DEVELOPMENT OF QUANTITATIVE METHODS FOR PROJECT SCHEDULING AND WORKFACE PLANNING UNDER TIME-DEPENDENT RESOURCE CONSTRAINTS

by

Ming Fung Siu

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

Doctor of Philosophy
in
Construction Engineering and Management

Department of Civil and Environmental Engineering
University of Alberta

ABSTRACT

Analytical decision support for project scheduling and workface planning under time-dependent resource constraints is limited in industrial-construction. Previous project scheduling research endeavors in the construction engineering and management domain focused on formulating resource-constrained project schedules by use of simulation and optimization techniques in order to shorten the total project duration based on the classic critical path method (CPM), subject to fixed resource supply over project period. Nonetheless, the following critical factors have not been adequately considered and thoroughly treated in devising quantitative solutions, namely: (i) the thresholds of resource supply limits considered being sufficient to complete the project in the shortest possible duration, (ii) the varied resource provisions over different time periods during the project duration, and (iii) the sufficiency of the control budget for executing the formulated project schedule, and the efficiency of the deployed resources utilized when executing the formulated project schedule.

Tackling the defined problems provides the motivation to deliver the present research. First, the resource supply-demand matching problem (RSDMP) approach is mathematically developed for scheduling construction projects with resource constraints. The result is an optimum resource-constrained schedule providing the shortest project duration with the leanest resource supply. The optimum resource requirement is identified between the lower and upper boundaries of resource supply limit. The optimum resource workflows of individual craft persons are presented.

Next, a modified RSDMP approach is mathematically formalized aiming to generate the optimum resource-constrained project schedule under time-dependent resource constraints. The resulting optimum schedule shortens total project duration while streamlining resource supply for each specified project time period. The computational efficiency of applying the modified RSDMP approach to the construction project with practical size and complexity is examined.

Then, a quantitative assessment approach is developed for mathematically characterizing budget sufficiency and resource utilization for a resource-constrained project schedule in an objective fashion. The method is applied for evaluating and visualizing budget sufficiency and resource utilization to assess multiple alternative resource-constrained project schedules as derived from any resource-based scheduling approaches, such as the practical scheduling approach (Primavera P6) and schedule optimization techniques (RSDMP approaches).

In close collaboration with a major contractor of industrial-construction in Alberta Canada, the practical application needs have been identified on plant shutdown and maintenance projects to justify the problem statement for this research and motivate its solution formulations. As such, apart from the example case studies adapted from textbooks used to illustrate the developed quantitative scheduling techniques, a plant shutdown and maintenance project serves a real-world case to demonstrate the applications of the developed approaches in practical settings.

The academic contributions of this research work are demonstrated by the development of quantitative scheduling methods developed for planning industrial-construction project. The resource supply-demand matching problem (RSDMP) is generalized; while formalizing the

RSDMP approach which consists of a mathematical model, a two-stage optimization approach, and an innovative use of a refined resource-activity interaction table. The RSDMP approach is then modified in coping with time-dependent resource constraints. The analytical metrics of budget sufficiency and resource utilization are defined from project scheduling perspectives, including budgeted units, deployed units, scheduled units, budget sufficiency index, budget sufficiency variance, resource utilization index, and resource utilization variance.

The industrial contributions of this research work are demonstrated by the implementation of the developed methods to improve the existing practice of planning plant shutdown and maintenance projects. In practice, the resources are budgeted and allocated based upon the rough estimate of resource supply for matching resource demand throughout the project duration. The assessment of budget sufficiency and resource utilization are commonly made based on experience. In contrast, the optimum RSDMP schedule is practically feasible and workface executable. The modified RSDMP optimum plan avoids undersupply and oversupply of resources for particular time periods. The budget sufficiency index/variance and resource utilization index/variance provide analytical bases to justify increasing the project budget or performing schedule optimization to effectively cope with contingencies (including unexpected work during project planning stage). In reality, this is inevitable during project execution.

