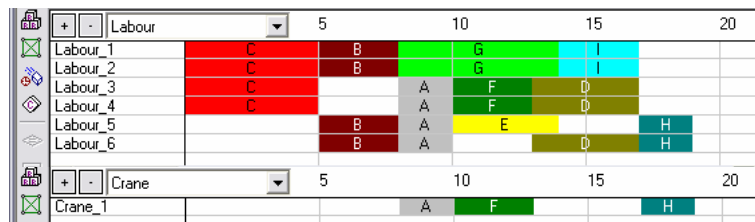


Figure 7. P3 resource leveling output in Scenario 2



a) Bar chart based on the early start schedule



b) Resource bar chart: Labor & Crane

Figure 8. S3 simulation output for Scenario 1

Table 3. Scheduling results comparison between P3 and S3 for Scenario 1

Activity	Duration (days)	Total Float		Priority
		P3	S3	
A	2	3	0	6
B	3	2	0	8
C	5	5	0	9
D	4	0	0	3
E	4	5	5	4
F	3	3	0	5
G	6	2	2	7
H	2	0	0	1
I	3	2	2	2
Total project duration		19	19	

Total Float (TF) is important because it allows a contractor to shift resources from an activity with float to an activity without float in an effort to keep the project schedule. TF on an activity is the amount of time by which the activity can be delayed without prolonging the project's scheduled completion date as derived from the forward pass of CPM. Generally, backward pass computations are required so to determine activities' late finish times, and further, derive TF as the difference between the late finish and early finish times. However, Fondahl (1991) indicated "the conventional concept of float time breaks down in a resource-constrained project". As such, the backward pass analysis for determining TF would fail on a CPM network schedule incorporating resource limits or calendar constraints, potentially yielding incorrect TF on some activities (Wallwork 2002, Kim and Garza 2005).

As for our example scenario 1, the TF values of Activities A, B, C and F produced by *P3* and *S3* are contrasted in Table 3. For instance, TF of Activity A is 3 days as shown in Figure 9(a). Suppose the duration of Activity A is increased by 1 day [as shown in Figure 9 (b)], which is less than TF available (3 days). But the total project duration ends up increasing from 19 days to 20 days [Figure 9 (b)]. This has violated the TF definition. The same measures were carried out for each activity to check the validity of total float values and found that *P3* generates overstated TF values for Activities A, B, C and F. As mentioned in the literature review, *P3* can handle resource-constrained scheduling problems, but the background theories remain proprietary and unpublished. In this example case, it is observed that total float determination is based on precedence relationships between activities but will give rise to errors when taking into account of the resource constraints.

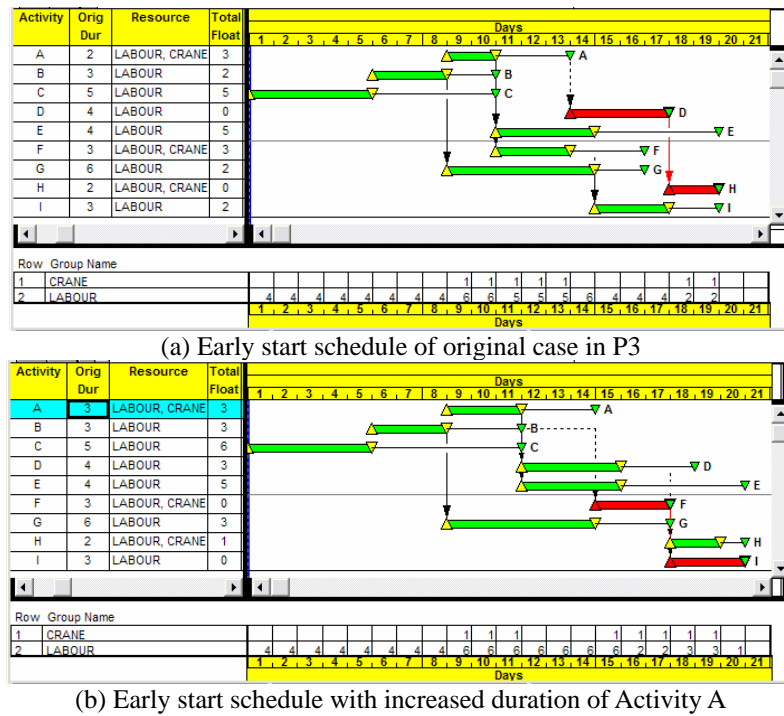


Figure 9. Forward pass: P3 output screens for Scenario 1

II. New Total Float Determination Algorithm

In an effort to address P3's limitations, we herein introduce a new total float (TF) determination algorithm for checking the validity of TF and deriving the accurate TF for those activities whose TF are overstated by P3. The simulation-based TF determination algorithm is implemented in S3. In this TF analysis method, it is not necessary to carry out any backward pass calculation. Instead, the effect of extending the duration of one activity on the total project duration is observed. TF's interpretation in CPM provides the theoretical underpinning, namely: TF is the maximum amount of time that activity duration can increase without extending the total project duration.

As illustrated in Figure 10, given a schedule under resource availability constraints, S3 obtains the *base* project duration by executing CPM analysis subject to all the schedule constraints (including activity times, logical relationships, resource availability). Then one activity is selected as current and its TF is initialized as zero. By perturbing its duration by

an increment of 1 day, *S3* assesses the effect of such activity delay on the total project duration by re-doing CPM analysis subject to the same constraints. The *updated* project duration is recorded for comparison with the *base* project duration. TF increases by 1 day only if the updated project duration is not greater than the *base* project duration. Otherwise, the TF for the current activity will be fixed and the difference between the *updated* and the *base* project duration represents the *project extension effect* for the current activity (the *project extension effect* will be further discussed in Scenario 2). Upon completing TF analysis on the current activity and prior to processing the next one, the duration of the current activity is restored to its original value. The above TF determination procedure automatically repeats on all the activities in the network to obtain TF values.

According to the total float analysis, the correct activity-resource criticality information can be obtained. The project manager, therefore, should pay more attention on these critical activities during construction work. For the further study, we evaluated the scheduling performance of *Microsoft (MS) Project (Professional 2003)* in the same case study. Interested readers could refer to the APPENDIX C – Scheduling Results Validation among MS Project, P3 and S3 for more details.

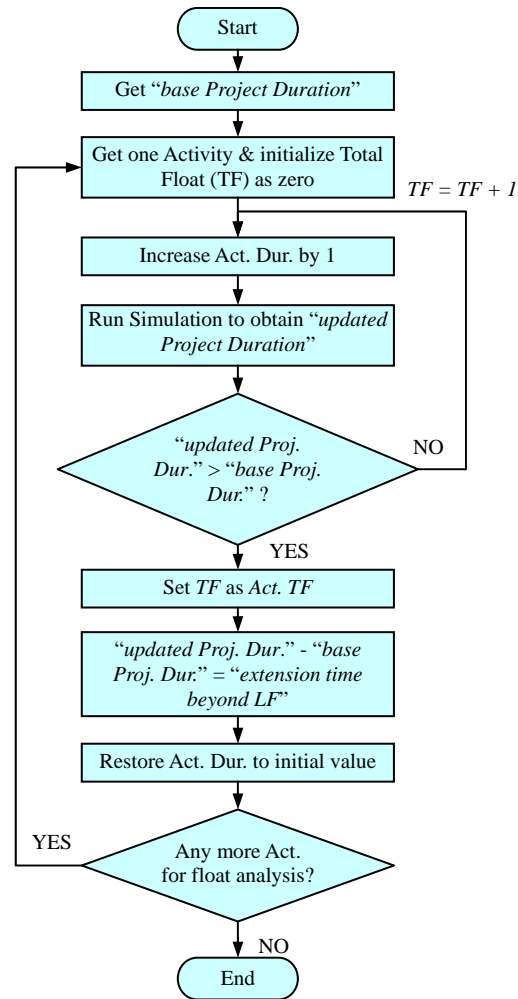


Figure 10. Algorithm flowchart of accounting for total float on each activity

III. Determination of Total Project Cost

While cost and duration are closely related, both estimates are of great importance to the client. In addition to determining the total project duration, *S3* also features the determination of total project cost by finding the direct cost and indirect cost according to the corresponding resource provision and allocation. Estimating project cost involves identifying and considering various cost components. For a construction project, the project cost is mainly classified into two general categories: the direct cost and the indirect cost. The direct cost generally covers labor, equipment and raw material directly consumed in production activities. The indirect cost includes the expenditures on management, supervision and inspection.

In *S3* model, the total project cost (C_T) is to sum up direct and indirect costs as Eq. 1:

$$C_T = C_D + C_I \quad (1)$$

In Eq. 2, the direct cost (C_D) includes resources' productive cost (C_P) and resources' non-productive cost (C_{NP}). The resource schedule provides the details of the productive time and non-productive time of each resource. Thus, the resources' productive cost and resources' non-productive cost are calculated based on the working time and resource daily rate.

$$C_D = \sum_{i=1}^n (C_{Pi} + C_{NPi}) \quad (2)$$

And the indirect cost (C_I) is given in Eq. 3:

$$C_I = C_0 + D * C_d \quad (3)$$

Where, C_0 is the initial sum related to indirect cost, D is the total project duration, C_d is the indirect cost incurred per day.

In our example project, the initial cost, project daily expenditures and resource daily cost of labour and crane are assumed to be \$5000, \$1000, \$500 and \$1000 respectively. Given that the project completion period is 23 days, the indirect cost is \$28,000. According to the resource allocation results, *S3* obtained the start time and finish time for all the resources and calculated the corresponding productive and non-productive costs. As illustrated in Figure 11, the resource summary provides the detail of individual resources, and cost summary shows the cost information (i.e. indirect cost, direct cost and total project cost).

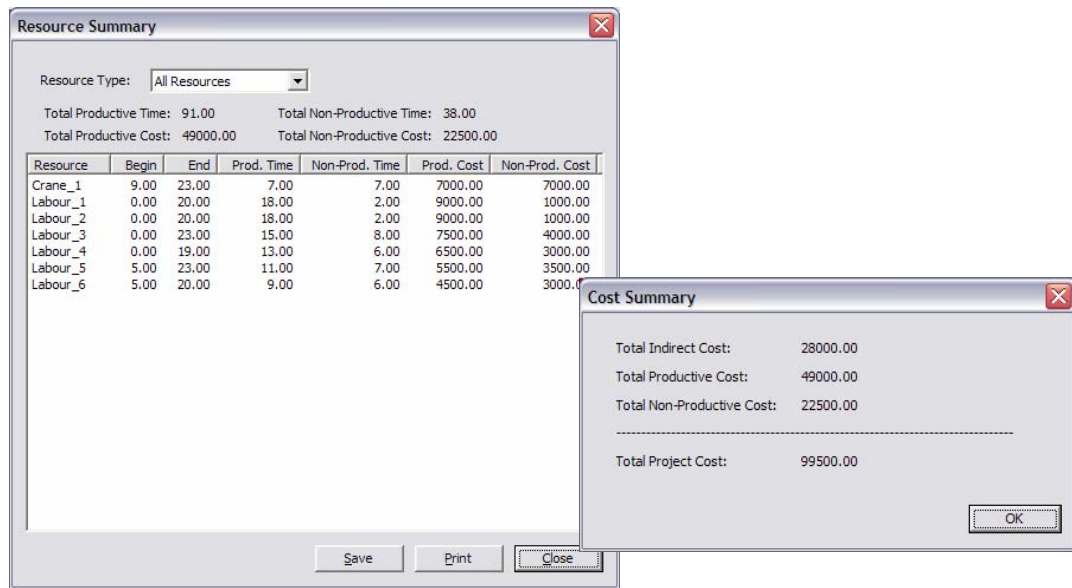


Figure 11. S3 simulation output: resource summary and cost summary

4.4.4 Scenario 2: Resource-Availability and Multiple Interruptions Constraints

In this scenario, the scheduling analysis of resource-constrained CPM model is demonstrated with resource/activity calendar constraints. Each individual resource can have its own work vs. non-work days schedule (i.e. laborers run on six work-day weeks, taking Sunday off; crane is available on five work-day weeks from Monday to Friday).

1. Scheduling Results Validation

In the second scenario of the above example scheduling with multiple resource-interruption and limited resource constraints, the same results of a total 23-day schedule were generated by *P3* (Figure 12) and *S3* (Figure 13). In addition to the activity bar chart schedule [Figure 13(a)], *S3* also produces a schedule in the format of a resource-activity interaction bar chart [Figure 13(b)]. Since the underlying method for handling multiple resource calendars is unpublished, this scenario also would be used to observe how *P3* incorporates the effects of multiple resource calendars on CPM scheduling given the activity calendar setting of “Meeting”.

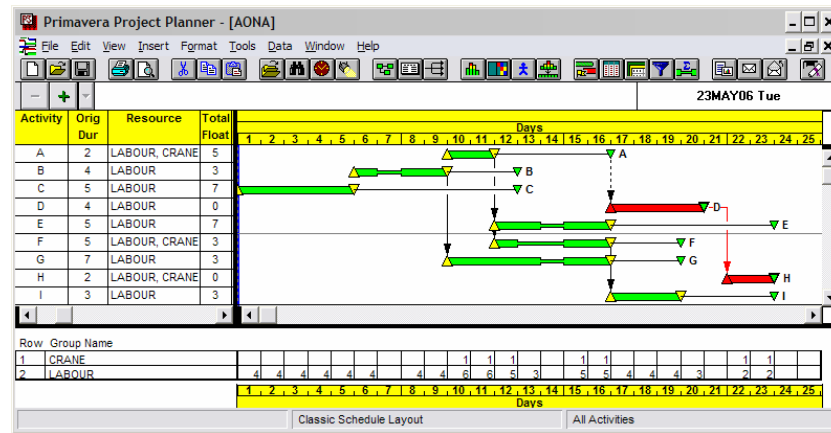


Figure 12. P3 resource leveling output in Scenario 2

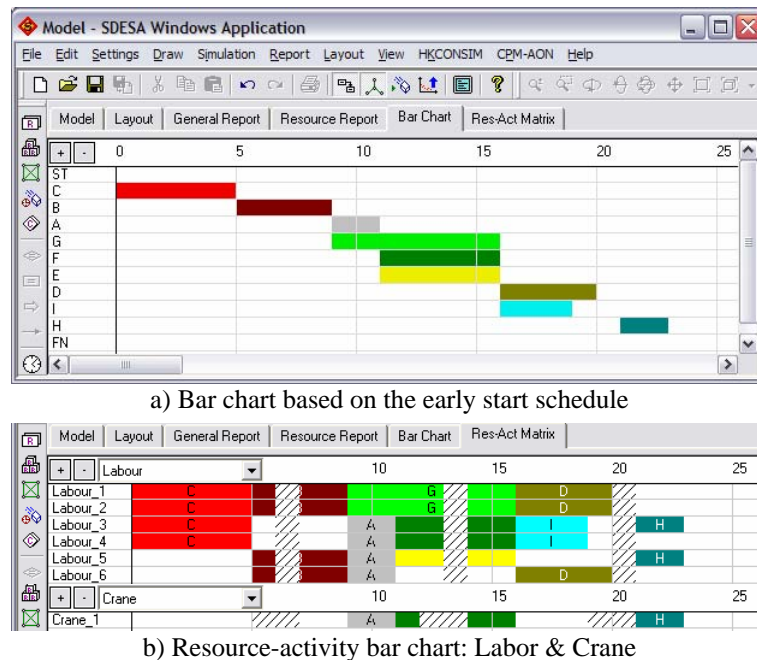


Figure 13. S3 simulation output for Scenario 2

As illustrated in Figure 12, the interruptions of each activity would be represented as necked bars in P3's Gantt chart view. For example, there is a 1-day interruption in Activity B since Day 7 is Sunday (non-working day of laborer). The similar view could be found in the Bar Chart of S3 which uses the shaded stripes to represent the activity or resource interruptions (Figure 13).

As summarized in Table 4, both P3 and S3 arrived at the total project duration of 23 days

but obtain different TF values for activities A, B, C and E. Similar to the findings in Scenario 1, *P3* overstated those total float values. By using the new total float determination approach, the criticality of an activity based on TF value can be accurately obtained from *S3*. In addition, the schedules derived from *S3* are more informative and detailed about the allocation of resources.

Table 4. Scheduling results comparison between P3 and S3 for Scenario 2

Activity	Duration (days)	Total Float		Priority
		<i>P3</i>	<i>S3</i>	
A	2	5	3	6
B	3	3	0	8
C	5	7	0	9
D	4	0	0	3
E	4	7	6	4
F	3	3	3	5
G	6	3	3	7
H	2	0	0	1
I	3	3	3	2
Total project duration		23	23	

II. Project Extension Effect due to Activity Delay

We herein explicitly define the project extension effect which is the magnitude of extending the total project duration due to delaying the completion of an activity by one day beyond its late finish time (LF). The project extension effect is generally equal to one day in terms of simple CPM and resource-constrained CPM considering daily maximum resource limits, as occurred in the base case and Scenario 1 (as summarized in Table 5). However, when multiple resource calendar constraints are imposed on CPM, the project extension effect can be greater than one day, which is encountered and explained in this case study.

In the schedule simulation results of Scenario 2 (Table 5), it is observed that 1 day delay beyond the late finish time on an activity could delay the total project duration by more than 1 day. For example, 1-day extension in activities A or F could lengthen the total project duration by 2 calendar days in Scenario 2. This differs from the conventional definition of

TF in CPM analysis. In short, *S3* provides project managers with a more reliable way of analyzing resource-availability and multi-calendar constraints in a straightforward manner.

Table 5. Extension of total project duration affected by 1-day delay beyond late finish on activity

Activity	Duration (days)	Project Extension Time (day)		
		<i>Base case: No constraint</i>	<i>Scenario 1: Resource limit</i>	<i>Scenario 2: Resource limit + Calendars</i>
A	2	1	1	2
B	3	1	1	1
C	5	1	1	1
D	4	1	1	1
E	4	1	1	1
F	3	1	1	2
G	6	1	1	1
H	2	1	1	1
I	3	1	1	1
Total project duration		14	19	23

Across the three scenarios, only activity E consistently have non-zero TF, while activities A, B, C, F and H would always be critical, and hence the project manager should pay more attention on the progress of these activities. In addition, project planners should concern the resource-activity criticality (what resources are critical when working on which critical activity) rather than activity-based criticality.

4.5 Stochastic Analysis: PERT Simulation

CPM uses only one constant value (most likely duration) to represent an activity duration, but PERT uses three time estimates (optimistic, most likely, pessimistic durations) for each activity. Since P3 has no probabilistic capabilities and PERT analysis, we would focus on the performance of PERT analysis by using the classic PERT method and *S3*'s PERT simulation computation in the following sections.

4.5.1 Classic PERT

The classic PERT takes into account the uncertainty of activity duration to analyze the overrun risk of total project duration. The expected duration, standard deviation and variance would be determined to evaluate the likelihood of achieving project completion time through the classic PERT calculations. In order to combine three estimates to perform PERT analysis, the expected duration, standard deviation and variance were determined by the following expressions:

$$\mu = \frac{L + 4M + U}{6} \quad (4)$$

$$v = \left(\frac{U - L}{6}\right)^2 \quad (5)$$

$$\sigma = v^{1/2} \quad (6)$$

where

μ is expected duration,

L, M & U are the optimistic, most likely, and pessimistic durations respectively

σ is standard deviation, and

v is variance.

By considering the uncertainty of activity duration, the central limit theorem of classic PERT provides approximate theoretical foundation to combine activity duration distributions. The expected project completion time is equal to the sum of the expected activity durations along the critical path. Similarly, the variance is the sum of the variances of activity durations on that path. However, the PERT mean project time is always an underestimate of the true project mean (Ahuja et al. 1994). This bias in the mean estimate, which is called the “merge event bias”, is mainly caused by ignoring the near-critical paths in determining project completion time probabilities. Ahjua et al. (1994) also indicated that a stochastic simulation study on PERT is a solution to tackle the merge event bias by using the true properties of activity duration distributions in simulation.

4.5.2 Stochastic Simulation in S3

I. Considering Activity-Duration Uncertainties

Because of the probabilistic and stochastic nature of the real world operation, statistical distributions would be based on the project planner's data as input models. Generally, the simulation modeling is to fit a discrete or continuous probability distribution from a set of sample data. In particular, the beta distribution is useful for describing empirical data and can be either symmetric or skewed. When sample data are not available or observations are too expensive to be carried out, subjective information extracted from the construction practitioners on the construction processes would be used to determine the distribution of activity durations.

Unfortunately, there is no practice of storing large amounts of historical operation data in construction consultants and contractors. The main difficulty in simulation input modeling involves the subjective estimation of statistical characteristics (such as mode, mean and variance for modeling each activity). Due to the unpredictable nature of construction processes, several simple distribution types such as discrete probability, uniform and triangular distributions would be recommended for fitting activity durations. Note, according to the user requirements, S3 provides different types of statistical distributions (i.e. uniform, normal, triangular, discrete probabilities and beta, etc.) for input modeling.

II. Monte Carlo Simulations

As discussed in the previous sections, the most common technique to tackle the merge event bias is Monte Carlo simulation when addressing a scheduling plan involves uncertainty factors. To overcome the merge event bias of the classic PERT, the whole statistical

distribution of each activity-duration is utilized during simulation: the activity durations is randomly sampled from the corresponding time distribution in each simulation run.

While classic PERT systematically underestimates the probability of completing a project, the concept of Monte Carlo simulation (in Figure 14) is implemented in *S3* PERT model. The simulation model creates probability distributions which assign a probability to each possible value of a random variable and then takes the random variable to perform experiments with many variations of the input. The resulting output is stored for statistical analysis.

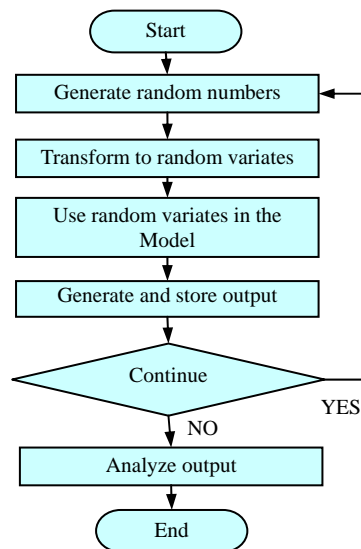


Figure 14. Flowchart of Monte Carlo simulations (Ahuja et al. 1994)

Given a certain input scenario, one Monte Carlo run of simulation randomly samples statistical distributions to derive a system output, and a number of Monte Carlo simulation-runs (n) result in an average of the system output. Due to the random nature of activity durations, the system output would be different in each simulation run. Given large enough n , the averaged system output converges to a certain confidence interval.

III. PERT Simulation Model in S3

Stochastic simulation model, like CPM model analysis, uses network diagram representation to analyze the scheduling problem. After constructing a CPM network, the user designates three time estimates for each activity as inputs to the simulation, based either on statistical sampling of actual data or subjective information, or combining both. The uncertainties of activity-durations are considered in S3 to enable the scheduler to estimate the most likely total project duration and obtain the corresponding distribution.

After Monte Carlo multiple-run simulation analysis, a confidence level on the performance measure should also be established due to the probabilistic and stochastic nature of simulation modeling. A cumulative probability distribution for project duration reveals the likelihood of completing a project by a particular date.

On the other hand, the critical index (CI) of activity could be determined based on the further analysis of simulation results. By the definition, the critical index for an activity in a percentage term is the number of simulation runs in which the activity is critical, divided by the total number of simulation runs. Similar to the proposed total float analysis (refer to the section 4.4), the critical index approach is related to the effect of activity delay on extending the total project duration. While the extension of activity duration cause the increase of the total project duration, the corresponding activity should be critical in this simulation run.

4.5.3 Sample Application: Base Case Scenario

I. Base Case Scenario: Comparing with Classic PERT

In this sample application, the same AON network taken from Section 4.4 is used to illustrate the PERT calculation. The activity durations were modified to form a sample PERT model, and the time estimates of activity duration are listed in Table 5. In the base

case scenario, the sample PERT network without imposing resource constraints is used to show the difference between the classic PERT calculation and *S3* stochastic simulations analysis.

Table 6. Activity durations of sample PERT network

Activity	Duration Estimates (day)		
	<i>Optimistic (L)</i>	<i>Most likely (M)</i>	<i>Pessimistic (U)</i>
A	1	2	3
B	2	3	4
C	3	5	6
D	3	4	7
E	3	4	6
F	2	3	5
G	3	6	7
H	1	2	4
I	2	3	5

As summarized in Table 7, the expected duration, variance and standard deviation were computed and then used to carry out classic PERT calculation. As a result, the mean total project duration and standard deviation of normal distribution are determined as 13.67 days and 0.97 respectively.

Table 7. Details of classic PERT network

Activity	Classic PERT model		
	<i>Expected duration</i>	<i>Standard deviation</i>	Variance
A	2	0.333	0.111
B	3	0.333	0.111
C	4.833	0.5	0.25
D	4.333	0.667	0.444
E	4.167	0.5	0.25
F	3.167	0.5	0.25
G	5.667	0.667	0.444
H	2.167	0.5	0.25
I	3.167	0.5	0.25

On the other hand, the activity duration given as 3-point estimates (L, M, U) was entered in the *S3* platform for further stochastic PERT analysis. To check and evaluate *S3* stochastic simulation analysis, the discrete probability distributions are defined in *S3*, assuming that

the chances for L, M and U to occur are 1/6, 4/6 and 1/6 respectively. The simulation results were generated after 500 runs as listed in Table 8, and compared with classic PERT analysis results. S3 produced the statistical results such as probability density function (PDF) and cumulative probability density function (CDF) curves of the project completion time drawn from the simulation results as shown in Figure 15.

Table 8. Base case scenario: PERT simulation results versus classic PERT analysis

Statistics of project completion time (days)	S3 multiple simulation results	Classic PERT analysis results
Minimum duration	9	N/A
Maximum duration	18	N/A
Mean duration	13.91	13.67
Standard deviation	1.75	0.97
Variance	3.05	0.94
95% confidence interval	13.76-14.07	N/A
Probability of completing by day 15	85%	91%

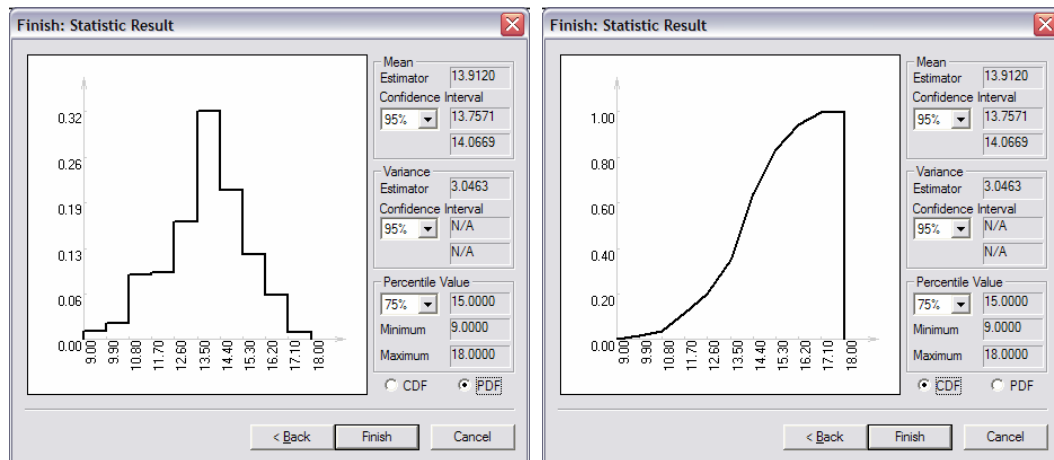


Figure 15. S3's statistic results: PDF and CDF graphs

In addition, S3 simulation results provide an assessment of the probability of completing the project by a certain desired duration. For example, the project planner can look into CDF graph to find out the probability that the project can be finished within a specified time period. The probability of completing the project by Day 15 is around 85% which was read from the generated cumulative probability curve (Figure 16). For the classic PERT method, the probability of completing the project by Day 15 is calculated from a theoretical normal

cumulative distribution, the mean and standard deviation of which are obtained based on the central limit theorem. While the mean and standard deviation of normal distribution are 13.67 and 0.97 respectively, the control date is converted to a standardized term for the standard normal distribution $[(15-13.67)/0.97 = 1.37]$. By looking up the standard normal distribution table, the cumulative probability of completing the project by Day 15 is determined to be 91%.

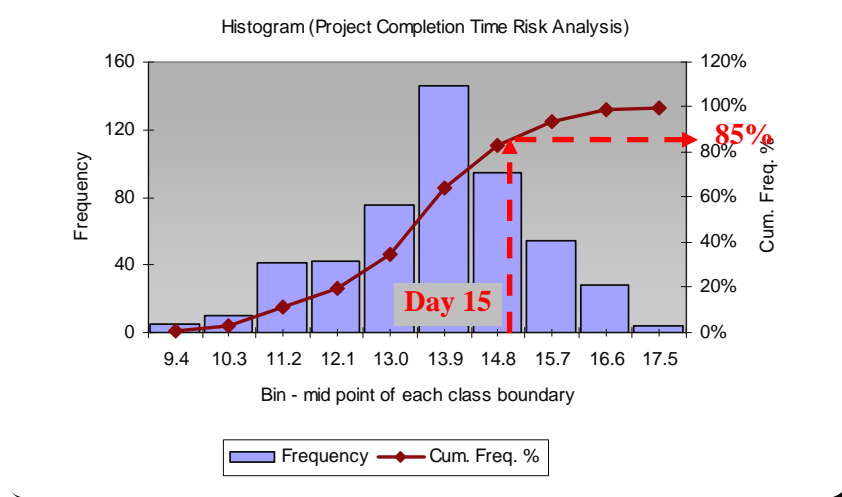


Figure 16. S3 multiple simulations results for base case scenario

According to the comparison in Table 8, (1) the mean calculated by PERT analysis is an underestimate of the mean resulting from S3 analysis ($13.67 < 13.91$), (2) the variance estimated by the classic method is only one third of that resulting from S3 ($0.94 < 3.05$) and (3) the classic PERT schedule overrun risk is also underestimated ($85\% < 91\%$). This shows the limitation of the classic PERT analysis due to the “merge event bias”. If the network is larger and has more activities, the bias will become more obvious.

Moreover, the critical index (CI) of each activity was determined based on the simulation results. The activity criticality in terms of CI resulting from S3 is compared with the path criticality resulting from the classic PERT method in Table 9. According to the critical indices of activities C, G and I are over 95%, this means that these three activities are

critical most of time. Based on the classic PERT analysis results, we would not concern the progress of activity B since it is not on the critical path. However, CI of activity B (15.6%) indicates the activity has probability of being critical rather than the absolute zero percent from the classic PERT analysis. It is noted that the CI concept of the *S3* analysis can better differentiate the activity criticality than the classic PERT calculation.

Table 9. Base case scenario: Comparison of critical index and path criticality

Activity	Critical Index, CI (<i>S3</i> analysis)	On/off critical path (Classic PERT analysis)
A	2.0%	Off
B	15.6%	Off
C	96.4%	On
D	2.0%	Off
E	0	Off
F	3.0%	Off
G	98.8%	On
H	2.0%	Off
I	99.6%	On

Furthermore, *S3* can perform PERT simulations subject to resources availability and interruption constraints. Similar to the abovementioned deterministic CPM case study, Scenario 1 considers the constraints of maximum six laborers and one crane available on any given day. In Scenario 2, both resource limits and resource calendar constraints are involved in the scheduling analysis.

II. Scenario 1: Considering Resource Limits Constraint

In the first scenario, with imposing resource-availability constraints, the *S3* simulation results were generated after 500 runs as listed in Table 10. The mean project completion time is extended from 13.91 in the base case to 19.34 days in Scenario 1. Apart from project duration, *S3* also determines total project cost by analyzing the direct cost and indirect cost according to the specified schedule on resource provision and allocation. The mean project cost including direct and indirect costs is \$84,563 in this scenario. Based on the resource

limits and the activity priority setting as specified, the histograms of the project completion time and total project cost are drawn from the simulation results as shown in Figure 17.

Table 10. S3 PERT simulation results of scenario 1: project duration and cost

Simulation results statistics	Project completion time (day)	Total project cost (\$)
Minimum	14	61000
Maximum	25	106000
Mean	19.34	84563
Standard deviation	2.17	8839
95% confidence interval	19.15-19.53	83788-85338

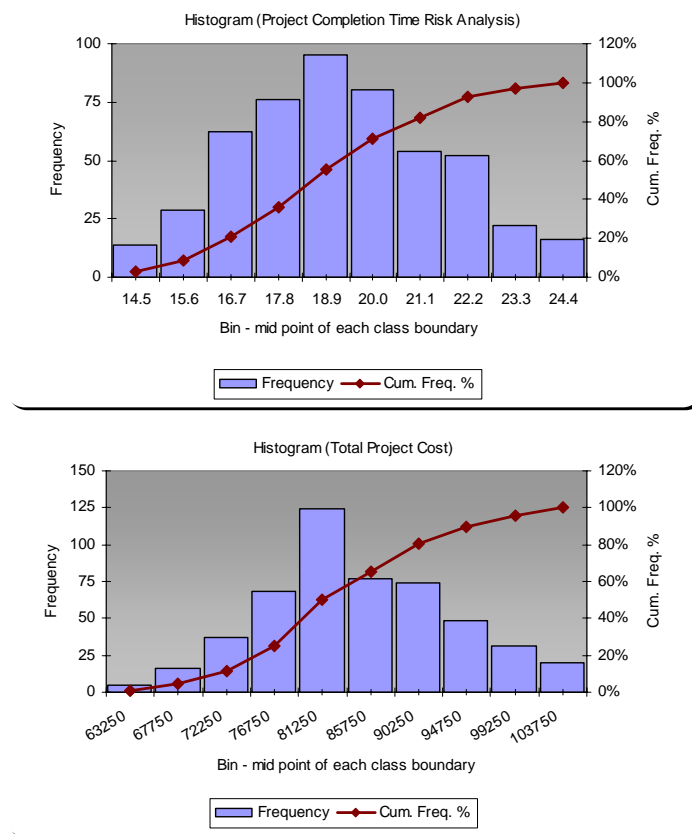


Figure 17. Histograms of project duration and cost in scenario 1

III. Scenario 2: Considering Resource Limits and Interruption Constraints

Each individual resource can have its own work pattern (i.e. six laborers run on six work-day weeks, taking Sunday off; one crane is available on five work-day weeks from

Monday to Friday). With the resource-availability and interruption constraints, the *S3* simulation results were generated after 500 runs as illustrated in the histograms of the project completion time and total project (Figure 18). Considering the interruptions, the mean project completion time extends from 19.34 in the scenario 1 to 22.97 days in Scenario 2. The mean project cost also increases from \$84,563 to \$98,372. Figure 18 shows the histograms of the project completion time and total project cost.

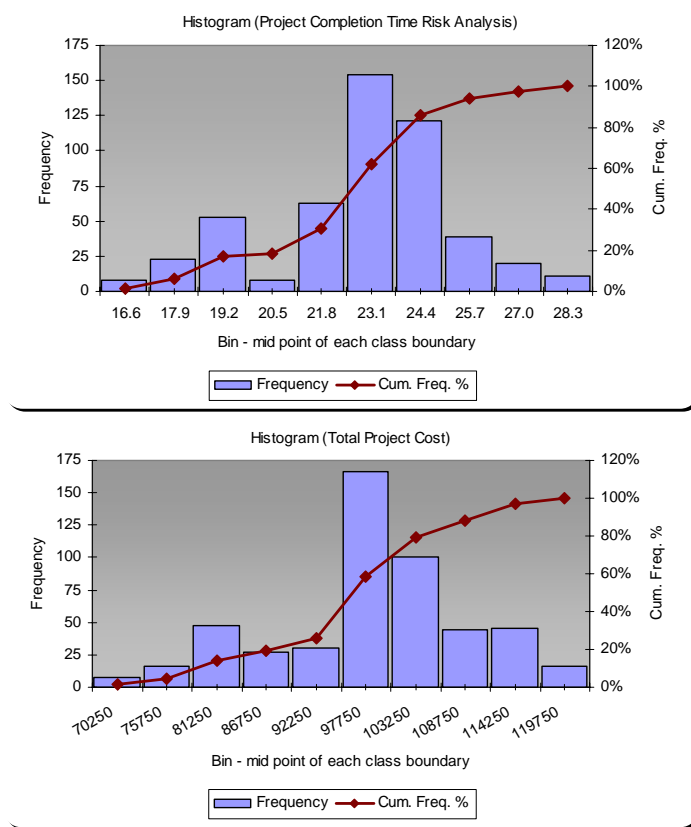


Figure 18. Histograms of project duration and cost in scenario 2

The details of activity critical index, project completion time and the corresponding project cost are summarized in Table 10. In both Scenarios 1 and 2, Activities B, C, D and H have high CI, so project manager should have these activities finished on schedule.

Table 11. S3 PERT simulation results: Scenarios 1 and 2 versus base case

Simulation statistical results		Base case	Scenario 1: With resource limits	Scenario 2: With resource limits & interruptions
Critical Index (%)	<i>A</i>	2.0	66.6	40.6
	<i>B</i>	15.6	100	81.8
	<i>C</i>	96.4	100	81.8
	<i>D</i>	2.0	90.4	73.8
	<i>E</i>	0	0.6	0.4
	<i>F</i>	3.0	65.8	38.6
	<i>G</i>	98.8	36.6	31.6
	<i>H</i>	2.0	90.4	92.4
	<i>I</i>	99.6	23.6	18.6
Duration (d)	<i>Minimum – maximum</i>	9 – 18	14 – 25	16 – 29
	<i>Mean</i>	13.91	19.34	22.97
	<i>Standard deviation</i>	1.75	2.17	2.55
	<i>95% confidence interval</i>	13.76 – 14.07	19.15 – 19.53	22.75 – 23.20
Cost (\$)	<i>Minimum – maximum</i>	14000 – 23000	61000 – 106000	67500 – 122500
	<i>Mean</i>	18912	84563	98372
	<i>Standard deviation</i>	1745	8839	10867
	<i>95% confidence interval</i>	18759 – 19065	83788 – 85338	97420 – 99324

4.6 Chapter Summary

The conventional resource constrained scheduling techniques (like *P3*) would not provide correct floats and critical path under resource constraints. A new total float (TF) determination approach is proposed for checking the validity of TF and deriving the accurate TF for those activities whose TF are overstated by *P3*. Base upon the simulation results of both deterministic and stochastic scheduling problems, the case study clearly shows the benefits of *S3* over those commercial scheduling software packages with the consideration of multiple resource limits and calendars. .

In addition, we define the project extension effect which is the magnitude of extending the total project duration due to delaying the completion of an activity by one day beyond its late finish time (LF). The new approach provides project managers with a reliable way of analyzing multi-calendar scenarios in a more accurate manner.

To conclude, by executing the *S3* simulation, we can look into the project forecast such as project completion time and budget and the utilization level achieved for the resources involved, along with total float and criticality index at the activity level under both deterministic and uncertain scenarios.

CHAPTER 5

OPTIMIZATION FOR RESOURCE SCHEDULING

5.1 *PSO Framework in S3*

S3 was developed to facilitate resource-constrained project scheduling based on user-specified project information. “What-if” scenarios can be easily explored to obtain the project schedule and resource allocation plan, but it is still difficult to decide on the optimal combinations of activity sequence and resource allocation, resulting in the minimum project duration or cost. Based on a valid S3 simulation, the particle swarm optimization (PSO) can be integrated to automatically optimize the resource schedule. In this research, PSO is embedded in S3 to decide on the optimal combination of the activity priorities for resource allocation together with the optimum resource limits in order to attain the shortest project duration or the least project cost. It will apply on deterministic and stochastic project scheduling scenarios to demonstrate the PSO-enabled optimization functionality of the S3 software in the following sections.

5.1.1 *Fundamental principle of PSO*

PSO is a population-based iterative algorithm, and starts with a population of randomly generated solutions called particles. The particles evolve over generations in approaching the optimum solution by the following rules:

Each particle is treated as a point in a D-dimension space, and the i^{th} particle is represented as $x_i=(x_{i1}, x_{i2}, \dots, x_{iD})$. Each particle has a fitness measure, which is the performance

measure of the function or system being optimized. The velocity and position in the hyperspace of a particle are tracked. The particle's best position that corresponds with the minimum fitness measure achieved so far in the search process is denoted as p_{best} . Likewise, the best position of all particles in the population achieved so far is denoted as g_{best} .

Once the p_{best} and g_{best} are identified in current iteration, each particle updates its velocity and position by certain equations prior to starting the next iteration. From one generation to the next, particles keep memory of their previous positions and update themselves by adjusting their internal velocity and position. In the global context, particles move toward the stochastic average of p_{best} and g_{best} ; while in the local context, particles have information only of their own and their nearest neighbors' best solutions, thus particles move toward the positions as guided by p_{best} and l_{best} . Note l_{best} represents the position of the particle with the best evaluation in the nearest neighborhood of the current particle. Both p_{best} and g_{best} are constantly updated over iterations in seeking the optimum. This process is repeated until user-defined stopping criteria are satisfied.

Since the present study focuses on the application of scheduling tool, the basic concept of PSO algorithm is presented in this section. Interested readers could refer to the APPENDIX B – PSO Algorithm for more details. Next the PSO model formulation in integration with the S3 is described.

5.1.2 PSO Model Formulations

In order to apply PSO on simulation model, the major task is to define the particle representation. In the proposed optimization analysis, a PSO particle solution is represented by the set of values associated with the problem variable-dependent variables.

In this section, we describe the formulations of a PSO algorithm for $S3$. The proposed PSO approach uses particles to represent the priority values in scheduling problems. Given n as the number of activities, p as the type of resources, and q as the number of individual resources, the multiple-dimension particle structure can be used to represent the potential solution to the $S3$ model. The optimization process is divided into two steps: (1) to search the optimal priority of each activity and limits of different resources, and (2) to search the optimal priority of each individual resource. Thus, we setup a search space in $n+p$ and q dimensions in step 1 and step 2 respectively. The problem's parameters in a $S3$ simulation model are mapped to a PSO particle as in Figure 20. In the first step of optimization, it is noted that the first n dimensions are the priority of each activity, and the remaining p dimensions are the amounts of different resource types. The second step of finding the priority of corresponding individual resources, which is optional and recommended only after finding out the optimal resource limits or setting desired resource limits. Thus, the search space is q dimensions in step 2. In an optimization setting, the lower and upper limits for those dimensions could be defined by users. Commonly, the upper ranges of activity priority, resource limits and resource priority are defined as the total number of activities, double the original resource sizes and the number of resources or each type, respectively.

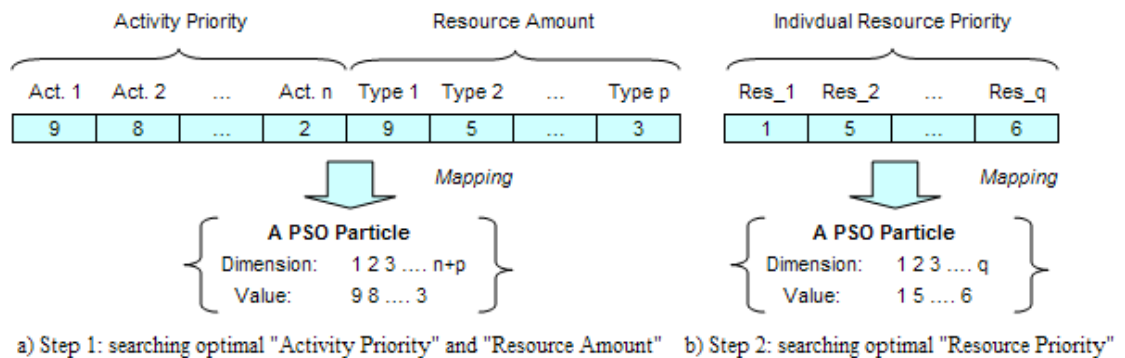


Figure 19. PSO particle mapping in $S3$ model

5.1.3 Procedure of PSO in S3

After the formations of the CPM simulation model and the PSO particle structure, we can implement the PSO S3 to find the optimum solutions to resource-constrained scheduling problems, in five major steps: (1) deciding the particle evaluation criteria (objective function), (2) generating an initial population of particles, (3) generating CPM simulation model, (4) computing fitness measure from simulation results, and (5) executing particles' evaluation and evolution.

PSO works as the searching engine underlying S3. Figure 20 shows how PSO interplays with the S3 simulation model during optimization. The program provides the flexibility for the user to experiment with and decide on the population of particle size, the number of iterations and range of variables for optimization search. The process begins by generating an initial population randomly. By automatically adjusting the priority values for activities and limits of resources, S3 would consider resource allocation and all precedence relationships simultaneously to obtain the fitness measure. A number of Monte Carlo simulation runs results in an average of the system output, which is then fed back to the optimization engine as the fitness measure. Through a specified number of iterations, the optimal solution would be reached.

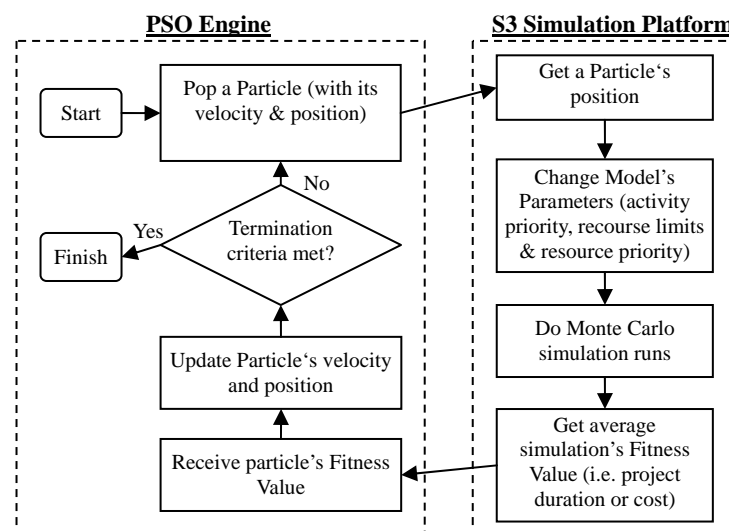


Figure 20. Interaction between PSO engine and S3 simulation platform

5.2 *Deterministic Simulation-Optimization Analysis*

In dealing with the deterministic CPM models, there are two objective options for optimization analysis, namely, the “minimize total project duration” and “minimize total project cost”. Simulation-optimization analysis can be in minimizing costs or maximizing efficiency while making the best use of the limited resource available.