In essence, the developed planning methodologies not only make academic contribution by advancing the state-of-the-art in construction engineering and management, but also remain practically relevant to the critical industrial-construction planning practice, enabling project managers, project schedulers, and field superintendents to make informed, sound decisions in terms of project scheduling, resource allocation, and project budgeting.

PREFACE

This thesis is the original work by Ming Fung Francis Siu. It is organized in paper format. It is written on the basis of the related research papers, as below.

Technical papers in referred journals:

1. Siu, M. F., Lu, M., and AbouRizk, S. (2015). “Resource supply-demand matching scheduling approach for construction workface planning.” Journal of construction engineering and management, ASCE. 10.1061/(ASCE)CO.1943-7862.0001027, 04015048, 17 pages.

2. Siu, M. F., Lu, M., and AbouRizk, S. (2015). “Zero-one programming approach to determine optimum resource supply under time-dependent resource constraint.” Journal of computing in civil engineering, ASCE. 10.1061/(ASCE)CP.1943-5487.0000498, 04015028, 14 pages.

3. Siu, M. F., Lu, M., AbouRizk, S., and Tidder, V. (2016). “Quantitative assessment of budget sufficiency and resource utilization for resource-constrained project schedules.” Journal of construction engineering and management, ASCE. 10.1061/(ASCE)CO.1943-7862.0001106, 04016003, 21 pages.

Conference papers in referred proceedings:

1. Siu, M. F., Lu, M., AbouRizk, S., and Tidder, V. (2013). “Improving sophistication and representation of skilled labor schedules on plant shutdown and maintenance projects.” 13th international conference on construction applications of virtual reality. Oct. 30–31, 2013, London, United Kingdom, 160–171.

2. Siu, M. F., Lu, M., and AbouRizk, S. (2014). “Strategies for optimizing labor resource planning on plant shutdown and turnaround.” ASCE Construction research congress 2014. May 19–21, 2014, Atlanta, Georgia, United States, 1676–1685.

3. Siu, M. F., Lu, M., and AbouRizk, S. (2014). “Bi-level project simulation methodology to integrate superintendent and project manager in decision making: shutdown/turnaround applications.” Winter simulation conference 2014. Dec. 11–14, 2014, Savannah, Georgia, United States, 3353–3364.

4. Siu, M. F., Lu, M., and AbouRizk, S. (2015). “Methodology for crew-job allocation optimization in project and workface scheduling.” ASCE international workshop on computing in civil engineering. Jun. 21–23, 2015, Texas, Austin, United States, 652–659.

ACKNOWLEDGEMENT

This research was funded by National Science and Engineering Research Council (NSERC).

Respectfully, the author wishes to acknowledge his academic advisors (Lu, M., and AbouRizk, S.) for their research and teaching support throughout the course of this research study. Their continual trust and inspiration have advanced not only the author’s academic achievement but also have contributed to the maturity necessary to cope with the rest of the author’s life.

Thanks are due to the author’s industrial advisors (Tidder, V., Pelchat, D., Matson, B., and Wilson, D.) for sharing their knowledge and experience in planning industrial plant shutdown and maintenance projects. They also helped to validate the defined research problems and practical case studies as denoted in this thesis.

Appreciations are sincerely extended to the examination committee members (Mohamed, Y., Han, S., Yeung, T., Askari-Nasab, H., and Issa, R.) for proofreading this research thesis. They spent time with the author for providing critiques to advance this research work.

Importantly, the author would like to express deep appreciation of love, understanding, and support unreservedly given by his fiancée (Yeung, C.). Her encouragement, patience, and unreserved support have made possible the accomplishment of this research study.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION[1]

This chapter outlines the research background, problem statements, research objectives, research methodologies, and thesis organization.