The performance of *S3* deterministic simulation-optimization analysis is demonstrated on the CPM-AON network, used in Chapter 4. We take the abovementioned scenario 2 from Section 4.4.4 as a testing case. In this case, both resource limits and resource calendars constraints are involved in the scheduling problem. By experimenting with the sample project, the particle population size from 20 to 50 is found to be a reasonable compromise between diversifying solutions and processing time for scheduling projects of size similar to the one being studied. Based on the review of a related research (Lu et al. 2006), the following PSO parameters were used: the population size of 30; the inertia weight w from initial 0.9 down to 0.4 in the end; c_1 and c_2 are both set as 2. In this optimization analysis, a fixed number of iterations (100) were executed with the population size of 20.

5.2.1 *Minimization of Total Project Duration*

Being able to achieve shorter project duration adds competitiveness to a contractor. In general, resource allocation is required to reschedule the project tasks so that a limited number of resources can be efficiently utilized to keep the shortest project duration. In this situation, the objective function of “shortest project duration” is, therefore, chosen for evaluating alternatives and determining the optimum state of the project system.

The basic task of resource allocation optimization is deciding the order in which to schedule the individual activities. The *S3* would consider resource allocation and all precedence

relationships simultaneously to obtain the total project duration in evaluating each particle of PSO. Given a certain input scenario (i.e. priority of activity and limits of resources), a single simulation runs is executed to obtain a value of total project duration in the deterministic CPM setting. The value is then fed back to the optimization engine as the fitness measure. After the PSO arrives at the shortest project duration, the project manager could follow the resulting activity sequences and resource allocation according to the schedule from *S3*.

For our example project in the section 4.4, given six laborers available working on 6 work-day week and one crane available on 5 work-day week, the project completion period is 23 days, as derived from *P3* by the option of automatic forward resource leveling. Under the same resource constraints, the project duration shortens to 19 days after deterministic simulation-optimization analysis by *S3* (Figure 21). The scheduling results are summarized in Table 12, with a priority code 9 standing for the highest priority, and 1 for the lowest in resource allocation. Also note activities' TF before and after the optimization analysis are contrasted.

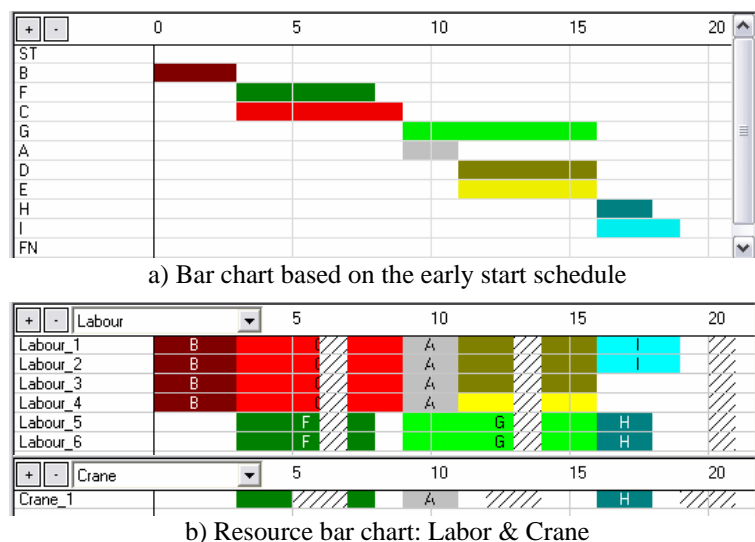
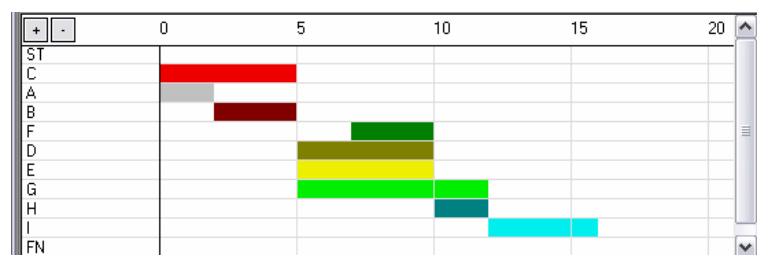


Figure 21. S3 simulation output for project duration optimization scenario 1

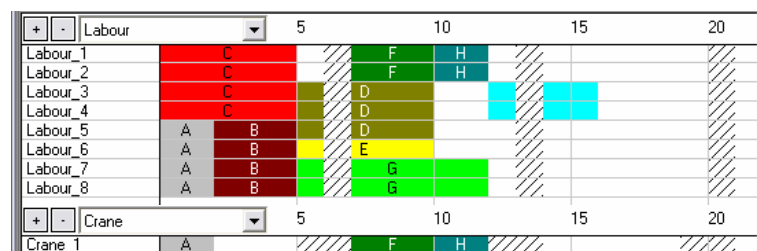
Table 12. S3 scheduling and optimization results of minimizing total project duration

Activity	Original Scenario based on P3 Result		Optimization Scenario 1		Optimization Scenario 2	
	Priority code	Total float	Priority code	Total float	Priority code	Total float
A	5	0	2	0	4	0
B	8	0	4	0	4	0
C	9	0	4	0	5	0
D	4	0	4	0	2	3
E	3	2	1	3	1	5
F	7	0	7	1	5	2
G	6	2	3	0	1	0
H	1	0	1	1	1	2
I	2	2	1	0	1	0
No. of laborers	6		6		8	
No. of crane	1		1		1	
Total project duration	23		19		16	

From the standpoint of contractors, completing the task on schedule is paramount to their reputation and competitiveness, so that the contractors are willing to hire more labors or rent more equipment to increase the productivity. Under such a circumstance, the S3 optimization objective could be set as minimizing total project duration within a specific range of resources. In this 2nd scenario, the quantities of labor and crane were set to be bounded on [4, 12] and [1, 2] respectively before optimization. When the system reached the optimum state in regard to project duration minimization, a total of 8 laborers were needed to attain the construction period of 16 days (in Figure 22). The details (i.e. resource limits, priority code and total float) of this new scenario are also listed in Table 12, and compared with the previous scenarios.



a) Bar chart based on the early start schedule



b) Resource bar chart: Labor & Crane

Figure 22. S3 simulation output for project duration optimization scenario 2

5.2.2 *Minimization of Total Project Cost*

As mentioned in the above sections the clients or contractors wish to finish their project as soon as possible, but the acceleration of construction progress comes with an increase to the whole project budget. Project planners should investigate the costs and benefits of completing the project early. In order to become profitable and competitive, it is also crucial for a contractor business to be able to deploy fewer resources and organize more efficiently its manpower and equipment resources during the construction. In this case, we should find out the activity sequence and combination of resource crew sizes that result in the minimum project cost. Hence, the objective of the scheduling problem is defined as minimization of total project cost.

In addition to minimizing total project duration under fixed limits of resource availability, S3 also features the minimization of total project cost by finding the optimum resource limits and the associated activity priorities for resource allocation. Before the discussion of the project cost optimization with S3, the concept of construction project cost should be presented first.

Many researchers have pointed out that construction time and cost are intricately related. For a construction project, the direct cost generally covers labor, equipment and raw material directly consumed in production activities and is inversely correlated with time: the shorter activity time (project duration) comes along with higher direct cost. On the other hand, the indirect cost includes the expenditures on management, supervision and inspection, which has a positive correlation with the project duration (the longer the project duration, the higher the indirect cost). As illustrated in Figure 23, the total project cost has a minimum point in a project duration-cost relationship curve.

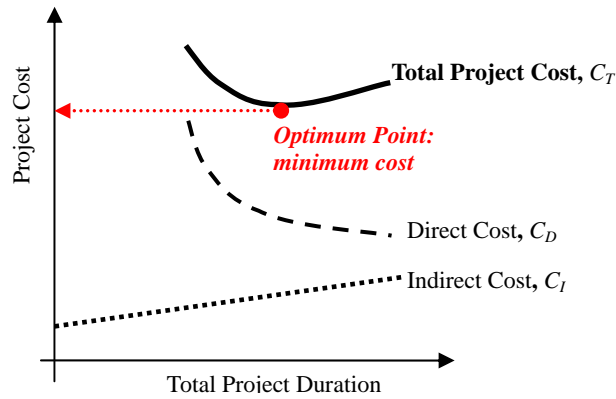
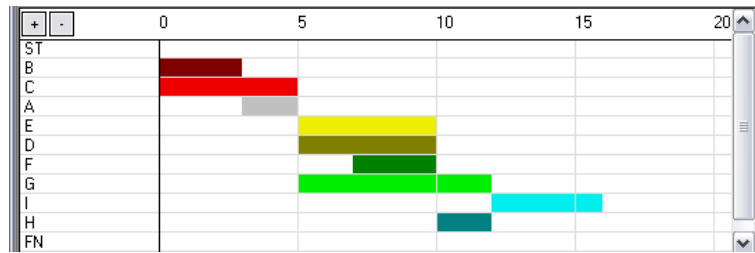


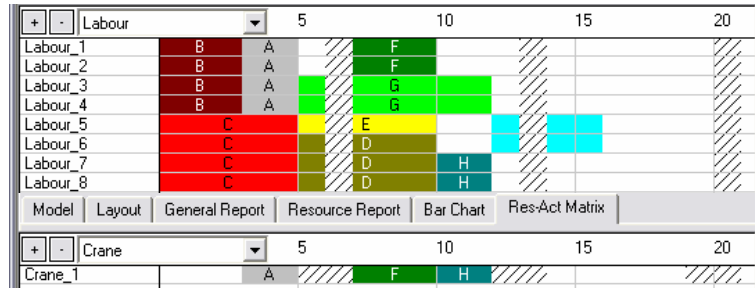
Figure 23. Total project duration-cost relationship

In our example project, the initial cost, project daily indirect-cost expenditures and daily costs of laborer and crane are assumed to be \$5000, \$1000, \$500 and \$1000 respectively. Given the 19-day optimal schedule under 6 laborers and 1 crane, which is obtained by S3 optimization of minimizing total project duration (refer to Scenario 1 in the previous section), the total project cost is determined as \$89,000.

With consideration of the cost and availability constraints of resources, the quantities of labor and crane were set to be bounded on [4, 12] and [1, 2] respectively before S3 simulation-optimization analysis. By adjusting the resource quantities and the activity priorities simultaneously, the optimization analysis eventually yielded an optimum solution: the total project cost is \$78,000, the eight laborers need to be hired, and the total project duration is 16 days. The resultant resource bar chart is shown in Figure 24. The optimization results for the resource allocation and time-cost tradeoff scenarios are summarized in Table 13. Note with 2 extra laborers added, the indirect cost reduces to \$21,000 due to the total project duration being shortened (16 days), while the direct cost also decreases in comparison with the previous scenario due to the reduction of non-productive cost of crane (from 8 hours to 0 hour). In this case, arranging all activities that require the crane as compact as possible will mean saving in crane rental cost.



a) Bar chart based on the early start schedule



b) Resource bar chart: Labor & Crane

Figure 24. S3 simulation output for project cost optimization scenario

Table 13. S3 scheduling and optimization results of minimizing total project cost

Scenario	Original: based on P3 Result		S3 Optimization: Min. Project Duration		S3 Optimization: Min. Project Cost	
Activity	Priority code	Total float	Priority code	Total float	Priority code	Total float
A	5	0	2	0	2	0
B	8	0	4	0	6	0
C	9	0	4	0	4	0
D	4	0	4	0	1	3
E	3	2	1	3	8	5
F	7	0	7	1	1	2
G	6	2	3	0	1	0
H	1	0	1	1	1	2
I	2	2	1	0	6	0
No. of laborers	6		6		8	
No. of crane	1		1		1	
Total project duration (d)	23		19		16	
Total project cost (\$)	99,500		89,000		78,000	
[direct cost & indirect cost]	[71,500 & 28,000]		[65,000 & 24,000]		[57,000 & 21,000]	

5.3 Stochastic Simulation-Optimization Analysis

In dealing with the stochastic S3 simulation models, an objective for optimization analysis, namely, the “optimize total project duration” is provided. By using the PSO technique, we can optimize the project schedule in terms of attaining the shortest project duration under the stochastic setting due to the consideration of uncertainties in activity times.

5.3.1 Optimization Procedures

As mentioned in Chapter 4, the duration of each activity is randomly sampled from the corresponding statistical distributions in each simulation run, and a large number of simulation runs are required in order to produce the CDF of total project duration. To accelerate the minimization process of total project duration in the stochastic settings, a 2-stage optimization process is developed. The first stage of the optimization is similar to the deterministic simulation-optimization analysis. Given a certain input scenario (i.e. priority of activity and ranges of resource limits), one Monte Carlo run of simulation is executed to obtain total project duration. The project duration value is then fed back to the PSO engine as the fitness measure. Generally, the initial stage of the optimization process is relatively slow since it is difficult to obtain a well global particle position in a large search space. Through a number of single-run PSO iterations, a relatively good starting point (i.e. priorities of activities and ranges of resource limits) would be obtained to initiate the second stage of the optimization. In the second stage, we increase the number of Monte Carlo simulation-runs (n) so as to result in an average of the system output. Given a large enough n , the averaged system output is generally steady, which is then fed back to the optimization engine as the fitness measure. Through such a optimization process, optimal or near-optimal priorities of activities can eventually be obtained in a relatively short computing time.

5.3.2 Sample Application

In this section, the performance of S3's stochastic simulation-optimization analysis is demonstrated on the PERT-AON network, which is also used in Chapter 4. We take the Scenario 2 from section 4.5.4 as a testing case. For this example project, both resource limits and resource calendars constraints are involved in the scheduling problem (six laborers available working on 6 work-day week and one crane available on 5 work-day week).

In this stochastic simulation-optimization analysis, two stages of PSO-based optimization process (50 iterations in step 1 and 50 iterations in step 2) were executed, and the following PSO parameters used: the population size of 20; the inertia weight w from initial 0.9 down to 0.4 in the end; c_1 and c_2 are both set as 2. In this setting, each particle's fitness measure in terms of average total project duration (day) was evaluated based on 1 and 10 simulation run(s) in stage 1 and stage 2 respectively.

Based on the activity sequence derived from $P3$ by the option of automatic forward resource leveling, the average project completion period of this base case is 22.97 days through $S3$ simulation. Under the same resource constraints and by adjusting the priority of each activity, $S3$ powered by PSO engine shortened the average project duration shortens to 20.91 days. The scheduling results of the 1st scenario are summarized in Table 14, with the histogram of the project completion time as shown in Figure 25.

Table 14. $S3$ Base case scenario: PERT simulation results versus

Scenario		Base case: Based on P3 scheduling results	Scenario 1: Adjust activity priority	Scenario 2: Adjust activity priority & resource limits
Priority Code	A	5	1	4
	B	8	6	9
	C	9	3	5
	D	4	1	4
	E	3	1	3
	F	7	5	1
	G	6	3	2
	H	1	1	1
	I	2	1	1
Resource	No. of laborers	6	6	8
	No. of crane	1	1	1
Duration (d)	Minimum – maximum	16 – 29	13 – 28	11 – 22
	Mean	22.97	20.91	16.76
	Standard deviation	2.55	2.47	1.82
	95% confidence interval	22.75 – 23.20	20.69 – 21.13	16.60 – 16.92
Cost (\$)	Minimum – maximum	67500 – 122500	56500 – 132000	60500 – 118000
	Mean	98372	95079	86474
	Standard deviation	10867	11405	9974
	95% confidence interval	97420 – 99324	94079 – 96079	85600 – 87348

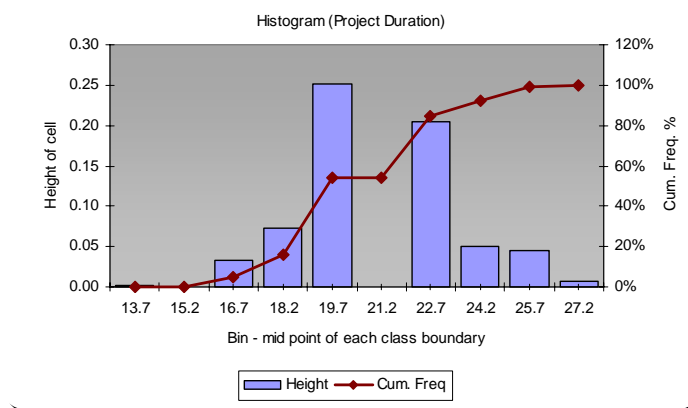


Figure 25. Histograms of project duration in optimization scenario 1

In addition to the arrangement of activity sequence, *S3* can also help the project manager optimize the configuration of the resource size, aimed to utilize the limited amounts of resources to accelerate construction progress within a specific range of resources. With consideration of the cost and availability constraints of resources, in this second scenario, the quantities of labor and crane were set to be bounded on [4, 12] and [1, 2] respectively for the optimization. When the system reached the optimum state in regard to project duration minimization, a total of 8 laborers were needed to attain the short construction period – 16.76 days (in Figure 26). The details (i.e. resource limits and priority code) of this new scenario are listed in Table 14, and compared with the previous scenarios.

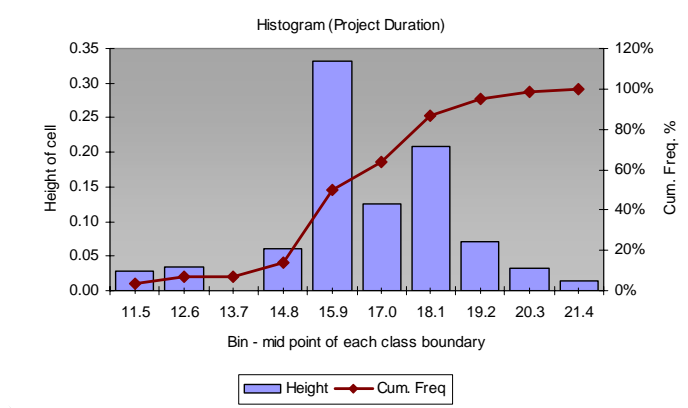


Figure 26. Histograms of project duration in optimization scenario 2

5.4 Chapter Summary

In this chapter, a powerful evolutionary algorithm called PSO was introduced in solving large scale, complex and realistic resource-constrained scheduling problems. The “deterministic” and “stochastic” simulation-optimization scenarios are considered and are obtained the experimental results of a typical AON network problem. Construction project duration and cost minimization are the two most important aspects of decision making during project scheduling. By using the PSO technique to search for an optimum set of resources and activity priorities, we can improve the project schedule in terms of attaining the shortest project duration or the least project cost.

The research has placed emphasis on finding efficient, cost-effective solution to such a stochastic simulation-optimization combined problem. PSO has been successfully used as a powerful and efficient search mechanism for near-optimal solutions in large-scale problems. It could generate an optimal plan considering resources’ availability, transit and utilization, uncertainties and interruptions in construction operations, and project time/cost minimization, leading to more accurate and relevant planning, more effective project implementation and control, and completing projects within schedule and under budgets.

CHAPTER 6

CASE STUDY: PRACTICAL IMPLEMENTATION OF S3

6.1 *S3 Application*

As mentioned in the chapter 1, the present research is concerned with designing a feasible, reliable and cost-effective project scheduling methodology by integrating evolutionary optimization techniques with stochastic operations simulation modeling. Thus, the simulation-optimization tool, *Simplified Simulation-based Scheduling (S3)*, was developed to aid project managers in handling limited resource allocation, complication of activity-interruption constraints and activity-time uncertainties in planning practical construction projects.

In general, the detailed level of a project plan depends on user's requirements, the sophistication of work breakdown structure, and the accuracy of activity duration estimation. By systematically analyzing the project of different detailed level, the project manager can plan their project in step-by-step fashions, as illustrated with the case study of applying *S3* on a Hong Kong civil construction project.

6.2 *Case Study: Project Description*

The case study based on Hong Kong's construction site scheduling practices looks into the construction of a single cell box culvert in Tin Shui Wai Reserve Zone. A 250m long single-cell box culvert namely, Northern Culvert was proposed to discharge runoff

generated from the northwest part of the Reserve Zone to the existing Western Drainage Channel. The whole box culvert was to be constructed in 17 bays. In view of the tight construction programme, the contractor proposed to construct Bay 1 to Bay 8 and Bay 9 to Bay 17 of the box culvert in parallel, one work front working downstream from Bay 8 to Bay 1 and the other work front working upstream from Bay 9 to Bay 17.

Prior to the construction of box culvert, the marine mud layer below the foundation level was replaced by a layer of 400mm thick compacted rock fill materials. In addition, it was revealed from the additional borehole records that the thickness of marine mud layer underneath Bay 1 to Bay 8 was 2m thicker than was expected. Therefore, excavation for an additional 2m thick marine mud layer and subsequent deposition of rock fill materials was also included in the construction of Bay 1 to Bay 8. Bay 17 of the box culvert also included two 1650mm diameter pre-cast concrete pipes at its 800mm thick end wall to convey runoff generated from the northwest part of the Reserve Zone. The details of this construction project are attached in the APPENDIX D – Project Details of Case Study.

In the box culvert construction work, there are totally 33 activities. Available resources for different activities are 4 bar benders & fixers [BBF], 4 backhoes with excavator [BE], 3 crawler mounted cranes [CMC], 2 carpenters (Formwork) [CF], 5 concreter's laborers [CLB], 1 drainlayer [DL], 8 skilled laborers [LB] and 4 rollers [RR]. The precedence relationships of the AON network, as well as the cost and the resource requirements of activities, are shown in Table 15 and Figure 27, respectively.

Table 15 Activity detail of case study

Act.	Descriptions	Dur. (d)	Resource Requirement							
			BBF	BE	CMC	CF	CLB	DL	LB	RR
A	General excavation	16		4					8	
B1	Excavation of additional 2m thick marine mud	8		2					4	
B2	Deposition and compaction of 2m thick additional rock fill materials	16		2	1				4	2
B3	Placing and compaction of 400mm thick rock fill	12		1					4	2
B4	Laying of 75mm thick blinding concrete	3			1		2		6	
B5	Fixing of steel reinforcement for base slab & side walls (lower part)	32	2						4	
B6	Erection of formwork for base slab & side walls (lower part)	16				1			4	
B7	Concreting of base slab & side walls (lower part)	4			1		3		4	
B8	Erection of falsework for top slab	32							6	
B9	Fixing of steel reinforcement for top slab & side walls (upper part)	20	2		1				3	
B10	Erection of formwork for top slab & wide walls (upper part)	20				1			4	
B11	Concreting of top slab & side walls (upper part)	5			1		3		4	
C1	Placing and compaction of 400mm thick rock fill	12		1					3	2
C2	Laying of 75mm thick blinding concrete	3			1		2		4	
C3	Fixing of steel reinforcement for base slab & side walls (lower part)	32	2						3	
C4	Erection of formwork for base slab & side walls (lower part)	16				1			4	
C5	Concreting of base slab & side walls (lower part)	4			1		3		4	
C6	Erection of falsework for top slab	32							5	
C7	Fixing of steel reinforcement for top slab & side walls (upper part)	20	2		1				3	
C8	Erection of formwork for top slab & wide walls (upper part)	20				1			4	
C9	Concreting of top slab & side walls (upper part)	5			1		3		3	
D1	Placing and compaction of 400mm thick rock fill	2		1					2	1
D2	Laying of 75mm thick blinding concrete	1			1		2		2	1
D3	Fixing of steel reinforcement for base slab & side walls (lower part)	5	1						2	
D4	Erection of formwork for base slab & side walls (lower part)	2				1			4	
D5	Concreting of base slab & side walls (lower part)	1			1		3		2	1
D6	Erection of falsework for top slab	4							4	
D7	Fixing of steel reinforcement for top slab & side walls (upper part)	6	2		1				2	
D8	Erection of formwork for top slab & wide walls (upper part)	3				1			4	
D9	Concreting of top slab & side walls (upper part)	1			1		3		2	1
E1	Submission, approval on concrete pipe manufacturer & Delivery of concrete pipes	90								
E2	Positioning of pre-cast concrete pipes at end wall	1			1			1	6	
F	Backfilling & Compaction	7		4					8	4
Available Resources Limit			4	4	3	2	5	1	8	4
Renting Rate/ Daily Cost (\$)			1600	1200	3200	1100	950	850	600	1800

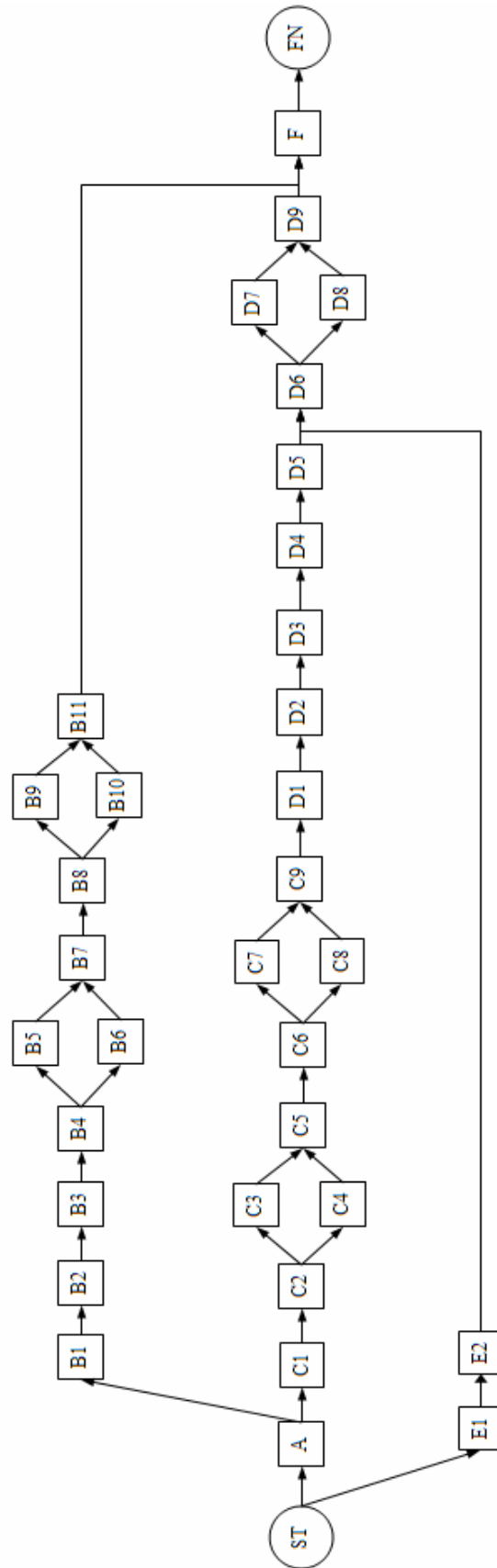


Figure 27. AON network of case study

6.2.1 Data Collection

Generally, the duration of an activity can be determined by one of three methods; by analyzing historical records from previously completed projects, by referencing publicly available manuals that provide costs and production rates for various types of work, or from the experience and judgment of the experts. In this case study, the activity durations were estimated by the construction practitioners.

Apart from activity duration estimation, the costs of project daily expense and each resource were also obtained from our case. The initial indirect cost and project daily indirect-cost expenditures are estimated to be \$300000 and \$15000 respectively. The resources provided for the project including the daily rates are summarized in Table 15. The daily rates for the resources are based on Monthly Return of Site Labour Deployment and Wage Rates for Construction Works for one of the ongoing Drainage Services Department's contracts in the month of March 2004 and HKCA Schedules for Plant Used in Dayworks Carried Out Incidental to Contract Work (2002).

6.2.2 Options of Project Scheduling

S3 was used to handle deterministic or stochastic analysis with different constraints such as resource availability and multiple interruptions. In the critical path method (CPM) scheduling projects, the duration of each activity is usually defined with a reasonable degree of certainty. Using the CPM, the assignment of one duration to each activity provides a deterministic process for the start and finish dates of each activity and a single finish date for the entire project. For some projects it may be difficult to estimate a reasonable single duration for one or more of the activities in the project schedule. There may be a range of durations that may apply to a particular activity, which makes it difficult to select just one duration to assign to the activity. The Project Evaluation and Review Technique (PERT)

method of scheduling uses three durations for each activity and the fundamental statistics to determine the probability of a project finishing earlier or later than expected.

Moreover, we use the latest evolutionary optimization algorithms to optimize the schedule in terms of attaining the shortest project duration or the least project cost, integrated with TF analysis. The *S3* first collected information by specifying the attributes for each task and providing the resources available; then it generated a simulation model in the SDESA simulation platform, including flow entity queue (holding activity task) and resource entity queue (holding all resources utilized in the system). The output of the what-if scenario analysis can be used to assess the feasibility of the project schedule.

Given data available, we can conduct different phases of project scheduling plan. The following four stages will be considered:

- Stage 1* In the initial stage of project schedule, project managers generally is required to create a traditional CPM analysis without any resource constraints.
- Stage 2* Based on the preliminary CPM scheduling plan, we would consider the resource scheduling to utilize the limited amounts of resources by using different optimization criteria (i.e. project duration minimization or project cost minimization).
- Stage 3* The detailed project scheduling would be carried out to deal with the constraints of resource availability and multiple interruptions simultaneously through deterministic simulation-optimization process.
- Stage 4* Similar to deterministic analysis, we could perform stochastic PERT simulation analysis under different constraints such as resource availability and multiple interruptions and then carry out the optimization to minimize the total project duration in consideration of activity-time uncertainties.

6.3 Stage 1: Deterministic CPM Analysis

In practice, the project planner first collects information by specifying the detail of each task. By analyzing each activity and its relationships among with other activities, the project planner should carry out a brief planning and scheduling before committing resources. With the activity duration represented by a constant value, the traditional CPM analysis produces a preliminary schedule without any consideration of resource constraints, allowing the project manager to assess the criticality of activities and determine the project duration and total cost.

In this deterministic analysis, both *P3* and *S3* arrived at the total project duration of 155 days with identical TF determined for each activity. The *S3* model is capable of accurately working out the CPM analysis, deriving the total project duration and float times (i.e. start times, finish times and total floats) as summarized in Table 15. All the screenshots of *S3* and *P3* scheduling results are attached in APPENDIX E – Detailed Scheduling Results of Case Study.

Table 16. S3 scheduling results of Stage 1 case

<i>Activity</i>	<i>Duration</i>	<i>ES</i>	<i>EF</i>	<i>LS</i>	<i>LF</i>	<i>FF</i>	<i>TF</i>
A	16	0	16	0	16	0	0
B1	8	16	24	16	24	0	0
B2	16	24	40	24	40	0	0
B3	12	40	52	40	52	0	0
B4	3	52	55	52	55	0	0
B5	32	55	87	55	87	0	0
B6	16	55	71	71	87	16	16
B7	4	87	91	87	91	0	0
B8	32	91	123	91	123	0	0
B9	20	123	143	123	143	0	0
B10	20	123	143	123	143	0	0
B11	5	143	148	143	148	0	0
C1	12	16	28	18	30	0	2
C2	3	28	31	30	33	0	2
C3	32	31	63	33	65	0	2
C4	16	31	47	49	65	16	18
C5	4	63	67	65	69	0	2
C6	32	67	99	69	101	0	2
C7	20	99	119	101	121	0	2
C8	20	99	119	101	121	0	2
C9	5	119	124	121	126	0	2
D1	2	124	126	126	128	0	2
D2	1	126	127	128	129	0	2
D3	5	127	132	129	134	0	2
D4	2	132	134	134	136	0	2
D5	1	134	135	136	137	0	2
D6	4	135	139	137	141	0	2
D7	6	139	145	141	147	0	2
D8	3	139	142	144	147	3	5
D9	1	145	146	147	148	2	2
E1	90	0	90	46	136	0	46
E2	1	90	91	136	137	44	46
F	7	148	155	148	155	0	0
<i>Total project duration: 155</i>							

Based on the above S3 analysis, project managers could obtain a preliminary schedule. If the managers want to obtain a more detailed plan on allocating limited resources, the stage 2 of the scheduling analysis should be carried out.

6.4 Stage 2: CPM Analysis with resource-availability constraints

Undoubtedly, resource-availability could have a significant effect on the preliminary CPM schedule obtained in the stage 1. After the project planner identifies resources needed to complete each task, resources are assigned to the activities in the scheduling models according to the resource requirements given. Note the resource availabilities remain unchanged over the project duration.

In this case, the resource-availability constraints were applied on *S3* and *P3* to compare the scheduling performance of both scheduling tools. In order to compare *S3* and *P3*, the same activity execution sequence in resource allocation –as followed by *P3*– applies to *S3*. As a result, both scheduling tools extend the total project duration from 155 days of stage 1 to 241 days. Similar to the findings in Section 4.4.3, the total float values of Activities A, B1 to B11 and C1 to C8 produced by *S3* and *P3* are contrasted in Table 17. This implies that *P3* generates overstated TF values for these activities while the TF determination does not take into account of the resource constraints.

Table 17. Scheduling results comparison between S3 and P3 for Stage 2 case

<i>Activity</i>	<i>Duration (days)</i>	<i>Total Float</i>		<i>Activity Sequence</i>
		<i>S3</i>	<i>P3</i>	
A	16	0	70	1
B1	8	4	70	4
B2	16	11	70	5
B3	12	11	70	8
B4	3	0	59	9
B5	32	0	59	10
B6	16	0	27	15
B7	4	0	27	16
B8	32	0	27	17
B9	20	0	27	19
B10	20	0	7	21
B11	5	2	6	29
C1	12	0	72	3
C2	3	0	72	6
C3	32	0	72	7
C4	16	12	69	11
C5	4	12	69	12
C6	32	0	57	13
C7	20	0	57	14
C8	20	0	5	18
C9	5	5	5	20
D1	2	5	5	22
D2	1	5	5	23
D3	5	5	5	24
D4	2	5	5	25
D5	1	5	5	26
D6	4	0	0	28
D7	6	0	0	30
D8	3	2	2	31
D9	1	0	0	32
E1	90	132	132	2
E2	1	0	0	27
F	7	0	0	33
Total project duration		241	241	

Moreover, by using the *S3* optimization functionality, we can optimize the project schedule in terms of attaining the shortest project duration or the least project cost.

While the project manager aims to utilize the limited resources to achieve the shortest project completion period, the project duration shortens to 228 days from 241 days in the base case through the *S3* optimization process under the same resource limits. The optimized scheduling results are summarized in Table 18, with a priority code 33 standing for the highest priority, and 1 for the lowest in resource allocation. Also note activities' TF before and after the optimization analysis are contrasted.

Table 18. S3 scheduling and optimization results of stage 2 case

Scenario	Original Case: based on P3 Result		S3 Optimization: Min. Project Duration		S3 Optimization: Min. Project Cost	
Activity	Priority code	Total float	Priority code	Total float	Priority code	Total float
A	33	0	31	0	32	0
B1	30	4	15	0	22	7
B2	29	11	19	0	11	0
B3	26	11	10	0	10	1
B4	25	0	9	0	8	1
B5	24	0	9	0	33	4
B6	19	0	11	1	12	20
B7	18	0	8	0	1	0
B8	17	0	25	0	33	0
B9	15	0	22	0	33	0
B10	13	0	28	0	30	0
B11	5	2	12	0	6	0
C1	31	0	25	1	33	0
C2	28	0	13	1	18	0
C3	27	0	17	1	27	0
C4	23	12	15	0	10	0
C5	22	12	10	1	4	0
C6	21	0	19	0	14	0
C7	20	0	22	0	21	0
C8	16	0	11	0	24	0
C9	14	5	9	1	8	0
D1	12	5	20	1	6	0
D2	11	5	16	1	8	0
D3	10	5	18	1	2	31
D4	9	5	21	1	1	3
D5	8	5	11	1	9	0
D6	6	0	16	0	1	0
D7	4	0	7	2	27	0
D8	3	2	6	0	27	3
D9	2	0	10	0	12	0
E1	32	132	9	65	17	99
E2	7	0	15	0	1	0
F	1	0	29	0	1	0
No. of bar benders & fixers		4		4		2
No. of backhoes with excavator		4		4		4
No. of crawler mounted cranes		3		3		1
No. of carpenters (formwork)		2		2		1
No. of concreting laborers		5		5		3
No. of drainlayer		1		1		1
No. of skilled laborers		8		8		13
No. of rollers		4		4		4
Total project duration (d)		241		228		208
Total project cost (\$)		11,911,050		11,225,850		9,020,450
[direct cost & indirect cost]		[8.00M & 3.92M]		[7.51M & 3.72M]		[5.60M & 3.42M]

Alternatively, we can choose “minimizing project cost” as the objective to determine the optimal activity sequence and the amounts of resource provisions in order to achieve the minimum total project cost. With the consideration of resource cost and requirements, we set the likely ranges of daily resource limits as summarized in Table 19. After optimization, the following results are obtained: the total project cost is reduced to \$9,020,450 and the total project duration is 208 days. The resource amounts are also changed: the four extra skilled laborers need to be hired, and the numbers of bar benders & fixers, cranes,

carpenters, concreting laborers are reduced by 2. The reason for reducing numbers of bar benders & fixers, crane, carpenter, concreting laborers is that they are not critical resources on this project. The overall optimization results for the “minimizing project duration” and “minimizing project cost” scenarios are summarized in Table 18.

Table 19. Parameter limits of each resource type

Resource	Minimum	Maximum
Bar benders & fixers	2	8
Backhoes with excavator	4	8
Crawler mounted cranes	1	6
Carpenters (formwork)	1	4
Concreting laborers	3	10
Drainlayer	1	2
Skilled laborers	8	16
Rollers	4	8

6.5 Stage 3: CPM Analysis with resource and interruption constraints

In the reality, interruptions associated with different resources and different contract requirements would be reflected in multiple calendars. If multiple resource interruptions are involved, the project scheduling will require adjustment on the total float values and the total project duration.

In the project, the holidays of skilled laborers were scheduled on Sundays. A sub-contractor crew, carpenters, was subject the same 6-days/week project calendar. Another sub-contractor responsible for concreting works was required to work in another construction site, thus their concreting laborers were only available on 4-day weeks from Monday to Thursday. All equipment would be available on the site every day.

Both *S3* and *P3* scheduling tools were used to perform the scheduling plan. By using the same activity execution sequence suggested by *P3*, both *S3* and *P3* scheduling tools

extended the total project duration from 241 days of stage 2 to 283 days of stage 3. According to Table 20, it is observed that *P3* generates overstated TF values for Activities A, B1 to B11, C1 to C9, and E1 to E2 while the TF determination does not take into account of the resource constraints.

Table 20. Scheduling results comparison between S3 and P3 for Stage 3 case

Activity	Duration (days)	Total Float		Project Extension Time by 1-day delay beyond LF	Activity Sequence
		S3	P3		
A	16	0	95	6	1
B1	8	0	96	6	3
B2	16	0	9	6	5
B3	12	0	5	6	8
B4	3	0	95	6	10
B5	32	0	96	6	11
B6	16	10	77	6	13
B7	4	0	77	6	16
B8	32	0	88	6	17
B9	20	0	38	6	21
B10	20	4	41	6	22
B11	5	0	17	6	29
C1	12	5	102	6	4
C2	3	3	99	6	6
C3	32	3	99	6	7
C4	16	0	95	6	9
C5	4	7	87	7	12
C6	32	0	58	6	14
C7	20	0	15	6	18
C8	20	0	15	6	19
C9	5	2	15	6	20
D1	2	0	0	6	23
D2	1	0	0	6	24
D3	5	0	0	6	25
D4	2	0	0	6	26
D5	1	0	0	6	27
D6	4	0	0	1	28
D7	6	0	0	1	30
D8	3	0	0	1	31
D9	1	0	0	1	32
E1	90	69	171	6	2
E2	1	0	102	6	15
F	7	0	0	1	33
Total project duration		283	283		

In addition, S3 produces the “project extension effect” as one output [the magnitude of extending the total project duration due to delaying the completion of an activity by 1-day beyond its late finish time (LF)]. As summarized in Table 20, it is observed that one day

delay beyond the late finish time on several activities could delay the total project duration by 6 or 7 calendar days. For example, 1-day extension in Activity C5 could lengthen the total project duration by 7 calendar days.

Similar to the previous stage, we also can carry out the optimization of “minimizing project duration” and “minimizing project cost”. Through the optimization of the resource allocation, the total project duration shortens to 275 days under the same resource constraints. Alternatively, S3 can target at minimizing the total project cost by finding the optimum number of resources along with optimal activity priorities for resource allocation. We set the same ranges of daily resource limits as used in the stage 2 case. After optimization, the following schedule results were obtained: the total project cost is cut by 33% (from 14M of P3 to \$9.3M of S3), the total project duration is reduced by 23% (from 283 days of P3 to 206 days of S3), and the resource amounts are also changed. The optimization results for the resource allocation and time-cost tradeoff scenarios are summarized in Table 21, with a priority code 33 standing for the highest priority, and 1 for the lowest in resource allocation.

Table 21. S3 scheduling and optimization results of stage 3 case

Activity	Duration (days)	S3 Activity Priority Code		
		Original Case: based on P3 Result	S3 Optimization: Min. project duration	S3 Optimization: Min. project cost
A	16	33	32	32
B1	8	31	29	32
B2	16	29	29	15
B3	12	26	21	14
B4	3	24	23	33
B5	32	23	28	28
B6	16	21	19	24
B7	4	18	16	13
B8	32	17	17	18
B9	20	13	14	1
B10	20	12	12	3
B11	5	5	7	1
C1	12	30	32	31
C2	3	28	25	26
C3	32	27	31	29
C4	16	25	23	20
C5	4	22	21	14
C6	32	20	13	17
C7	20	16	19	33
C8	20	15	13	13
C9	5	14	19	5
D1	2	11	11	11
D2	1	10	11	3
D3	5	9	9	30
D4	2	8	9	8
D5	1	7	8	23
D6	4	6	5	1
D7	6	4	4	3
D8	3	3	1	1
D9	1	2	5	2
E1	90	32	23	33
E2	1	19	8	1
F	7	1	1	1
No. of bar benders & fixers		4	4	2
No. of backhoes with excavator		4	4	4
No. of crawler mounted cranes		3	3	2
No. of carpenters (formwork)		2	2	1
No. of concreting laborers		5	5	3
No. of drainlayer		1	1	1
No. of skilled laborers		8	8	13
No. of rollers		4	4	4
Total project duration (d)		283	275	206
Total project cost (\$)		13,992,750	13,508,600	9,295,300
[direct cost & indirect cost]		[9.45M & 4.55M]	[9.01M & 4.43M]	[5.91M & 3.39M]

6.6 Stage 4: Stochastic PERT Analysis

On the other hand, activity's duration often are estimated by experienced project planner based on the subjective information in the absence of historical data. While construction project scheduling has to deal with uncertainty involved in activity durations, the abovementioned three stages of CPM model analysis fail to address the stochastic nature of construction works. In this situation, it is required to carry out stochastic project analysis.

While there is only a limited amount of data available for choosing an appropriate statistical distribution, the minimum, maximum and mode values of each activity are predicted by the project planner (Table 22). According to the user requirements, S3 provides different types of statistical distributions (i.e. uniform, normal, triangular, discrete probabilities and beta, etc.) for input modeling. According to the information/data about activity duration, input models can be established with regard to different types of distribution and the distributions' parameters. In this case study, the triangular distributions are defined for PERT model in S3 based on the details in Table 22. The input parameters for triangular distributions are in the order of the optimistic, the most likely, and the pessimistic time estimates in days.

The stochastic project analysis could be divided into three scenarios. The base case scenario is the straightforward PERT analysis ignoring any resource limit and resource calendar constraints. Scenario 1 considers the constraints of manpower and equipment resources available on any given day which is similar to the stage 2. In Scenario 2, both resource limits and resource calendar constraints are involved in the scheduling problem which is similar the problem given in the stage 3.

Table 22. Details of PERT network

Act.	Descriptions	Major Source of Uncertainties	Three-time Estimate (d)		
			<i>L</i>	<i>M</i>	<i>U</i>
A	General excavation	Inclement weather; and complication of the underground utilities	14	16	21
B1	Excavation of additional 2m thick marine mud	Equipment being positioned due to soft ground	6	8	13
B2	Deposition and compaction of 2m thick additional rock fill materials	Rock fill materials improperly stored on site	10	16	20
B3	Placing and compaction of 400mm thick rock fill	Rock fill materials improperly stored on site	10	12	16
B4	Laying of 75mm thick blinding concrete	Inclement weather	2	3	4
B5	Fixing of steel reinforcement for base slab & side walls (lower part)	Awaiting approval on bar bending schedule	24	32	40
B6	Erection of formwork for base slab & side walls (lower part)	Awaiting approval on temporary works design	12	16	24
B7	Concreting of base slab & side walls (lower part)	Defective must be replaced	3	4	5
B8	Erection of falsework for top slab	Inclement weather; material delivery	23	32	40
B9	Fixing of steel reinforcement for top slab & side walls (upper part)	Awaiting approval on bar bending schedule	12	20	24
B10	Erection of formwork for top slab & wide walls (upper part)	Awaiting approval on temporary works design	16	20	25
B11	Concreting of top slab & side walls (upper part)	Defective must be replaced	4	5	6
C1	Placing and compaction of 400mm thick rock fill	Rock fill materials improperly stored on site	10	12	16
C2	Laying of 75mm thick blinding concrete	Inclement weather	2	3	4
C3	Fixing of steel reinforcement for base slab & side walls (lower part)	Awaiting approval on bar bending schedule	24	32	40
C4	Erection of formwork for base slab & side walls (lower part)	Awaiting approval on temporary works design	12	16	24
C5	Concreting of base slab & side walls (lower part)	Defective must be replaced	3	4	5
C6	Erection of falsework for top slab	Inclement weather; material delivery	21	32	40
C7	Fixing of steel reinforcement for top slab & side walls (upper part)	Awaiting approval on bar bending schedule	14	20	26
C8	Erection of formwork for top slab & wide walls (upper part)	Awaiting approval on temporary works design	16	20	24
C9	Concreting of top slab & side walls (upper part)	Defective must be replaced	4	5	6
D1	Placing and compaction of 400mm thick rock fill	Rock fill materials improperly stored on site	1	2	3
D2	Laying of 75mm thick blinding concrete	Inclement weather	1	1	2
D3	Fixing of steel reinforcement for base slab & side walls (lower part)	Awaiting approval on bar bending schedule	4	5	6
D4	Erection of formwork for base slab & side walls (lower part)	Awaiting approval on temporary works design	2	2	3
D5	Concreting of base slab & side walls (lower part)	Defective must be replaced	1	1	2
D6	Erection of falsework for top slab	Inclement weather; material delivery	2	4	5
D7	Fixing of steel reinforcement for top slab & side walls (upper part)	Awaiting approval on bar bending schedule	5	6	7
D8	Erection of formwork for top slab & wide walls (upper part)	Awaiting approval on temporary works design	2	3	4
D9	Concreting of top slab & side walls (upper part)	Defective must be replaced	1	1	2
E1	Submission, approval on concrete pipe manufacturer & Delivery of concrete pipes	Awaiting approval on concrete pipe manufacturer; delivery problem	80	90	95
E2	Positioning of pre-cast concrete pipes at end wall	Inclement weather; ground conditions	1	1	3
F	Backfilling & compaction	Inclement weather; Maintenance	5	7	10

In these three different scenarios, the corresponding S3 models were created and analyzed.