1.1 Research background from an academic perspective

The definition of workface planning is the management of all related processes within a large project in order to deliver all elements necessary (such as tools and equipment), prior to the start of field-level execution, to enable the crews (individual craft persons) to perform quality work in a safe, effective, and efficient manner (COAA 2014). The work packaging technique facilitates workface planning by breaking down the project work into well-defined manageable pieces, defined as construction work package (CWP) or engineering work package (EWP) that can be executed, budgeted, measured, and controlled (CII 2013). The project progress, project cost, and crew productivity are generally measured on the basis of CWP/EWP. Before executing the works in the field, the construction team further develops the field installation work package (FIWP) as per each CWP/EWP. The FIWP is equivalent to the activity, as denoted in the Level 5 resource-constrained workface schedule. The project duration of the workface schedule is measured in hours or weeks (e.g., the workface plan with a 3-week look-ahead duration). Workface planning emphasizes the removal of field constraints such as site safety and spatial requirements, before executing the planned FIWP. The individual craft persons are allocated to execute specific FIWP

---

[1] Portions of this chapter have been published in the proceedings of the 13th international conference on construction applications of virtual reality. Oct. 30–31, 2013, London, United Kingdom, 160–171; construction research congress 2014. May 19–21, 2014, Atlanta, Georgia, United States, 1676–1685; winter simulation conference 2014. Dec. 11–14, 2014, Savannah, Georgia, United States, 3353–3364; ASCE international workshop on computing in civil engineering. Jun. 21–23, 2015, Texas, Austin, United States, 652–659.

in accordance with the resource-constrained project schedules. In line with the existing practice of industrial-construction, the proposed quantitative methods are intended to advance the existing knowledge of project scheduling and workface planning such that the defined work packages and its activities can be executed on time and within budget in the construction field.

A resource-constrained project schedule provides a baseline plan that is instrumental in guiding activity execution, and controlling resource supply and resources' workflow, ensuring manpower, material, tools, and equipment as required for executing particular activities will be ready at the right time. Essentially, it serves as a plan to achieve equilibrium between resource supply to the project and the project's demand for resources. It is crucial to provide the right quantities of resources – neither excessive nor inadequate – so as to satisfy activity execution demand for each time unit over the project duration. The resource supply depends on the aggregated resource demand of scheduled activities over the project time. The resource demand is governed by how individual activities are sequenced in the project schedule, such that mandatory precedence relationships are observed, while at a particular time point, resource demand is kept close to but not over the supply limit imposed for the project. Matching resource supply and demand to minimize project duration, while optimizing resource utilization over the project duration, is complicated as the two variables are interrelated (Seibert and Evans 1991).

The schedule formulated by critical path method (CPM) is stipulated in general contract conditions on the majority of construction projects. The CPM calculates activity start and finish times to guide project execution. However, the CPM schedule becomes convoluted, intractable, and misleading if resource constraints are imposed (Fondahl 1991). In the existing body of knowledge and the current practice of detailed scheduling and workface planning, a formal problem formulation in terms of determining theoretical optimum resource supply in order to match the resource demand for completing the project in the shortest total duration is non-existent. Seasoned schedulers commonly rely on the trial-and-error approach for obtaining the best match between resource supply and project demand, aiming to arrive at shorter total project duration. The trial-and-error process is generally tedious, time-consuming, and at best guided by heuristic rules. In light of the complex scheduling scenarios in reality, whether feasible solutions can be found much depends on luck, let alone arriving at the optimum solution. The shortest total project duration can be identical to or longer than the original project duration derived from critical path scheduling without imposing resource constraints, depending on whether the resource supply limits as specified are sufficient or not.

The quantities of resource supply are generally determined based on the aggregated demand of activities, which can vary at different stages of project execution. The quantity of each resource must be assigned within the practical range; the lower bound and the upper bound are generally estimated in consideration of budget, spatial and safety restrictions on site. The lower bound defines the minimal resource supply to satisfy resource requirements of each individual activity. The upper bound is the maximum resource availability limit to satisfy project requirements (such as total project budget, project's resource demand profile over time). At the planning stage, the determination of resource supply quantities for particular time periods is largely dependent on the experience of project schedulers, field superintendents and project managers, without any analytical decision support. The resource-based scheduling methodology focuses on the determination of optimum resource quantities for particular time periods between the specified resource availability boundaries to formulate the optimum schedule under time-dependent resource constraints, which is left unaddressed in previous related research.