The simulation results among three scenarios are generated after 500 Monte Carlo

simulation runs as summarized in Table 22. According to the critical index of each activity, project managers can pay more attention on the activities which have high CI values. For different scenarios, managers can obtain the simulation statistical results related to project duration and total cost (i.e. mean, minimum, maximum and standard deviation).

Table 23. S3 PERT simulation results: scenarios 1 and 2 versus base case

Simulation statistical results		Base case	Scenario 1: With resource limits	Scenario 2: With resource limits & interruptions
Critical Index (%)	A	100	100	23.4
	B1	64.2	8.6	0
	B2	64.2	1.2	1.4
	B3	64.2	1.2	1.4
	B4	64.2	100	54.0
	B5	64.2	99.8	2.6
	B6	0	71.6	39.4
	B7	64.2	71.6	65.2
	B8	64.2	100	52.6
	B9	26.8	42.8	52.6
	B10	53.6	100	27.4
	B11	64.2	24.2	60.0
	C1	44.0	98.6	23.4
	C2	44.0	99.6	35.0
	C3	44.0	99.6	34.8
	C4	0	0.8	39.4
	C5	44.0	0.8	60.0
	C6	44.0	100	52.6
	C7	30.4	48.8	31.6
	C8	24.6	80.2	30.6
	C9	44.0	4.0	57.8
	D1	44.0	2.6	49.6
	D2	44.0	2.6	64.4
	D3	44.0	2.6	50.2
	D4	44.0	1.8	50.2
	D5	44.0	100	62.2
	D6	44.0	100	38.6
	D7	44.0	24.2	38.6
	D8	0	100	64.4
	D9	44.0	100	100
	E1	0	0	0
	E2	0	100	42.8
	F	100	100	100
Duration (d)	Minimum – maximum	146.85 – 172.99	221.31 – 275.5	267.91 – 317.39
	Mean	160.06	245.47	294.21
	Standard deviation	5.00	8.18	9.58
	95% confidence interval	159.63 – 160.50	244.75 – 246.19	293.37 – 295.05
Cost (\$)	Minimum – maximum	2.50M – 2.89M	10.85M – 13.61M	13.21M – 15.72M
	Mean	2,700,953	12,088,463	14,513,685
	Standard deviation	74,986	414,276	494,283
	95% confidence interval	2.694M – 2.708M	12.052M – 12.125M	14.470M – 14.557M

Additionally, S3 generated the statistic results such as probability density function (PDF)

and cumulative probability density function (CDF) curves of the project completion time. For example, the histograms are drawn from the base scenario simulation results (in Figure 28). In addition, the histograms of total project duration and cost in the scenario 1 are generated (shown in Figure 29). Based on these histograms drawn from the PERT simulation results, project managers can then analyze the risks of schedule or budget overrun. For instance, the probability of completing the project by Day 255 is around 93% which was read from the generated cumulative probability curve (Figure 29). The probability of completing the project within \$12.5 millions is around 87% which was read from the generated cumulative probability curve. Thus, project manager can set up a financial plan for the project through the prediction of probability.

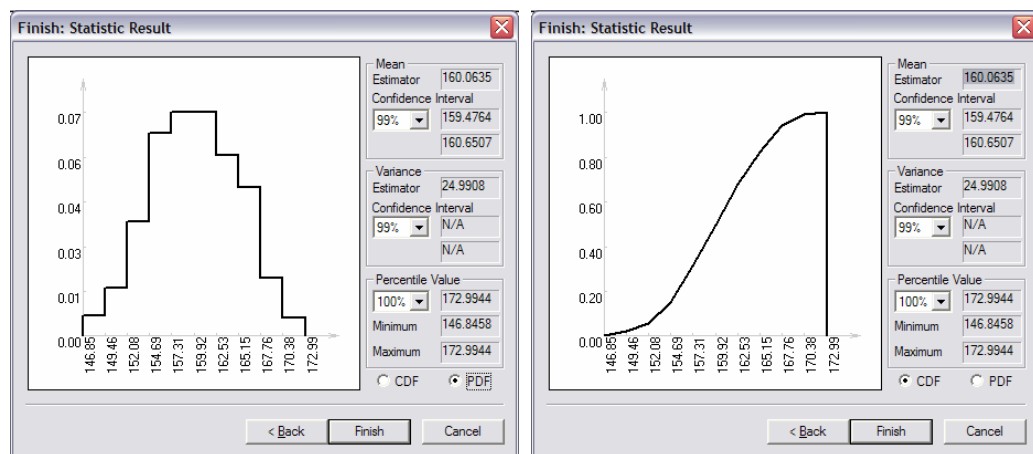


Figure 28. S3's statistic results: PDF and CDF graphs of base scenario

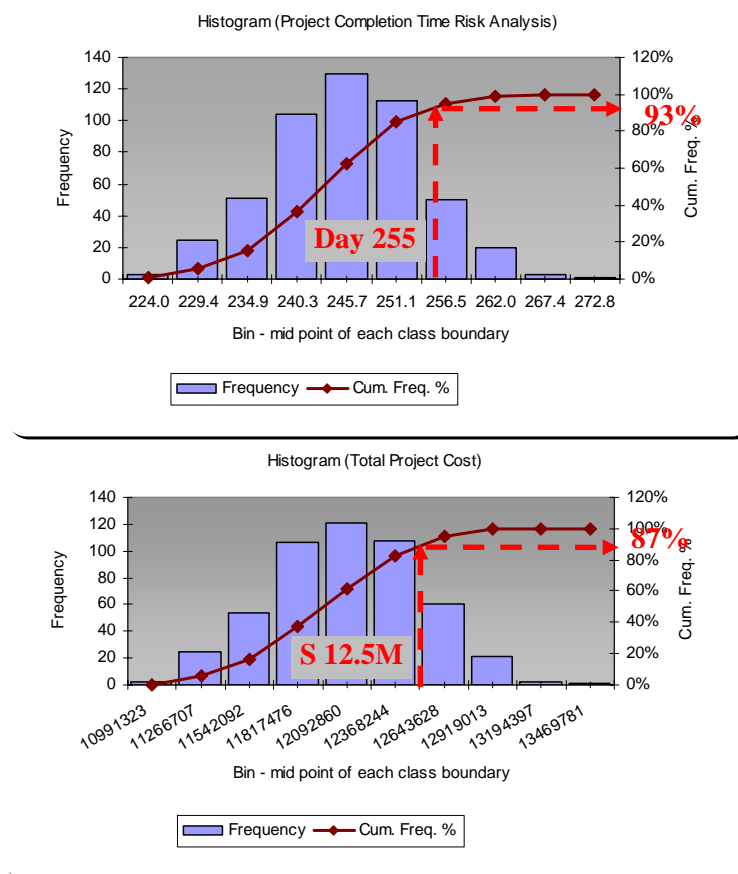


Figure 29. Histograms of project duration and cost in scenario 1

In addition to the arrangement of activity sequence, S3 can also help the project manager optimize the configuration of the resource size, aimed to utilize the limited amounts of resources while accelerating construction progress. Given specific ranges of resource limits, the optimization process would experiment with various resource combinations in an attempt to improve the fitness measure of the simulation model. With consideration of the cost and availability constraints of resources the quantities of all resources were set to be bounded for the optimization (Table 24). Based on the original cases of Scenarios 1 and 2, the project will be rescheduled so that a limited number of resources can be efficiently utilized while minimizing the unavoidable extension of project duration.

When the system reached the optimum state in regard to project duration minimization, a new combination of resources available was determined to attain the short construction

period – 160.56 days on average (-31%). The details (i.e. resource limits, project time and total cost) of this new scenario are listed in Table 24, and compared with the previous scenarios. Similar to the scenario 1, the duration of scenario 2 also could be reduced from 294d in the original case to 208d (-29%) through the resource provision optimization. Upon assessing these different scenarios, project planners can adopt the best strategy to their own advantage.

Table 24. S3 resource optimization results of stage 4 case

Simulation-optimization statistical results		Scenario 1: With resource limits		Scenario 2: With resource limits & interruptions	
		<i>Original</i>	<i>Optimization</i>	<i>Original</i>	<i>Optimization</i>
Resource	Bar benders & fixers [2~8]	4	4	4	4
	[range] Backhoes with excavator [4~8]	4	5	4	4
	Crawler mounted cranes [1~6]	3	3	3	3
	Carpenters (formwork) [1~4]	2	2	2	1
	Concreting laborers [3~10]	5	6	5	6
	Drainlayer [1~2]	1	1	1	1
	Skilled laborers [8~16]	8	15	8	16
	Rollers [4~8]	4	6	4	4
Duration (d)	<i>Minimum – maximum</i>	221.31 – 275.5	147.64 – 176.10	267.91 – 317.39	190.25 – 233.54
	<i>Mean</i>	245.47	160.56	294.21	208.31
	<i>Standard deviation</i>	8.18	5.00	9.58	7.37
	<i>95% confidence interval</i>	244.75 – 246.19	160.12 – 161.00	293.37 – 295.05	207.66 – 208.95
Cost (\$)	<i>Minimum – maximum</i>	10.85M – 13.61M	8.13M – 9.68M	13.21M – 15.72M	9.83M – 12.36M
	<i>Mean</i>	12,088,463	8,900,003	14,513,685	10,850,481
	<i>Standard deviation</i>	414,276	283,476	494,283	413,898
	<i>95% confidence interval</i>	12.052M – 12.125M	8.875M – 8.925M	14.470M – 14.557M	10.814M – 10.887M

6.7 Chapter Summary

We developed a framework for scheduling construction working plan based on schedule data and information available at the planning stage. It employs a schedule model and various analytical techniques, such as CPM, PERT, what-if scenario analysis, project time/cost minimization to determine the float values of each project activity. Along with a practical case study, we demonstrated how to conduct different phases of project scheduling based on different level of detail in the data available. Developing a project network model

under uncertainty would be beneficial to project managers in the forecast of a more realistic total project duration and cost.

In addition, we use the latest evolutionary optimization algorithms (PSO) to optimize the schedule in terms of attaining the shortest project duration or the least project cost, integrated with TF analysis. Through the *S3* simulation-optimization analysis, project managers can get a near-optimal resource-constrained scheduling solution, project duration and cost estimation, and the corresponding resource-activity float times. Given input data on activity-time uncertainties available, the optimization of the project system leads to the identification of implicit risks in project time or cost, activity criticality, along with the best resource configuration and activity priority.

CHAPTER 7

CONCLUSION

7.1 Findings and Conclusion

In the construction industry, the classic Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT) have been widely applied on the modern project scheduling management system since 1950s. Nonetheless, the current industry practices for scheduling construction projects still largely rely on managerial experiences and heuristic methods. It is essential to develop an effective, straightforward modeling and optimization approach for addressing limited resource allocation and complication due to activity-interruption constraints and activity-time uncertainties encountered in practical construction planning.

To address the practical needs as identified, a computer-based simulation tool has been developed in house for modeling and optimizing resource scheduling. We use the latest simulation and evolutionary optimization algorithms to optimize the project scheduling in terms of attaining the shortest project duration or the least project cost, integrated with total float analysis. This has resulted in the development of in-house software called the *Simplified Simulation-based Scheduling* (short as *S3*) system.

With the development of *S3*, our research has elucidated on some critical issues of resource-constrained scheduling in the application domain of construction project management. The findings provide useful input for users of project scheduling software to improve the scheduling tools as well as the accuracy of the resulting schedules. In developing *S3*, we have contrasted and evaluated *Primavera Project Planner (P3)*'s

functionality for critical path method scheduling under resource limit and calendar constraints based on an activity-on-node (AON) network with straightforward finish-to-start logic linking activities. We resorted to a case study to illustrate the limitations of *P3* along with the application of *S3*. *P3*'s limitations are identified in terms of giving faulty total float determination since the conventional total float (TF) analysis technique would fail on a CPM network schedule incorporating resource constraints and activity interruptions. Further, a new TF determination algorithm is developed for checking the validity of TF and deriving the accurate TF for those activities whose TF are overstated by *P3*. The new simulation-based approach for determining the TF entails observing the effect of extending the duration of each activity on the total project duration, which is proved to be straightforward and valid, and hence encoded into *S3*.

In this research, *S3* employs a schedule model to integrate various analytical techniques, such as CPM, PERT, what-if scenario analysis, project duration/cost minimization. It augments the predictability of total project duration and cost. A complete framework for resource-constrained CPM/PERT analysis has been proposed and implemented on a textbook example and a real construction project, ranging from (1) assessing the “criticality” of activities and resources under resource-availability and activity-interruption constraints, (2) running Monte Carlo simulations to conduct project scheduling analysis subject to the resource availability and calendar constraints, (3) performing float determination and resource-activity criticality analysis, to (4) using Particle Swarm Optimization (PSO) to optimize the activity execution sequence, the resource limits, and the resource use priority in finding the shortest time or least cost of a CPM/PERT schedule.

The power and simplicity of the proposed approach and its automated performance will facilitate its utilization by project managers in construction project planning. This new solution to CPM/PERT network analysis can provide project management with a convenient

tool to assess alternative scenarios based on computer simulations. Moreover, it provides the optimum configuration of resource provisions and the cost scheduling strategies.

Along with a practical case study, we demonstrated how to conduct different phases of project scheduling based on different level of detail in input data available. It is noted that *S3* would be a good simulation tool choice for various phases of construction project management. Dissimilar to other existing simulation tools, *S3* does not require the familiarity by the user with any software-specific terminology and modeling schematics to simulate the construction project systems. Through the *S3*'s simulation-optimization analysis, project managers can get an optimal or near-optimal resource-constrained scheduling solution, and determine project duration and total cost and the corresponding resource-activity float times.

7.2 Further Studies

So far, *S3* is limited to straightforward activity-on-node (AON) networks with finish-to-start logic relationships. Even though we advise to apply CPM/PERT analysis with resource constraints in AON instead of Precedence Diagram Method (PDM) format, there are still many cases that entail the use of additional logical relationships and negative lag times. In our ongoing work of making our approach more generic, we are developing the formalized methods for automatically preprocessing these “smart relationships” for *S3* analysis.

Moreover, we focused on the two resource optimization measures (project duration and cost minimization) in this research. More attentions will be drawn on the multi-objectives such as combining resource leveling, resource allocation and time/cost tradeoff. In the ongoing research, we will further assess the generality, feasibility and potential of the proposed

optimization procedures on stochastic simulation systems in tackling other combinatorial optimization problems (i.e. construction methods, material logistics planning and production operation, etc.).

In addition, being user-friendly is an important task for developing computer software. Since most construction practitioners are already used to the commercially available software packages, the applicability of *S3* system will be enhanced if the system is linked to commercial packages such as *P3* or allows data transfer from the existing scheduling software.

Since multiple parties would be involved in each construction project, the project scheduling plan system for communication, data transfer and information sharing is vital to its successful deployment and implementation. In particular, web-based technology should be considered to provide seamless integration and communication regardless of differences in hardware and location.

APPENDIX A – S3 User Guide

Simplified Simulation-based Scheduling

S3 @ SDESA

USER’S GUIDE



Construction Engineering and Management

Department of Civil & Structural Engineering

The Hong Kong Polytechnic University

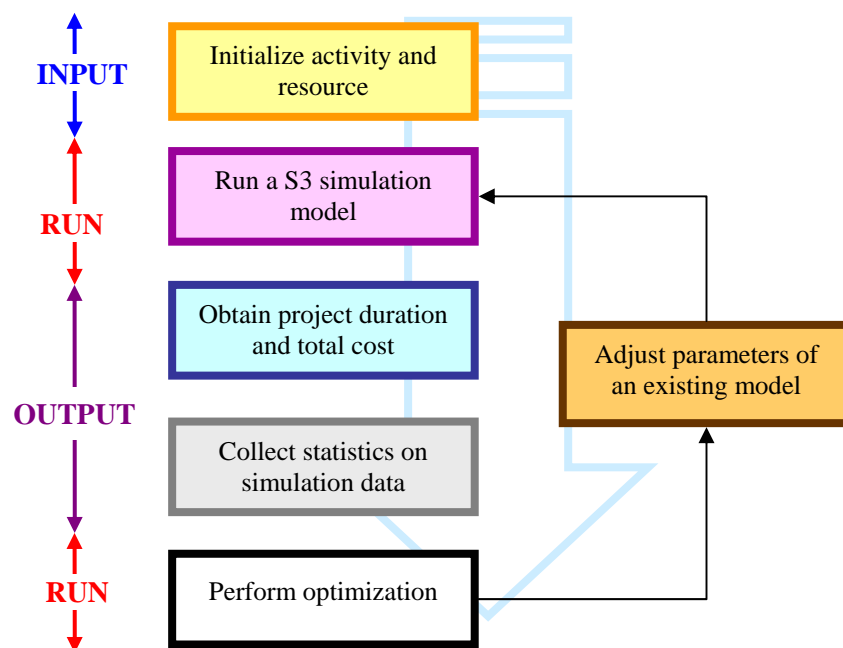
November, 2006

1. Introduction

To assist in construction project planning and resource scheduling, the simulation tool of *Simplified Simulation-based Scheduling* (short for *S3*) is developed within the SDESA platform (Simplified Discrete Event Simulation Approach) allowing for modeling, simulation analysis, and optimization of the project scheduling plan. Note that a Particle Swarm Optimization (PSO) based optimizer underlies the S3 to automatically find the best resource provisions so as to achieve the optimization goal of the shortest project duration or the least project cost.

1.1 About the User's Guide

This user guide explains how to use the S3 Project Detail Manager and the S3 platform for (1) initializing a project scheduling plan and specifying activity details, (2) generating and executing a S3 network model, (3) collecting and analyzing simulation results, and (4) searching the optimum solution based on a simulation model. The following flow chart maps out the procedures of applying S3.



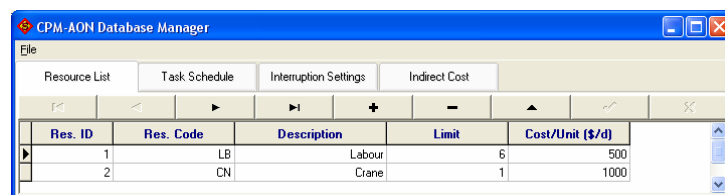
2. Input S3 Project Details

Before executing the *S3* model analysis, general settings such as activity details, resource information, and cost data should be defined firstly. The tool of “*CPM Database Manager*” provides the user with an easy-to-use interface for inputting the general project details. An input screen is designed for user to specify the details of activities and resource requirements as well as the resource availability and interruption constraints.

To start this tool, click Start, Programs, SDESA, and then select CPM DB Manager. The menu provides three functions related to *S3* database, namely, building a new model, opening a user-specified model and closing the currently opened model. Files in the “*CPM Database Manager*” format use the MDB extension. This chapter will introduce you to the menus and options you will use to key in your data and organize your scheduling plan.

2.1 Initialize Resource Details

As shown in the figure below, the tab pages available are “*Resource List*”, “*Task Schedule*”, “*Interruption Settings*” and “*Indirect Cost*”. The first step is to define the resource details by selecting *Resource List* page. Manpower, equipment and space blocks could also be tracked as a resource. To add a new resource, click the “plus” button or click the blank space adjacent to the field descriptions. The *Resource* window has four input areas: *Resource Code*, *Description*, *Limit* and *Cost*. This allows the user to specify the details (i.e. name, available quantity & daily cost) of a specific resource for a given time period.



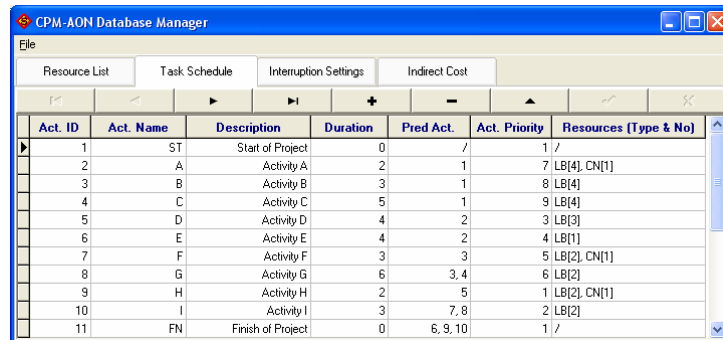
Res. ID	Res. Code	Description	Limit	Cost/Unit (\$/d)
1	LB	Labour	6	500
2	CN	Crane	1	1000

Above the *Resource List* table is a navigation bar for easily handling the input record table. There are nine buttons on the navigation bar from the left to right, which are “First record”, “Prior record”, “Next record”, “Last record”, “Insert record”, “Delete record”, “Edit record”, “Post edit”, and “Cancel edit”.

2.2 Initialize Activity Details

The second step is to define the activity details by selecting *Task Schedule* tab. To add a new activity, click the plus button or click the blank space adjacent to the field descriptions. *S3* automatically

assigns a unique ID to each activity you add. The Task window has six input areas: *Activity Name*, *Description*, *Duration*, *Preceding Activity*, *Activity Priority* and *Resource Required*. This allows the user to specify the details (i.e. description, duration, preceding activities & resource quantity) of a specific activity.

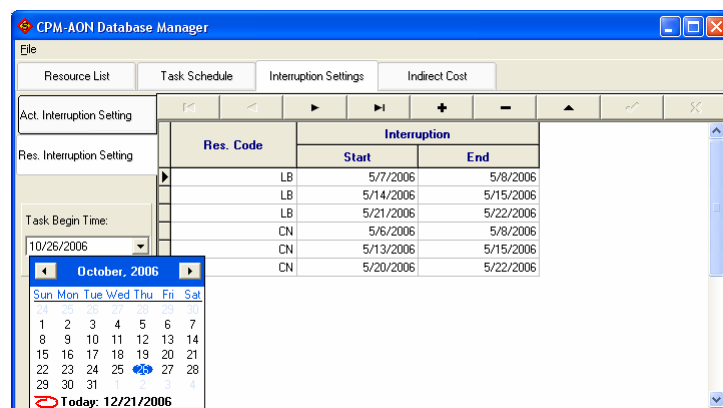


Act. ID	Act. Name	Description	Duration	Pred Act.	Act. Priority	Resources (Type & No)
1	ST	Start of Project	0	/	1	/
2	A	Activity A	2	1	7	LB[4], CN[1]
3	B	Activity B	3	1	8	LB[4]
4	C	Activity C	5	1	9	LB[4]
5	D	Activity D	4	2	3	LB[3]
6	E	Activity E	4	2	4	LB[1]
7	F	Activity F	3	3	5	LB[2], CN[1]
8	G	Activity G	6	3, 4	6	LB[2]
9	H	Activity H	2	5	1	LB[2], CN[1]
10	I	Activity I	3	7, 8	2	LB[2]
11	FN	Finish of Project	0	6, 9, 10	1	/

The priority is relative index to indicate the importance of activities as regarded by the project manager. When there is more than one activity requesting for one resource, S3 always allocates the resource to the one with the highest priority. The default priority value is 1, and a larger number stands for a higher priority. And if multiple activities have the same priority, the resource will serve the one with smallest activity ID first.

2.3 Define Interruptions to Activity & Resource (Activity/Resource Calendars)

Switching to the Interruption Settings tab gives the input settings of activity/resource interruptions. S3 allows user to add any regular interruptions (i.e. labour holiday, equipment maintenance period, etc.) into the model. Prior to entering the interruption, the user should set the project start date by using the calendar input interface. During the interruption period, the selected activity stops and every resource involved remains idle until the end of the interruption. Note the S3 algorithm automatically handles the overlapping of multiple activity or resource interruptions.