The assessment of budget sufficiency and resource utilization for a formulated resource-constrained project schedule is crucial to the successful delivery of a construction project. During the detailed planning and workface planning stages, such assessment is commonly made based on experience instead of analytical metrics. The assessment of a resource schedule is largely based on the following metrics: total project duration and resource direct cost. Thus, the following critical questions should be addressed from resource-based scheduling perspectives: How sufficient is the control budget for executing the formulated project schedule? How efficiently will the deployed resources be utilized when executing the formulated project schedule? To make the assessment of a resource schedule more comprehensive, the metrics on budget sufficiency and resource utilization are yet to be defined to add to knowledge in project management.

Finding definitive and analytical answers to the identified resource-based scheduling problems has provided motivation to carry out the present research. The practical application needs have been identified on plant shutdown and maintenance projects, as introduced in the next section, to justify the problem statement for this research and motivate solutions.

1.2 Research background from a practical perspective

Industrial-construction develops and maintains oil and gas processing plants. An oil refinery plant is typically composed of a generator, a reactor, and a fractionator. Through the introduction of a catalyst, chemical reactions take place in the regenerator and the reactor, which turns heavy oil (petroleum crude) to light oil (gasoline). The crude first enters the regenerator to blend with the stored catalyst. As oil vaporizes, catalytic cracking reactions take place. The hydrocarbons break down into smaller molecules. The vaporized hydrocarbons mixed with the catalyst flow into the reactor. The reactor segregates the mixture of hydrocarbon and catalyst into two separated portions. The catalyst flows back to the regenerator. The hydrocarbon products flow out from the regenerator and into the fractionator for light oil separation. Meanwhile, some byproducts such as coke, deposit on the surface of the catalyst and reduce catalyst reusability (Sadeghbeigi 2012). As time goes by, the chemical reactions deteriorate such that the reliability of the refinery plant decreases.

Plant shutdown and maintenance, commonly termed *turnaround* projects in the industry, aim to maintain the plant reliability and expand the current production capacity during normal plant operations. The plant completely shuts down during a turnaround period. Plant components are repaired, removed and upgraded. After the temporary structures are removed and existing facilities are inspected, repaired and renewed, the upgraded plant starts up. Subject to the contractually stipulated plant shutdown and startup dates, the turnaround is generally expected to complete within a tight time period without any delay. The contractor is pressed to deliver the plant upgrade and maintenance project within a short period of time because pushing back the plant start-up date by one day can lead to substantial economic losses. Turnaround projects commonly involve labor-intensive installation tasks completed by skilled workers of specialty trades. However, serious labor resource shortage problems (skilled trades) are experienced in the turnaround industry at large, especially for highly specialized trades. For instance, the recent turnaround projects in Alberta Canada had anticipated a serious shortage of boilermakers and pipefitters. The labor relations department in a company consults the turnaround schedulers to determine the work scope. From the work scope, the associated worker-hours and qualifications of the required skilled workers as needed for performing the turnaround activities are determined based on experience. The labor resource requests for the entire turnaround project are submitted to hiring halls thirty days prior to the start of the turnaround project.

Although Song et al. (2005) argued that moving labor-intensive jobs to locations with adequate skilled laborers eases labor resource shortages on site, the skilled labor resources such as boilermakers and pipefitters are still indispensable in executing field operations. Their hourly rates are high while their availability remains highly limited. The workers usually work inside the regenerator and the reactor. The working space is categorized as confined space—a restricted space which may become hazardous to a worker entering it due to the following considerations: the atmosphere can be hazardous (such as oxygen deficiency or enrichment, flammability, explosivity or toxicity); the changing circumstances within the space that present a potential for injury or illness; or the inherent characteristics of an activity can produce adverse or even harmful consequences within the space (OSSA 2013). Therefore, during project planning and execution stages, the planners must be aware of the maximum quantity of workers that are allowed to enter certain restricted locations, the workflow of individual skilled workers for delivering the work content, the optimum quantities of workers that are deployed to avoid undersupply and oversupply of resources for particular time periods, and the contingency of budgeted resources against uncertain and unexpected work.