Interruption		Start	End
Res. Code			
LB		5/7/2006	5/8/2006
LB		5/14/2006	5/15/2006
LB		5/21/2006	5/22/2006
CN		5/6/2006	5/8/2006
CN		5/13/2006	5/15/2006
CN		5/20/2006	5/22/2006

Task Begin Time: 10/26/2006

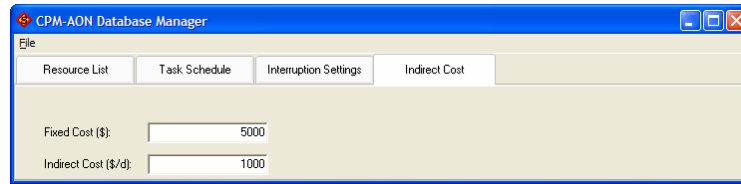
October, 2006

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

Today: 12/21/2006

2.4 Initialize Cost Details

The final step is to define the project cost details by selecting *Indirect Cost* tab. The Tab window has two input areas. This allows the user to specify the cost details (i.e. initial fixed indirect cost and daily indirect cost) of a specific project.



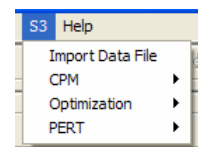
Upon confirming all the details of project scheduling, pressing the Close menu will automatically export the project details into a Microsoft Access file with an extension name of MDB. Then, it is ready to create a S3 simulation model. To close and exit the program, user can click the “X” button at the top-right corner of the window or select Exit menu.

3. Generate S3 Model

After creating the S3 data file by running through related modules (i.e. activity details, resource information and cost data) and saving into a MS Access file, the user can input the data file to S3 within the SDESA simulation platform. To start S3, click Start, Programs, SDESA, and then select SDESA. This chapter will outline the process of running a S3 simulation model.

3.1 S3 Menu

The S3 drop down menu located on the menu bar contains options for importing data, executing Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT) analysis, and carrying out the optimization.



Each of the selections available on the S3 menu is explained below.

Import Data File Select and import MS Access data file previously created in CPM Database Manager.

CPM Allow the user to carry out deterministic CPM analysis (i.e. single-run simulation, float analysis, cost and resource summary) for the current model.

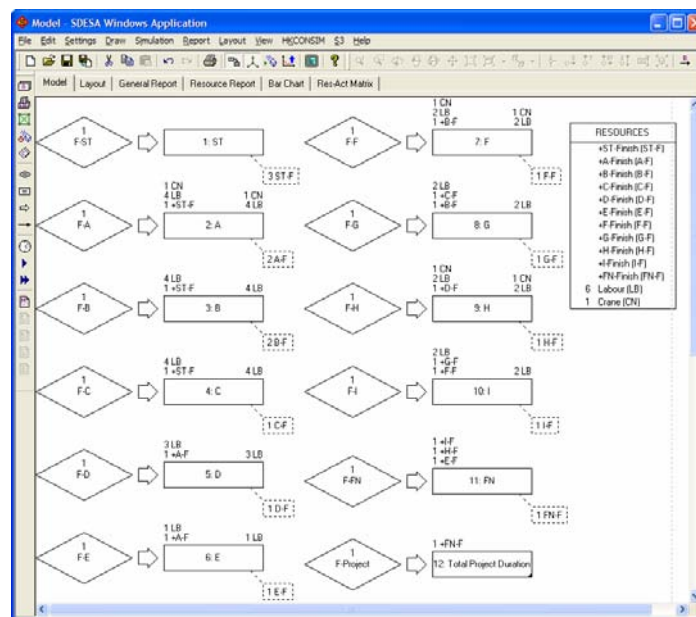
Optimization Define the PSO optimization settings and perform the optimization for the

current model.

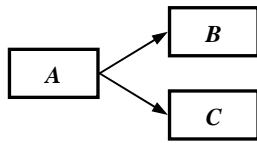
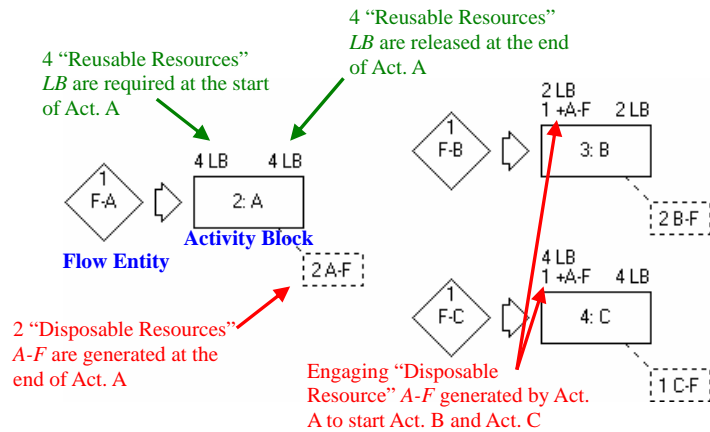
PERT Allow the user to carry out stochastic PERT analysis (i.e. multiple-run simulation, duration/cost summary and optimization) for the current model.

3.2 Convert Data File to a S3 Model

The S3 data file about project information can be loaded directly from any existing MDB file in SDESA platform by selecting *Import Data File* from S3 menu. Upon confirming the database file entry, pressing the “Open” button will automatically generate the S3 simulation model. A resource pool (a rectangle block holding corresponding input data) will be shown on the right hand side of the screen in S3 model.



According to the input details of activity-on-node (AON) network, the simulation model will be created in SDESA computer platform as follows. Firstly, each activity in the AON network is represented with one *Flow Entity* linked with one *Activity Block*, ensuring each activity is executed once only. Secondly, the *Disposable Resource Entity* in SDESA substitutes for the arrows in the AON, as shown in the following figure as a information unit to enforce the precedence relationship in AON. An activity generates *Disposable Resource Entities* (marked on the bottom right corner of the activity rectangle), which are requested to initiate its successors. When all its preceding activities are finished, as a result, all the required *Disposable Resource Entities* become available to trigger the start of the current activity (marked on the top left corner of the activity rectangle). Thirdly, we can specify the resource requirements in each activity. The *Reusable Resource Entities* requested by each activity, such as manpower and equipment, are also marked on the top left corner of the activity rectangle, while the *Reusable Resource Entities* to be released at the end of the activity are marked on the top right corner.

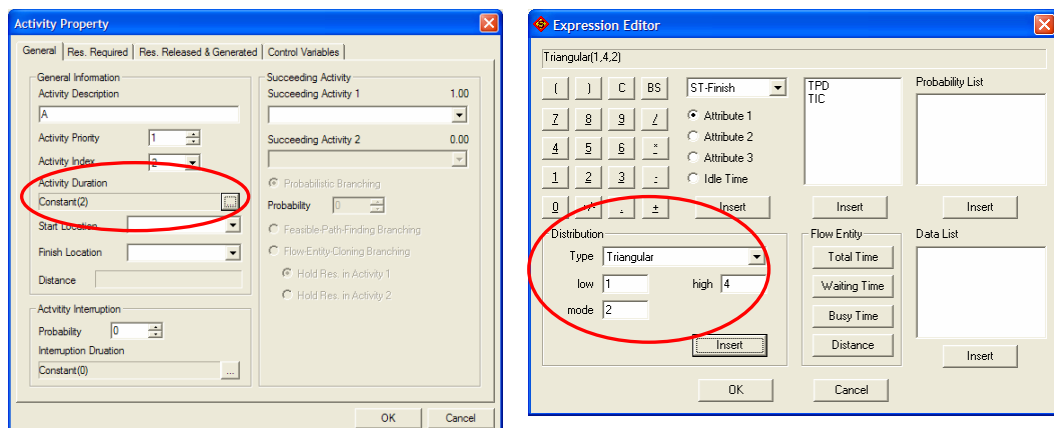
a) **AON Diagram**b) **S3 Model Diagram**

S3 will automatically convert the database file into a SDESA simulation model; however, the *Flow Entity* and *Activity Block* are often compactly placed and maybe difficult to read. Even with this poor activity placement, the user can reposition the activities by using the mouse to pick up and actually move an activity to a new location on the window page.

One and only one Start node is allowed in the network, which earmarks the milestone of the total project start. User specifies the project start time, the default value of which is 0. One and only one End activity is allowed in the network, which earmarks the milestone of the total project completion time.

3.3 Modify Activity Duration of the Current S3 Model

By using CPM-AON Database Management, all activity durations are defined in constant values for deterministic analysis. If the users want to carry out PERT analysis, it is suggested to modify the activity duration of the current S3 model. In order to edit the attributes of the activity, double-click the corresponding *Activity Block* to access the Activity Properties entry box. Change the Activity Duration to any probability distributions using the Expression Editor. In the Expression Editor, user is allowed to select different distribution type in a list box and key in the parameters.



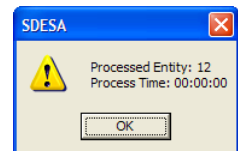
4. Start S3 Simulation

The S3 tool provides user with two options to control the simulation (i.e. deterministic CPM analysis and stochastic PERT analysis) for different requirements.

4.1 CPM Analysis

4.1.1 Start Single-Run Simulation

S3 allows user to run a single simulation run in order to produce the utilization rates and work schedules for the corresponding resources. When a model has been well setup, user can start the dynamic simulation model experiment by clicking S3> CPM> Start Simulation. After the single-run simulation is complete, there will be a message box popping up, showing the number of Process Entity processed and the total analysis time taken.

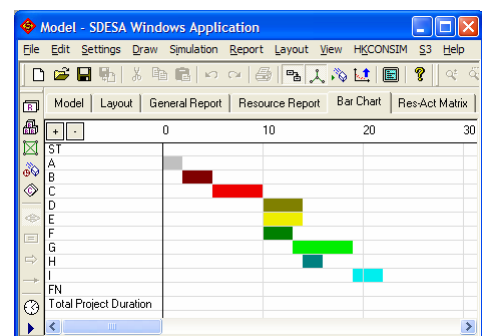


4.1.2 Collect Simulation Results

Report Output in S3 includes the summary report of the model, and the detailed figures of model processing data for both activity and resource.

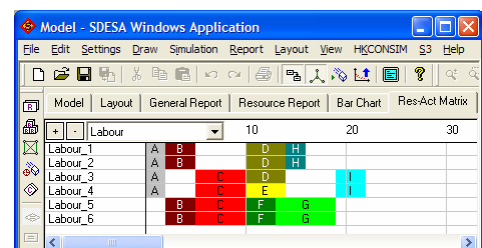
Early Schedule Bar Chart

Bar charts are relatively easy to read, and frequently used in project management presentation. Switching to the “Bar Chart” tab in SDESA gives the project schedule in the Gantt chart format. It shows the working sequence and early start/finish times of each activity, as well as the project completion time.



Resource Bar Chart

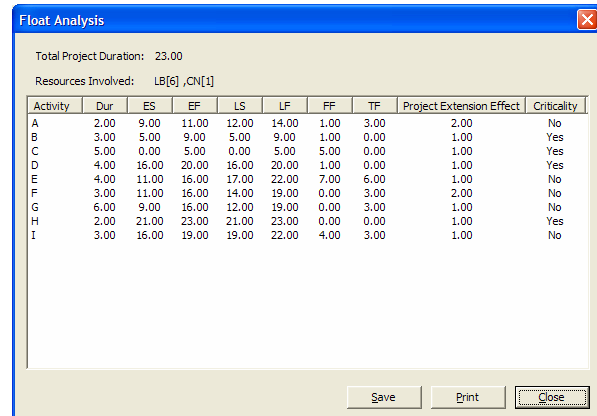
Switching to the “Res-Act Matrix” tab in SDESA gives the resource-activity interaction matrix in a color scheme that is consistent with the previous bar chart. Individual resources with specific name/ID are listed in the left hand side column.



For deterministic analysis, S3 also specially develops three main analysis reports including float analysis, resource summary and cost summary. The data in these reports can be saved in a text file for backup or further reporting.

Float Analysis

Through the Float Analysis, user can obtain total project duration and scheduling details of each activity. To start float analysis, select S3, CPM, and then Float Analysis. The activity times (Early Start, Early Finish, Late Start, Late Finish, Free Float and Total Float) are displayed to user for each activity. In addition, S3 explicitly defines the project extension effect which is the magnitude of extending the total project duration due to delaying the completion of an activity by one day beyond its late finish time (LF). This effect is also summarized in the Float Analysis result table.



Float Analysis

Total Project Duration: 23.00

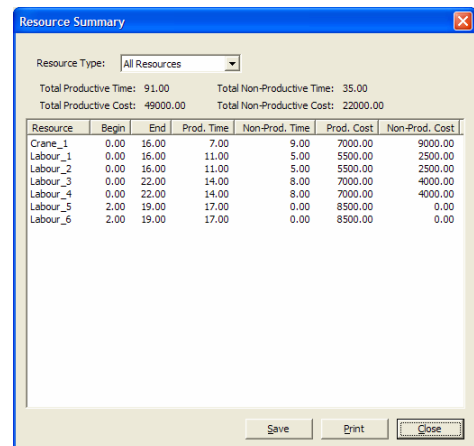
Resources Involved: LB[6], CN[1]

Activity	Dur	ES	EF	LS	LF	FF	TF	Project Extension Effect	Criticality
A	2.00	9.00	11.00	12.00	14.00	1.00	3.00	2.00	No
B	3.00	5.00	9.00	5.00	9.00	1.00	0.00	1.00	Yes
C	5.00	0.00	5.00	0.00	5.00	5.00	0.00	1.00	Yes
D	4.00	16.00	20.00	16.00	20.00	1.00	0.00	1.00	Yes
E	4.00	11.00	16.00	17.00	22.00	7.00	6.00	1.00	No
F	3.00	11.00	16.00	14.00	19.00	0.00	3.00	2.00	No
G	6.00	9.00	16.00	12.00	19.00	0.00	3.00	1.00	No
H	2.00	21.00	23.00	21.00	23.00	0.00	0.00	1.00	Yes
I	3.00	16.00	19.00	19.00	22.00	4.00	3.00	1.00	No

Save Print Close

Resource Summary

Resource Summary includes the details of all reusable resources. To review the Resource Summary, click S3>CPM> Resource Summary in the top menu. User can obtain overall productive time/cost and non-productive time/cost for the whole resource group as well as on individual resource. For each individual resource, the working start time and end time are also determined.



Resource Summary

Resource Type: All Resources

Total Productive Time: 91.00 Total Non-Productive Time: 35.00

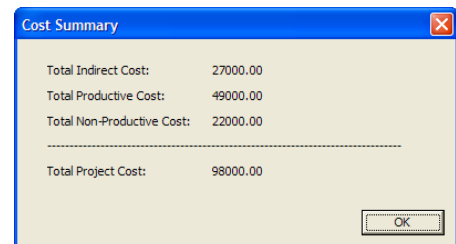
Total Productive Cost: 49000.00 Total Non-Productive Cost: 22000.00

Resource	Begin	End	Prod. Time	Non-Prod. Time	Prod. Cost	Non-Prod. Cost
Crane_1	0.00	16.00	7.00	9.00	7000.00	9000.00
Labour_1	0.00	16.00	11.00	5.00	5500.00	2500.00
Labour_2	0.00	16.00	11.00	5.00	5500.00	2500.00
Labour_3	0.00	22.00	14.00	8.00	7000.00	4000.00
Labour_4	0.00	22.00	14.00	8.00	7000.00	4000.00
Labour_5	2.00	19.00	17.00	0.00	8500.00	0.00
Labour_6	2.00	19.00	17.00	0.00	8500.00	0.00

Save Print Close

Cost Summary

Cost Summary includes total indirect cost, total productive/non-productive resource cost and total project cost.



Cost Summary

Total Indirect Cost: 27000.00

Total Productive Cost: 49000.00

Total Non-Productive Cost: 22000.00

Total Project Cost: 98000.00

OK

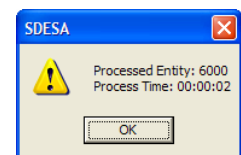
4.2 PERT Analysis

Under most circumstances, simulation modeling is “stochastic” as most activity times are defined by a range of probability distributions rather than a point value. As the duration of activities in the simulation model is usually defined with probability distributions, a large number of simulation runs can reveal the true properties of a simulation output, preventing any biased result due to inadequate statistical sampling. It is, therefore, suggested to carry out multiple-run PERT simulation in S3 analysis.

4.2.1 Start Multiple-Run Simulation

To initiate the multiple simulation runs, select S3>PERT>Simulation>Start Multi-Runs. S3 allows user to define the number of runs and select the relevant statistic results. By default, all activities and resources are ticked. In addition, the function of random seed setting allows user to redo the experiment and obtain the same set of output data by choosing the same random seed.

Complete the settings on the dialog box and press OK to start the simulation process. Similar to the single run, a message box that summarizes the number of entities processed and the total processing time will pop up automatically, once the multiple simulation runs is completed.




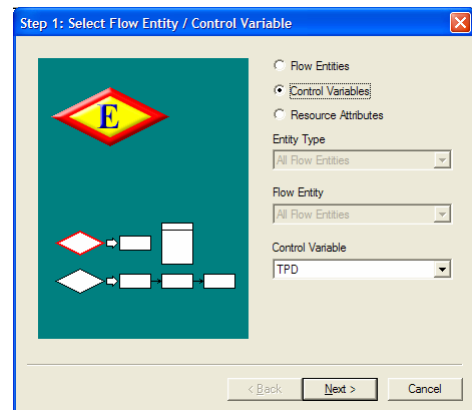
4.2.2 Collect Simulation Results

Similar to CPM analysis, Report Output in S3 includes the summary report of the model, the detailed figures of model processing data for both activity and resource, and the associated statistics which help making decision in project planning. User also can obtain the early schedule bar chart and resource bar chart for each simulation run. For stochastic analysis, S3 also develops three main output reports including the histograms of the total project duration, the simulation output data of project duration and total cost, and the resource utilization data.

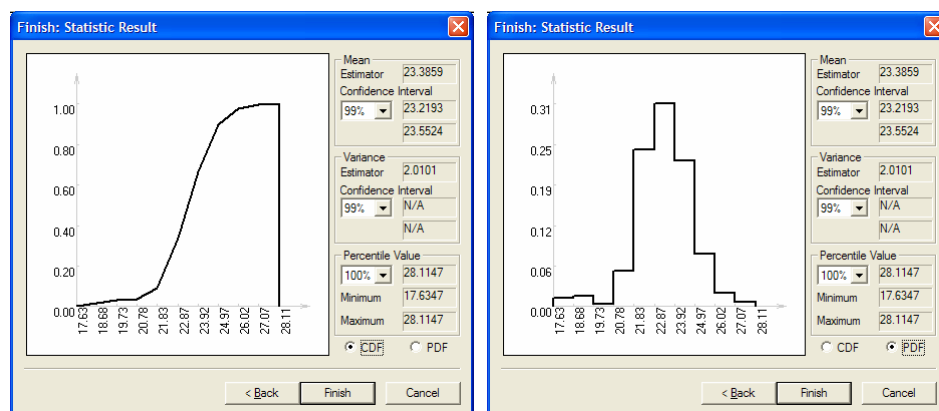
Total Project Duration (TPD)

Though multiple simulation runs, the total project duration (TPD) are recorded in each simulation for further analysis. The statistics of the project finish time are displayed in the “Statistic Result” page of the *Control Variable*, TPD. The selected statistical figures [Probability Distribution Function (PDF) diagram and Cumulative Distribution Function (CDF) diagram] are plotted by the following steps:

- 1) Press “” or select Report>Data Statistic in the top Menu bar
- 2) In the Selection dialog box, choose “Control Variables”
- 3) In the same dialog box, choose *TPD* in the “Control Variables” list
- 4) Press the “Next” button at the bottom.



To assist making better decisions, S3 provides user with the statistical descriptors such as mean, variance, minimum & maximum, and confidence interval.



Distribution of Project Duration and Total Cost

In addition, total project duration and the corresponding total project cost are recorded in each simulation for further analysis. Click S3> PERT> Duration/Cost Summary. The popup window displays total project duration and total project cost in each simulation run and in overall average.

Run	Total Project Duration	Total Project Cost
1	22.62	94891.27
2	21.11	89782.26
3	23.68	103910.65
4	21.56	94389.55
5	25.91	112082.78
6	22.22	93550.94
7	26.45	116120.58
8	22.79	98417.58
9	23.68	102970.90
10	18.05	81111.60
11	24.23	101761.93
12	21.94	93210.29
13	24.13	105280.15
14	24.09	106845.17

Average Total Project Duration: 23.39
Average Total Project Cost: 101944.84


Critical Index (CI) of Activity

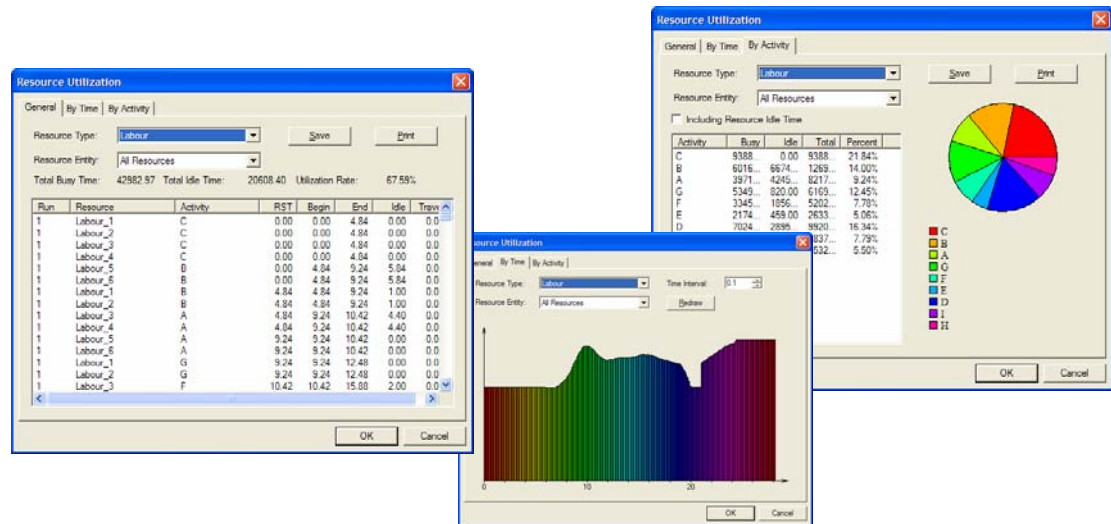
Through multiple simulation runs, the critical index (CI) of each activity is provided for further analysis. Click S3> PERT> Simulation> Critical Index. The popup window displays the critical index for each activity.

No.	Activity	C.I.
1	A	0.020
2	B	0.156
3	C	0.964
4	D	0.020
5	E	0.000
6	F	0.030
7	G	0.988
8	H	0.020
9	I	0.996

Resource Utilization

Switching to the “Resource Report” tab in SDESA gives a collection of simulation outputs on

resource utilization. It provides the time data of a resource being utilized in different activities. To be more convenient, this report also provides histogram and pie chart to show the resource occupation proportions. User can read the report by pressing  or Report>Resource Utilization. The report provides the time data (i.e. total busy time, total idle time and utilization rate) of each resource in different activities for reference.