In practice, formulating valid hour-by-hour turnaround schedules remains challenging as effectively allocating the skilled workers of specialty trades for delivering the turnaround project on time and within budget is difficult. The critical path method (CPM) − which was originally formalized for project planning and scheduling analysis (Kelley and Walker 1959) − is the de-facto technique to schedule turnaround projects. However, CPM is not adequate to account for turnaround-specific project factors, including supply quantities of skilled labor resources, who perform specific tasks with a specific permit and license, are highly limited; the resource availability limits normally vary in different project time periods to ensure the site spatial and safety requirements; and the budget sufficiency and resource utilization are characterized such that the contingency can be reserved against any unexpected work. The scheduling software system, Primavera P6 (marketed by Oracle Inc.), is commonly used to generate a feasible turnaround schedule and cope with labor resource constraints. However, Primavera P6 can only provide a Gantt chart to represent start and finish times of scheduled activities. Primavera P6 is not able to (i) determine the optimum quantities of workers as-needed in the field, (ii) visualize the workflow assigned to each individual resource, and (iii) quantify the budget sufficiency and resource utilization based upon the formulated schedule (Siu 2011). As such, the quantities of skilled laborers as needed, the workflow of individual skilled workers, and the budget sufficiency and resource utilization, are solely estimated based on practical experiences of the turnaround schedulers, project managers, and field superintendents.

1.3 Problem statement

Previous project scheduling research endeavors in the construction engineering and management domain focused on formulating resource-constrained project schedules using simulation and optimization techniques in order to shorten the total project duration based on the classic critical path method (CPM), subject to fixed resource supply over the project period. However, these methods inadequately considered (i) the thresholds of resource supply limits considered being sufficient to complete the project in the shortest possible duration, (ii) the varied resource provisions over different time periods during the project duration, and (iii) the sufficiency of the control budget for executing the formulated project schedule, and the efficiency of the deployed resources to be utilized when executing the formulated project schedule.

The currently available resource-based scheduling techniques based on simulation and evolutionary-algorithm approaches, along with the existing project scheduling software systems, lack the mathematical formulations of resource-constrained project schedules to overcome the aforementioned limitations. Simulation is a technique adept in modeling a problem, based on a collection of heuristic rules, when uncertain events are considered with probabilities. The purpose of simulation is to explore and experiment with what-if scenarios based on a representation of the problem on a computer. Thus, simulation is not an optimization technique (Law and Kelton 2000). On the other hand, an evolutionary-algorithm based approach (metaheuristic) is based on the idea of search. The associated iterative procedure is used to sequentially search for better solutions (Blum and Roli 2003). Although better solutions are guaranteed, the solutions cannot be deemed as the theoretical optimum. Pidd (2009) also made a point that planning applications in operations research and management science are often focused on planning what resources are needed to achieve the desired optimum plan mathematically. The solution framework based on simulation and evolutionary-algorithm approaches is not intended to generate theoretical optimums. It lacks scientific rigor and visibility, though the generated results are valuable for cross-checking the analytical results and for guiding practical implementations.

Based on the above observations, the solution framework to the problem formulation being addressed in this research is based on mathematical approach. In order to achieve a balance between making academic contributions and making the deliverables relevant to improving current practice of industrial-construction, the developed scheduling methods are applied to address the complexity and uncertainty of scheduling the turnaround projects. The theoretical results, as empowered by the mathematical, simulation, and evolutionary-algorithm optimization approaches, are also immediately useful in practice, enabling both field superintendents and project management to make informed, sound decisions in terms of project scheduling, resource allocation, and project budgeting.

1.4 Research objectives

The research aim is to develop novel quantitative scheduling methods for planning industrial-construction projects, in order to advance the existing knowledge of resource-based project scheduling, while improving the existing practice of planning turnaround projects under time-dependent resource constraints. The research objectives are outlined below.

1. To develop a novel quantitative method for formulating resource-constrained project schedules, so as to determine theoretical optimum resource supply for delivering construction projects and facilitate workface planning of allocating work to individual craft persons.

2. To develop a novel quantitative method for formulating resource-constrained project schedules in consideration of time-dependent resource constraints. Theoretical optimum resource quantities for particular time periods are identified within the specified resource availability boundaries.

3. To develop a novel quantitative method for characterizing budget sufficiency and resource utilization of resource-constrained project schedules. Defined metrics are applied to objectively assess any resource-constrained project schedules in a straightforward, consistent fashion.

1.5 Research methodologies

The research methodologies with respect to delivering each research objective are outlined below.

1. To conduct literature reviews of project scheduling and workface planning methodologies in the construction engineering and management domain, and the operations research and management science domains, for laying the groundwork to generalize the resource supply-demand matching problems (RSDMP);

   To comprehend the current scheduling practice of matching resource supply and resource demand by participating in planning the resource workflows to deliver turnaround projects, in coordination with the turnaround schedulers, field superintendents and project managers;

   To formalize RSDMP scheduling approach by developing a mathematical model along with a two-stage optimization approach, while visualizing the resource workflows by designing a resource-activity interaction table;

   To conduct an example case study based on a textbook example and practical case study based on a turnaround project, by applying the RSDMP approach to obtain the analytical solutions, which are cross-validated against simulation based and evolutionary-algorithm based solutions.

2. To conduct literature reviews of resource-constrained project scheduling methodologies in the construction engineering and management domain, and the operations research and management science domains, for defining time-dependent resource constraints;

   To comprehend the current scheduling practice of determining resource supply quantities for different project periods in order to avoid undersupply and oversupply of resources by participating in planning the resource supply for particular time periods, in coordination with the turnaround schedulers, field superintendents and project managers;

   To formalize RSDMP scheduling approach in association with time-dependent resource constraints by developing a mathematical model along with a two-stage optimization approach, while presenting the matrix and vector formulations of the mathematical model;

   To conduct an example case study based on a textbook example and a practical case study based on a turnaround project, by applying the modified RSDMP approach so as to demonstrate the method application and computing efficiency.

3. To conduct literature reviews of schedule assessment methodologies in the construction engineering and management domain, for defining the metrics of budget sufficiency and resource utilization from project scheduling perspectives;

To comprehend the current scheduling practice of appraising a formulated resource-constrained project schedule by participating in estimating the control budget and formulating a resource schedule, in coordination with the turnaround schedulers, field superintendents and project managers;

To formalize a quantitative assessment approach in connection with a resource-constrained project schedule by defining and visualizing the analytical metrics of budgeted unit, deployed unit, scheduled unit, budget sufficiency index, budget sufficiency variance, resource utilization index, and resource utilization variance;

To conduct an example case study based on a textbook example and a practical case study based on turnaround projects, by evaluating and contrasting the defined metrics on multiple alternative schedules as derived from Primavera P6 and RSDMP approaches, while validating the analytical metrics against the simulation approach.

1.6 Thesis organization

This thesis consists of five chapters.

Chapter 1 introduces the research backgrounds from both academic and practical perspectives. The problem statement is introduced related to the present study. The research aim and objectives are set based on the research background and problem statement described. The research methodologies are identified with respect to achieving each research objective. The thesis organization is given at the end.

Chapter 2 proposes the quantitative method for formulating the project schedules with resource constraints. It provides a critical review of state-of-the-art resource-based scheduling research. The resource supply-demand matching problem (RSDMP) is defined in contrast with the established resource-based scheduling problems, including resource leveling, resource allocation, and time-cost/time-resource tradeoff. Further, the RSDMP scheduling approach, which consists of a mathematical model, a two-stage optimization approach, and a resource-activity interaction table, is formalized. An example case study is used to demonstrate the calculation procedure of the approach. A case study based on a real-world turnaround project is presented to demonstrate its application in practical settings. Conclusions are drawn at the end.