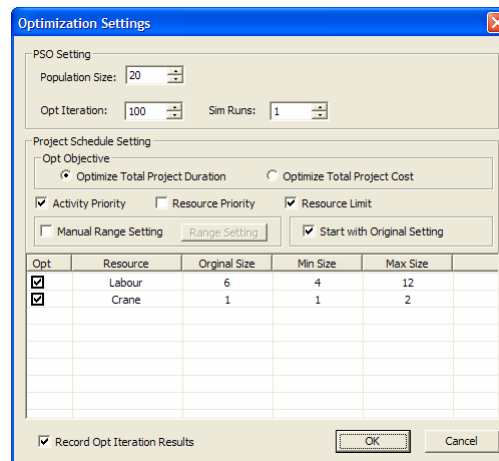


5. Start S3 Optimization

Typically, most people use simulation tools to predict and improve the system performances by modeling the actual operations. User can freely setup and try out different scenarios, but it is difficult to seek the optimal activity sequences or optimal combination of resource provisions, which leads to the optimal system performance. The S3's PSO-based optimization function provides user with two options (i.e. deterministic CPM analysis and stochastic PERT analysis) to improve the project performance.

In dealing with the deterministic S3 simulation models, there are two objective options for optimization analysis, namely, the “optimize total project duration” and “optimize total project cost”. By using the PSO technique to search for an optimum set of resources and activity priorities, we can optimize the project schedule in terms of attaining the shortest project duration (“resource allocation”) or the least project cost (“time/cost tradeoff”).

To use the optimizer, select S3> Optimization> Start Optimization. In “Optimization Settings” dialog box, user can have various options to setup the optimization constraints and the objective.



Optimization Settings

PSO Setting

Population Size: 20

Opt Iteration: 100 Sim Runs: 1

Project Schedule Setting

Opt Objective

☒ Optimize Total Project Duration ☐ Optimize Total Project Cost

☒ Activity Priority ☐ Resource Priority ☒ Resource Limit

☐ Manual Range Setting ☒ Start with Original Setting

Opt	Resource	Original Size	Min Size	Max Size
<input checked="" type="checkbox"/>	Labour	6	4	12
<input checked="" type="checkbox"/>	Crane	1	1	2

☒ Record Opt Iteration Results

PSO Parameters Setting

Population size, optimization iteration & simulation run : The number of particles that are stored in optimization process; the criteria for controlling the number of iterations to find the optimum result; and number of simulation runs in each iteration

Optimization Objectives

Optimize total project duration / Optimize total project cost : The objective function can be set to either minimize the total project duration (resource allocation) or minimize project cost (time/cost tradeoff)

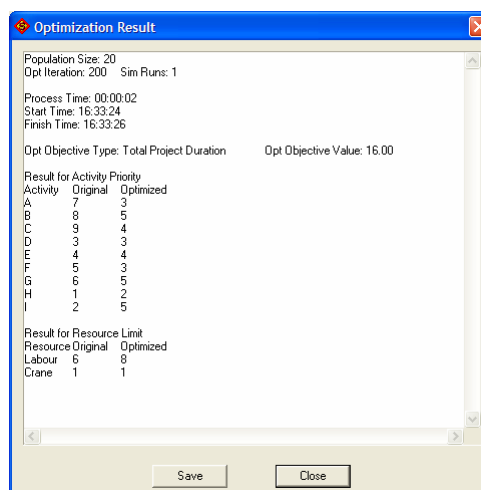
Optimization Variables

Activity priority : It is index to indicate the relative importance of activities when there is more than one activity requesting for one resource (the larger the number, the higher the priority for allocation)

Resource priority : It is index to indicate the relative importance of resource when there is more than one resource of the same type ready at the same time (the larger the number, the higher the priority for allocation)

Resource limit : User can set two boundary values for each resource group

Once the optimization process starts, the program will remain in running stat until an optimization result window will pop up at the end. The window shows the processing time, the optimal objective value, the optimal activity priority, and the optimal combinations of resources. The optimal scenario as identified is already stored in the current S3 model, so user can save this scenario as a new model file in SDS extension format.



Optimization Result

Population Size: 20
Opt Iteration: 200 Sim Runs: 1

Process Time: 00:00:02
Start Time: 16:33:24
Finish Time: 16:33:26

Opt Objective Type: Total Project Duration Opt Objective Value: 16.00

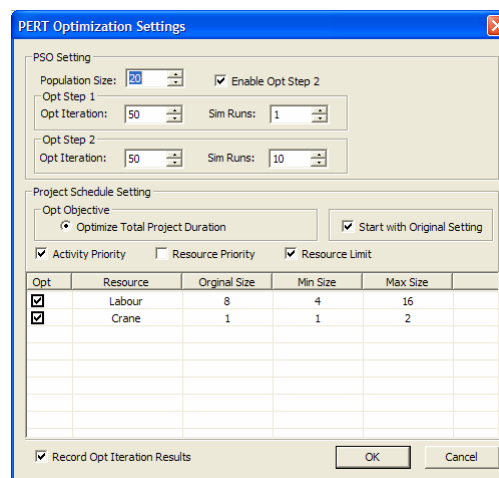
Result for Activity Priority

Activity	Original	Optimized
A	7	3
B	8	5
C	9	4
D	3	3
E	4	4
F	5	3
G	6	5
H	1	2
I	2	5

Result for Resource Limit

Resource	Original	Optimized
Labour	6	8
Crane	1	1

Another objective option is the “optimize total project duration” for dealing with the stochastic PERT simulation models. Similar to deterministic cases, we can optimize the project schedule in terms of attaining the shortest project duration (“resource allocation”) by using the PSO technique to search for an optimum set of resources and activity priority. Most settings are the same as these setting for deterministic case. The main difference is that the optimization process is divided into two steps (step 1 for initialization of optimization search; step 2 for fine-tuning). User can define different simulation runs and the number of iterations in two optimization steps. The user can use more simulation runs to avoid the simulation output distortion due to sampling errors, however, it requires much longer processing time. The default setting is a good compromise. In general, all default values are recommended.



The dialog box titled "PERT Optimization Settings" contains the following sections and controls:

- PSO Setting:**
 - Population Size: 20
 - Opt Step 1:
 - Opt Iteration: 50
 - Sim Runs: 1
 - Opt Step 2:
 - Opt Iteration: 50
 - Sim Runs: 10
 - ☒ Enable Opt Step 2
- Project Schedule Setting:**
 - Opt Objective: ☒ Optimize Total Project Duration
 - ☒ Start with Original Setting
 - ☒ Activity Priority ☐ Resource Priority ☒ Resource Limit
- Resource Allocation Table:**

Opt	Resource	Original Size	Min Size	Max Size
<input checked="" type="checkbox"/>	Labour	8	4	16
<input checked="" type="checkbox"/>	Crane	1	1	2
- ☒ Record Opt Iteration Results
- Buttons: OK, Cancel

Note that the processing time is highly dependent on the number of population size, the total number of activities and the computer power.

APPENDIX B – PSO Algorithm

Particle swarm optimization (PSO) was an algorithm proposed by Kennedy and Eberhart in 1995. This algorithm was inspired by the social behavior of bird flocking. PSO is a population-based iterative algorithm, and starts with a population of randomly generated solutions called particles. Each particle flies in the problem search space (analogous to the search process for food by a bird swarm) looking for the optimal position to land. The particles evolve over generations in approaching the optimum solution by the following rules:

Each particle is treated as a point in a D-dimension space, and the i^{th} particle is represented as $x_i = (x_{i1}, x_{i2}, \dots, x_{iD})$. Each particle has a fitness measure, which is the performance measure of a function or a system being optimized, and the velocity and position in the hyperspace of a particle are tracked. The particle's best position that corresponds with the minimum fitness measure achieved so far in the search process is denoted as p_{best} . Likewise, the best position of all particles in the population achieved so far is denoted as g_{best} .

Once the p_{best} and g_{best} are identified in current iteration, each particle updates its velocity and position by equations (1) and (2) prior to starting the next iteration. The velocity and position of a particle are two main properties defining its state.

$$v_{id}^{k+1} = v_{id}^k + c_1 \times r_1 \times (p_{id}^k - x_{id}^k) + c_2 \times r_2 \times (p_{gd}^k - x_{id}^k) \quad (1)$$

$$x_{id}^{k+1} = x_{id}^k + v_{id}^{k+1} \quad (2)$$

Where v is the particle's velocity, x is its position; p_{id} and p_{gd} are respectively p_{best} and g_{best} ; the superscript k denotes the k^{th} iteration, c_1 and c_2 are the cognitive parameter and the social parameter respectively, both of which are generally set as 2; r_1 and r_2 are random numbers uniformly distributed on the range (0, 1). The pseudo code of the basic PSO algorithm is in the Figure 1.

From one generation to the next, a particle keeps memory of its previous positions and updates itself by adjusting its internal velocity and position. Note what differentiates the global version from the local version of PSO – both are commonly applied – lies in the g_{best} part of Eq. (1) (Eberhart and Kennedy 1995). In the global version, particles move toward the stochastic average of p_{best} and g_{best} ; while in the local version, particles have information only of their own and their nearest neighbors' best, thus particles move toward the positions as guided by p_{best} and l_{best} . Note l_{best} represents the position of the particle with the best evaluation measure in the nearest neighborhood of the current particle. The following Eq. (3) gives the local version, where p_{id} is l_{best} .

$$v_{id}^{k+1} = v_{id}^k + c_1 \cdot r_1 \cdot (p_{id}^k - x_{id}^k) + c_2 \cdot r_2 \cdot (p_{id}^k - x_{id}^k) \quad (3)$$

Figure 1. Pesudocode for the PSO algorithm

```

For each particle {
  Initialize particle;
}
Do{
  For each particle {
    Calculate fitness value;
    If (fitness value < pbest){
      Update pbest;
    }
    If (pbest < gbest) Update gbest;
  }
  For each particle {
    Calculate particle velocity v according Eq. (1);
    If (v > Vmax) v = Vmax;
    Else if (v < -Vmax) v = -Vmax;
    Calculate particle position x according Eq. (2);
    If (x > Xmax) x = Xmax;
    Else if (x < -Xmax) x = -Xmax;
  }
} While maximum iterations or is not attained;

```

A parameter called the inertia weight w is introduced into PSO to balance the global and local search strategies. It can be a positive constant or a positive linear or nonlinear function of time. A large inertia weight facilitates the global search, while a small inertia weight on the local search. The modified equation is as follows:

$$v_{id}^{k+1} = w \cdot v_{id}^k + c_1 \cdot r_1 \cdot (p_{id}^k - x_{id}^k) + c_2 \cdot r_2 \cdot (p_{gd}^k - x_{id}^k) \quad (4)$$

Another parameter k called the constriction coefficient was introduced in (Clerc 1999) with the intention that it could guarantee a PSO to converge.

$$v_{id}^{k+1} = k \cdot [v_{id}^k + c_1 \cdot r_1 \cdot (p_{id}^k - x_{id}^k) + c_2 \cdot r_2 \cdot (p_{gd}^k - x_{id}^k)] \quad (5)$$

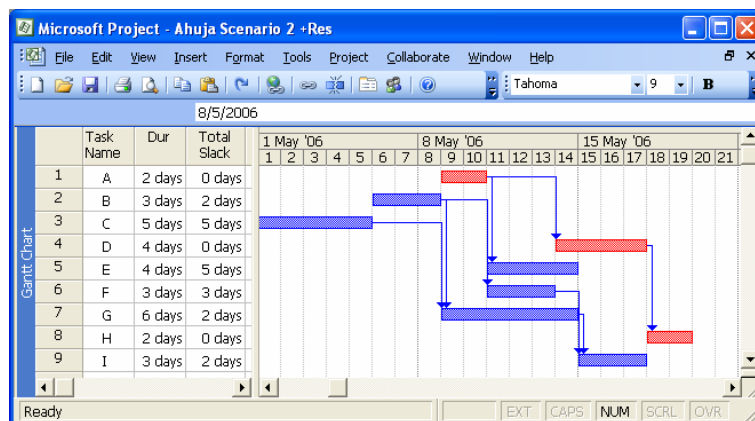
$$k = \frac{2}{\left| 2 - \varphi - \sqrt{\varphi^2 - 4\varphi} \right|}, \quad \varphi = c_1 + c_2 \quad \varphi > 4 \quad (6)$$

Suitable selection of the PSO parameters can provide a balance between the global and the local search. Based on the review of a related research (Lu et al. 2006), a fixed number of iterations (50) were executed, and the following PSO parameters used: the population size of 30; the inertia weight w from initial 0.9 down to 0.4 in the end; c_1 and c_2 are both set as 2. Both p_{best} and g_{best} are constantly updated over iterations in seeking the optimum. This process is repeated until user-defined stopping criteria are satisfied.

APPENDIX C – Scheduling Results Validation among MS Project, P3 and S3

In the research, comparison of the scheduling results between *P3* and *S3* was carried out. This case study shows that both tools generated identical total project duration but different total float values. The float values produced by *P3* and *S3* were cross-checked.

For the further study, we evaluated the scheduling performance of *Microsoft (MS) Project (Professional 2003)* in the same case study. Scenario 1 considers the constraints of a maximum of six laborers and one crane available on any given day. Note *MS Project* provides an option of automatic resource leveling. We checked the validity of total project duration and activity float times. The same results (i.e. activity sequence, total project duration) were obtained. The output screen of *MS Project* is given in the following figure.



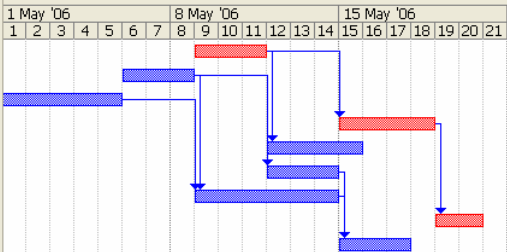
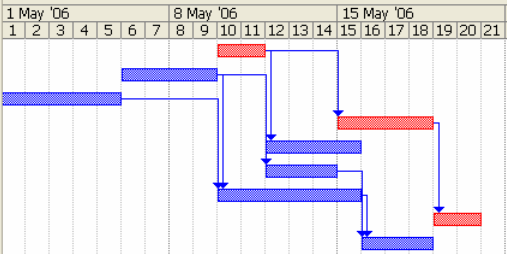
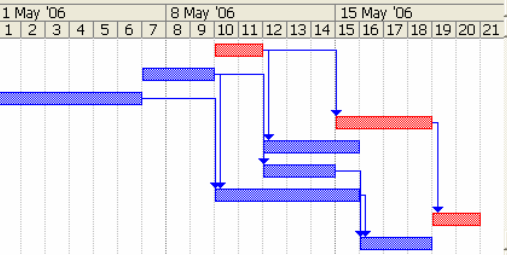
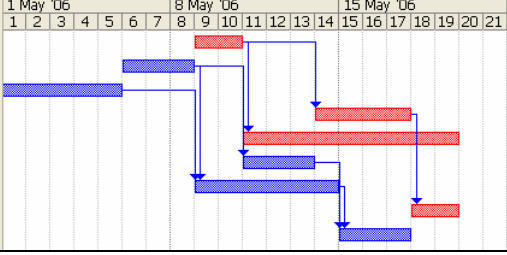
Accordingly, MS Project produces the different total float values compared with those from the *P3* and *S3* values in Table 3. As for our example scenario 1, the different TF values were produced by *P3*, *MS Project* and *S3* on Activities A, B, C and F, as contrasted in Table 3.

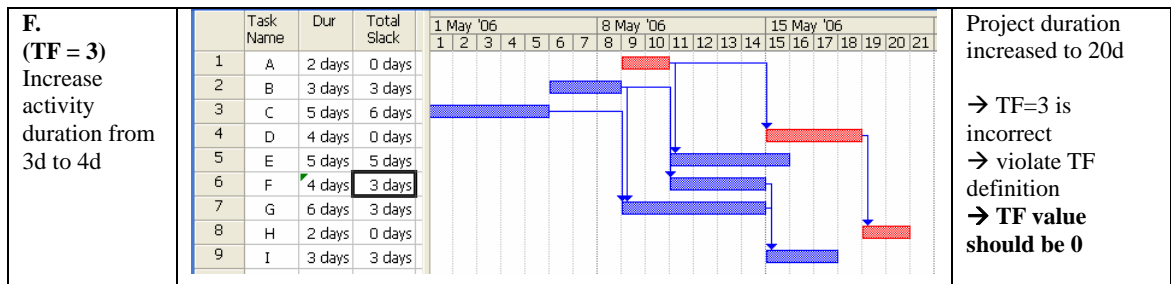
Table 25. Scheduling results comparison between *P3* and *S3* for Scenario 1

Activity	Duration (days)	Total Float			Priority
		<i>P3</i>	<i>MS Proj</i>	<i>S3</i>	
A	2	3	0	0	6
B	3	2	2	0	8
C	5	5	5	0	9
D	4	0	0	0	3
E	4	5	5	5	4
F	3	3	3	0	5
G	6	2	2	2	7
H	2	0	0	0	1
I	3	2	2	2	2
Total project duration		19	19	19	

The new total float (TF) determination algorithm being proposed for deriving accurate TF is implemented in *S3*. In this TF analysis method, it is not necessary to carry out any backward pass calculation. Instead, TF's interpretation in CPM provides the theoretical underpinning, namely: TF is the maximum amount of time that activity duration can increase without extending the total project duration.

For instance, TF of Activity B is decided as 2 days by *MS Project*. Suppose the duration of Activity B is increased by 1 day, which is less than TF available (2 days). But the total project duration ends up increasing from 19 days to 20 days. This has violated the TF definition. The iterative algorithm was carried out for each activity and found that *MS Project* generates overstated TF values for Activities B, C and F. The findings are summarized in the following table.

Activity	MS Project Output																				Remarks			
A. (TF = 0) Increase activity duration from 2d to 3d	Task Name	Dur	Total Slack																					
	1	A	3 days	0 days																				
	2	B	3 days	3 days																				
	3	C	5 days	6 days																				
	4	D	4 days	0 days																				
	5	E	4 days	5 days																				
	6	F	3 days	3 days																				
	7	G	6 days	3 days																				
	8	H	2 days	0 days																				
	9	I	3 days	3 days																				
B. (TF = 2) Increase activity duration from 3d to 4d	Task Name	Dur	Total Slack																					
	1	A	2 days	0 days																				
	2	B	4 days	2 days																				
	3	C	5 days	6 days																				
	4	D	4 days	0 days																				
	5	E	4 days	5 days																				
	6	F	3 days	3 days																				
	7	G	6 days	2 days																				
	8	H	2 days	0 days																				
	9	I	3 days	2 days																				
C. (TF = 5) Increase activity duration from 5d to 6d	Task Name	Dur	Total Slack																					
	1	A	2 days	0 days																				
	2	B	3 days	2 days																				
	3	C	6 days	5 days																				
	4	D	4 days	0 days																				
	5	E	4 days	5 days																				
	6	F	3 days	3 days																				
	7	G	6 days	2 days																				
	8	H	2 days	0 days																				
	9	I	3 days	2 days																				
E. (TF = 5) Increase activity duration from 4d to 9d	Task Name	Dur	Total Slack																					
	1	A	2 days	0 days																				
	2	B	3 days	2 days																				
	3	C	5 days	5 days																				
	4	D	4 days	0 days																				
	5	E	9 days	0 days																				
	6	F	3 days	3 days																				
	7	G	6 days	2 days																				
	8	H	2 days	0 days																				
	9	I	3 days	2 days																				

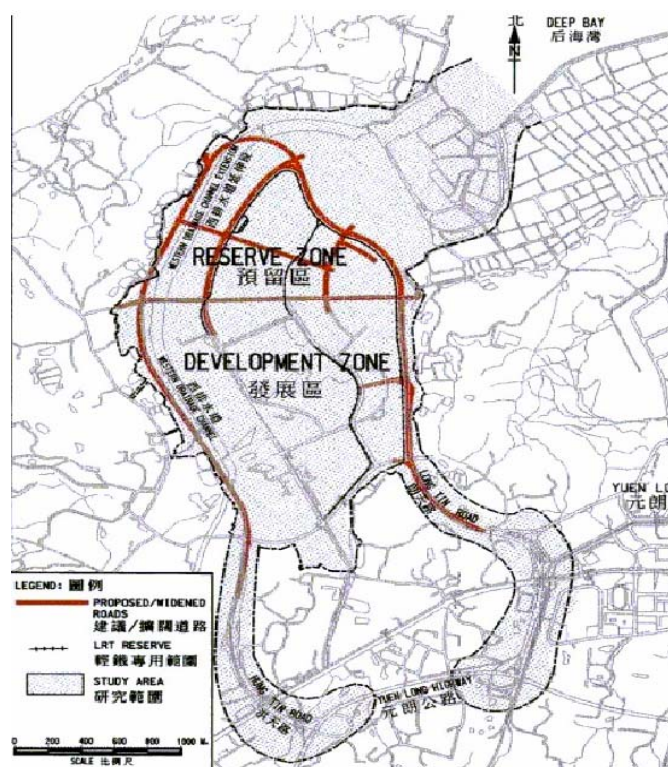


To conclude, *P3* and *MS Project* would –to a certain extent- overstate total float values in resource-constrained scheduling. According to the S3's total float analysis, the correct activity-resource criticality information can be obtained.

APPENDIX D – Project Details of Case Study

Project Background

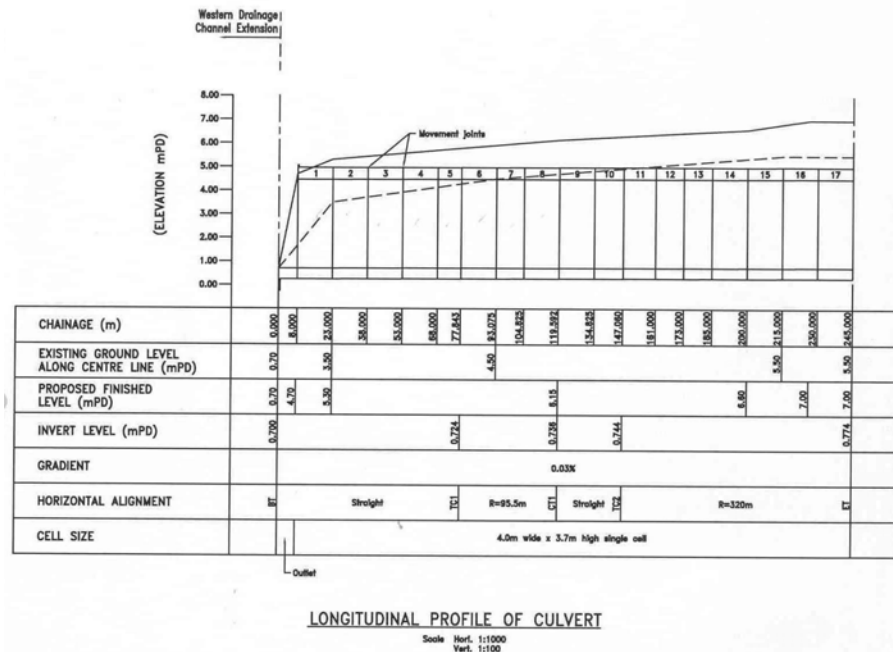
Tin Shui Wai Reserve Zone was identified by the Government in 1994 as a major area for residential development. The Reserve Zone area, located at the northern part of Tin Shui Wai Development Zone covered an area of 70 hectares. It was reclaimed from fishponds in early 90's and remained undeveloped. The key plan for Tin Shui Wai Reserve Zone is shown in the below figure.



The Reserve Zone would accommodate a population of 125,000 for both private and government developments. To cope with such population intake, engineering infrastructures such as roads, bridges, subways, drainage and sewerage facilities, utilities and landscaping were to be executed under three separate works contracts. The Contract No. is YL40/98 titled “Road D4 and Site Formation of Areas 112, 115 and 120” with a Contract sum of \$418 millions. The principal items of works for this Contract included construction of one vehicular bridge, two pedestrian footbridges, three subways, four drainage box culverts, site formation and road-and-drainage works.

Northern Culvert

A 250m long single-cell box culvert– namely– Northern Culvert was proposed to discharge runoff generated from the northwest part of the Reserve Zone to the existing Western Drainage Channel. The internal dimensions of the box culvert were 4000mm by 3650mm including the 400mm by 400mm corner splays. The following figure shows the longitudinal profile of the box culvert.



As depicted on the longitudinal profile, movement joints were provided at spacing not exceeding 15m and the whole box culvert was to be constructed in 17 bays. In view of the tight construction programme, the Contractor proposed to construct Bay 1 to Bay 8 and Bay 9 to Bay 17 of the box culvert in parallel, one work front working downstream from Bay 8 to Bay 1 and the other work front working upstream from Bay 9 to Bay 17.

The marine mud layer below the foundation level was replaced by a layer of 400mm thick compacted rock fill materials. In addition, it was revealed from the additional borehole records that the thickness of marine mud layer underneath Bay 1 to Bay 8 was 2m thicker than was expected. Therefore, excavation for an additional 2m thick marine mud layer and subsequent deposition of rock fill materials was also included in the construction of Bay 1 to Bay 8.

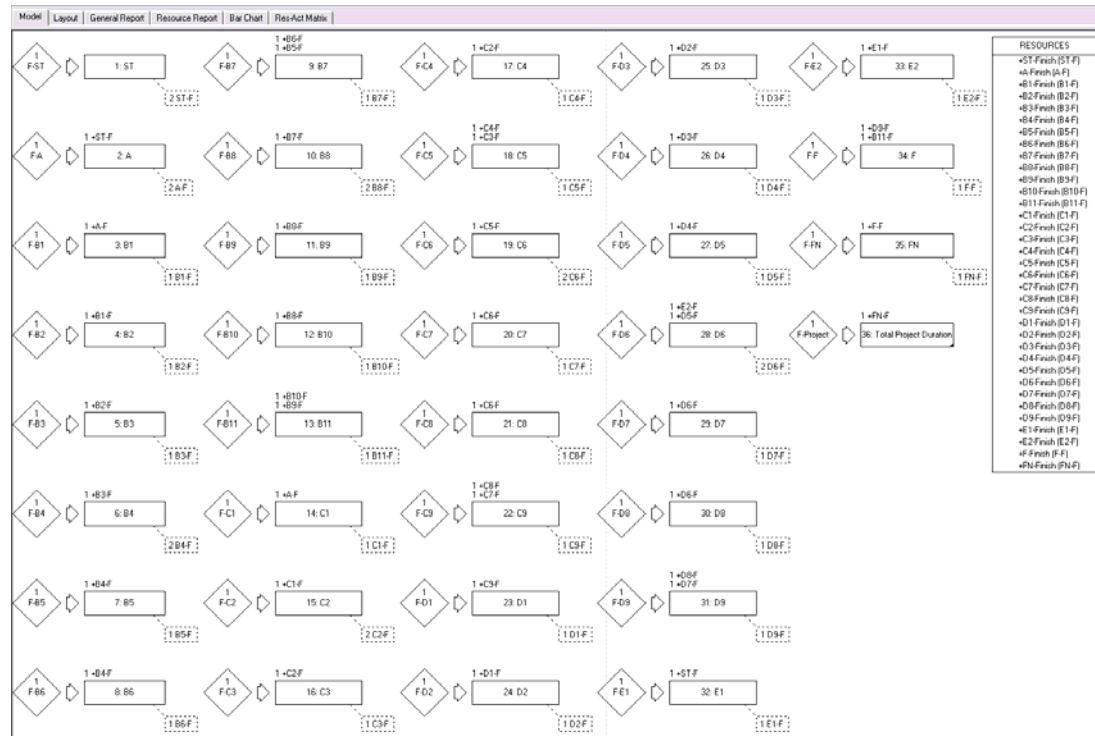
Bay 17 of the box culvert also included two 1650mm diameter pre-cast concrete pipes at its 800mm thick end wall to convey runoff generated from the northwest part of the Reserve Zone.

APPENDIX E – Detailed Scheduling Results of Case Study in Chapter

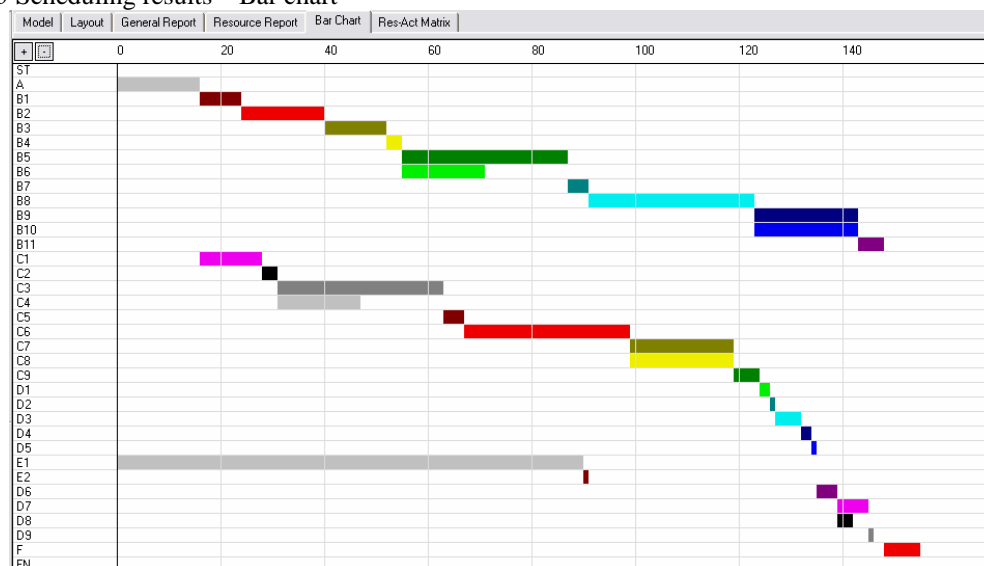
6

Stage 1: Deterministic CPM Analysis (without resource constraint)

S3 network model



S3 Scheduling results – Bar chart



S3 Scheduling results – Float analysis

Float Analysis

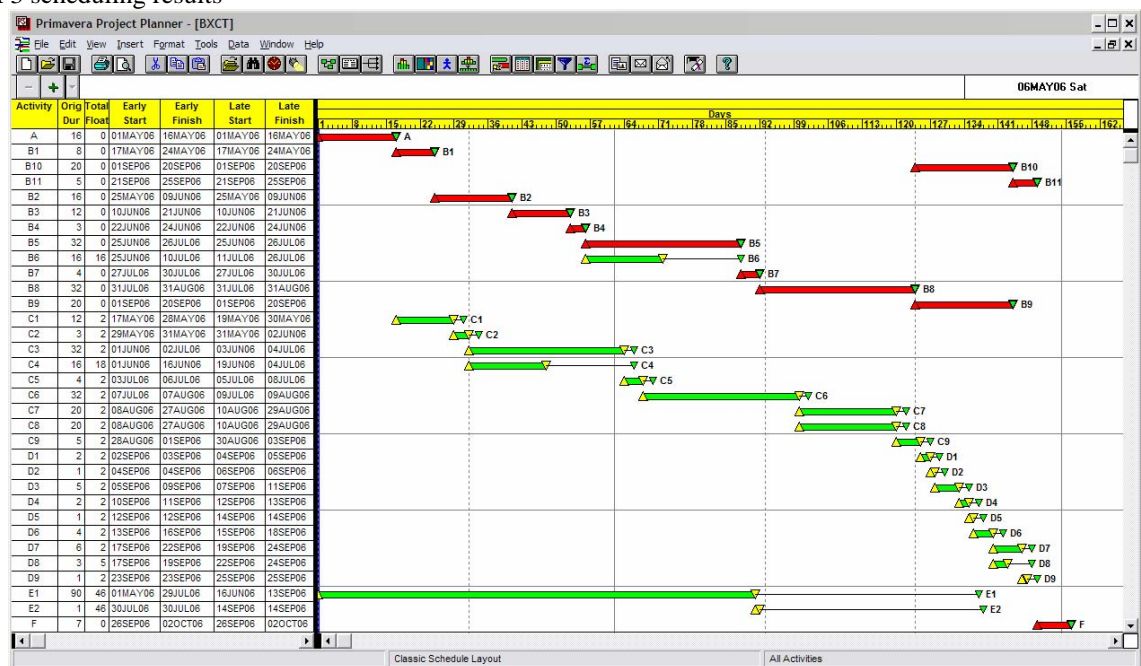
Total Project Duration: 155.00

Resources Involved:

Activity	Dur	ES	EF	LS	LF	FF	TF	Project Extension Effect	Criticality
A	16.00	0.00	16.00	0.00	16.00	0.00	0.00	1.00	Yes
B1	8.00	16.00	24.00	16.00	24.00	0.00	0.00	1.00	Yes
B2	16.00	24.00	40.00	24.00	40.00	0.00	0.00	1.00	Yes
B3	12.00	40.00	52.00	40.00	52.00	0.00	0.00	1.00	Yes
B4	3.00	52.00	55.00	52.00	55.00	0.00	0.00	1.00	Yes
B5	32.00	55.00	87.00	55.00	87.00	0.00	0.00	1.00	Yes
B6	16.00	55.00	71.00	71.00	87.00	16.00	16.00	1.00	No
B7	4.00	87.00	91.00	87.00	91.00	0.00	0.00	1.00	Yes
B8	32.00	91.00	123.00	91.00	123.00	0.00	0.00	1.00	Yes
B9	20.00	123.00	143.00	123.00	143.00	0.00	0.00	1.00	Yes
B10	20.00	123.00	143.00	123.00	143.00	0.00	0.00	1.00	Yes
B11	5.00	143.00	148.00	143.00	148.00	0.00	0.00	1.00	Yes
C1	12.00	16.00	28.00	18.00	30.00	0.00	2.00	1.00	No
C2	3.00	28.00	31.00	30.00	33.00	0.00	2.00	1.00	No
C3	32.00	31.00	63.00	33.00	65.00	0.00	2.00	1.00	No
C4	16.00	31.00	47.00	49.00	65.00	16.00	18.00	1.00	No
C5	4.00	63.00	67.00	65.00	69.00	0.00	2.00	1.00	No
C6	32.00	67.00	99.00	69.00	101.00	0.00	2.00	1.00	No
C7	20.00	99.00	119.00	101.00	121.00	0.00	2.00	1.00	No
C8	20.00	99.00	119.00	101.00	121.00	0.00	2.00	1.00	No
C9	5.00	119.00	124.00	121.00	126.00	0.00	2.00	1.00	No
D1	2.00	124.00	126.00	126.00	128.00	0.00	2.00	1.00	No
D2	1.00	126.00	127.00	128.00	129.00	0.00	2.00	1.00	No
D3	5.00	127.00	132.00	129.00	134.00	0.00	2.00	1.00	No
D4	2.00	132.00	134.00	134.00	136.00	0.00	2.00	1.00	No
D5	1.00	134.00	135.00	136.00	137.00	0.00	2.00	1.00	No
D6	4.00	135.00	139.00	137.00	141.00	0.00	2.00	1.00	No
D7	6.00	139.00	145.00	141.00	147.00	0.00	2.00	1.00	No
D8	3.00	139.00	142.00	144.00	147.00	3.00	5.00	1.00	No
D9	1.00	145.00	146.00	147.00	148.00	2.00	2.00	1.00	No
E1	90.00	0.00	90.00	46.00	136.00	0.00	46.00	1.00	No
E2	1.00	90.00	91.00	136.00	137.00	44.00	46.00	1.00	No
F	7.00	148.00	155.00	148.00	155.00	0.00	0.00	1.00	Yes

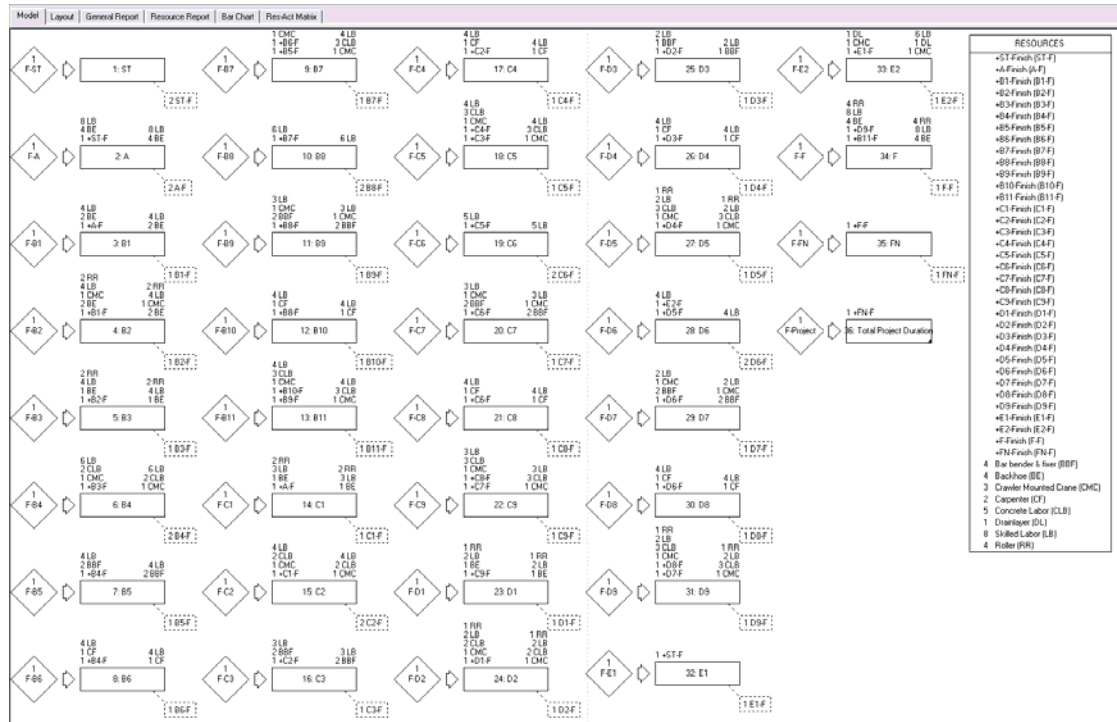
Save Print Close

P3 scheduling results

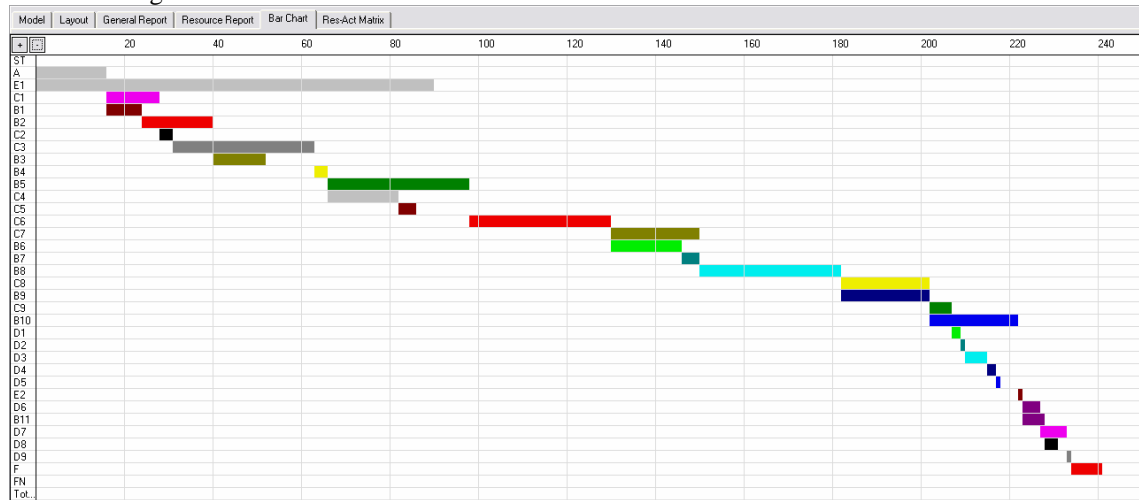


Stage 2: CPM Analysis with Resource Constraints

S3 network model

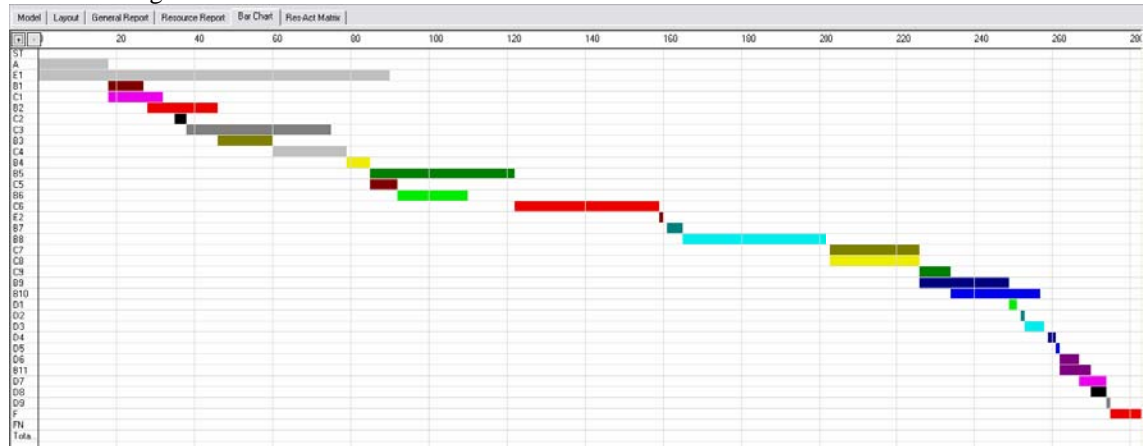


S3 Scheduling results – Bar chart

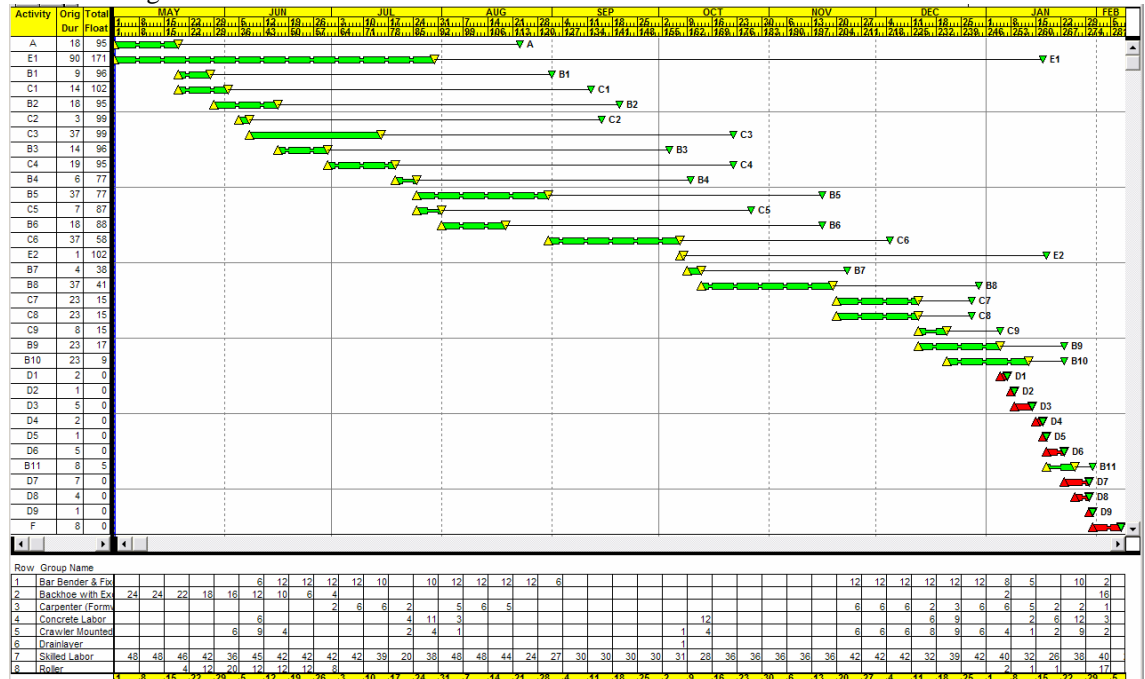


Stage 3: CPM Analysis with Resource and Interruption Constraints

S3 Scheduling results – Bar chart



P3 scheduling results

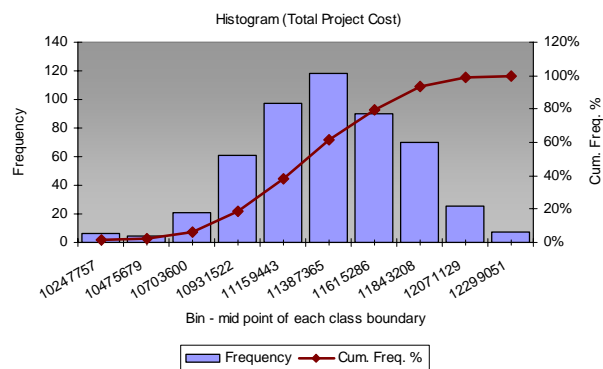
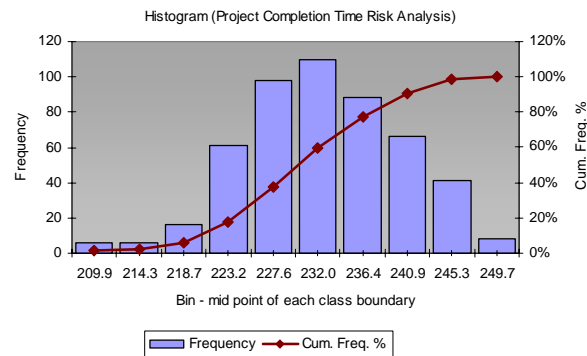


Stage 4: PERT Analysis with Resource and Interruption Constraints

S3 scheduling results - Histograms of total project duration and cost

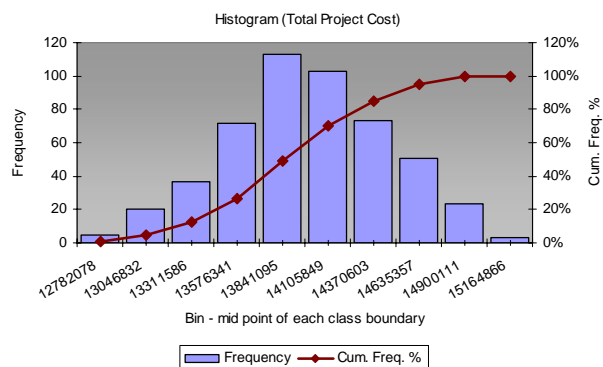
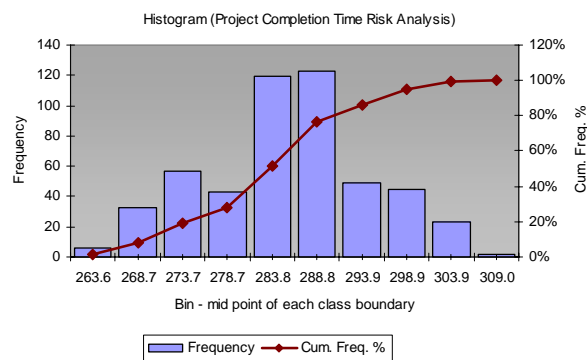
Scenario 1

- with resource limits



Scenario 2

- with resource limits & interruptions



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