Chapter 3 proposes the quantitative method for formulating the project schedules with time-dependent resource constraints, which define the varied supply of resources over different time periods during the project duration. It critically reviews the literature on resource-constrained project scheduling problems in connection with time-dependent resource constraints. The RSDMP model, as proposed in Chapter 2, is then modified, which is described along with a two-stage solution framework. An example case study is given to illustrate the calculation procedure and the standard matrix and vector formulation. A case study based on a real-world turnaround project serves as a test-bed case to demonstrate method application and computing efficiency. Conclusions are drawn at the end.

Chapter 4 proposes the quantitative method for evaluating budget sufficiency and resource utilization based on any resource-constrained project schedules. It gives a critical literature review in connection with the evaluation of budget sufficiency and resource utilization from project scheduling perspectives. Effective metrics for resource-constrained schedule assessment are then proposed. An example case study is used to demonstrate how to implement and verify the proposed metrics on multiple alternative schedules, which are derived from a practical scheduling approach (Primavera P6) and resource scheduling optimization approach (RSDMP approaches developed in Chapter 2 and Chapter 3). A case study based on a real-world turnaround project is utilized to demonstrate method application in practical settings. Conclusions are drawn at the end.

Chapter 5 presents the research conclusions of the thesis. The research contributions are recapitulated at the end.

Appendix A denotes the details of the turnaround project, including the activity and resource requirements.

Appendix B demonstrates the input-to-output processing in MATLAB for analytically solving the mathematical programming models by use of the standard matrix and vector formulations.

CHAPTER 2: RESOURCE SUPPLY-DEMAND MATCHING SCHEDULING APPROACH FOR CONSTRUCTION WORKFACE PLANNING[2]

2.1 Introduction

Through organizations such as Construction Industry Institute (CII) and Construction Owners Association of Alberta (COAA), both industry and academia have been attaching the importance of workface planning to productivity improvement in construction field activities (CII 2013; COAA 2014). COAA (2014) gives a definition of workface planning as “the process of organizing and delivering all the elements necessary, before work is started, to enable craft persons to perform quality work in a safe, effective and efficient manner.” For instance, Gouett et al. (2011) proposed activity analysis for workface productivity assessment; Fayek and Peng (2013) investigated the adaptation of workface planning within organizations and projects; Kim et al. (2015) inspected the relationships between workface execution and work-package planning. Despite headways made in workface planning over the past decade, the predominant use of resource-based scheduling method [originally developed for project scheduling, such as critical path method (CPM) formalized by Kelley and Walker (1959), and currently adapted by the mainstream scheduling software system Primavera P6] does not provide the proper resource supply-demand matching methodology to facilitate workface planning. Full realization of the potential of workface planning to address the needs of planning workflows for individual craft persons is not possible. Tackling this challenge has provided the author with motivation to define and deliver the present research.

---

[2] This chapter has been published in the journal of construction engineering and management, ASCE. 10.1061/(ASCE)CO.1943-7862.0001027, 04015048.

A resource-constrained project schedule essentially serves as a plan to achieve equilibrium between resource supply to the project and project's demand for resources. It is crucial to provide the right quantities of resources – neither excessive nor inadequate – to satisfy activity execution demand for each time unit (hour or day) over the project duration. On the majority of construction projects, formulating the schedule by CPM is stipulated in general contract conditions. The CPM calculates activity start and finish times to guide project execution. However, the CPM schedule becomes convoluted, intractable and misleading if resource constraints are imposed (Fondahl 1991; Kim and De la Garza 2003; Lu and Li 2003; De la Garza and Kim 2005). In the existing body of knowledge and the current practice of detailed scheduling and workface planning, a formal problem formulation in terms of determining the theoretical optimum resource supply in order to match the resource demand for completing the project in the shortest total duration is non-existent. A review of the literature in project scheduling has identified this knowledge gap.

With existing project scheduling techniques, the resource availability limits need to be fixed prior to resource allocation analyses. In regard to mainstream scheduling tools, such as Primavera P6, the common practice is to apply the maximum resource limits in hope of completing the project with a shorter total duration. Nonetheless, one crucial question is left unanswered: what are the thresholds of resource supply limits considered sufficient to complete the project in the shortest possible duration? Is it possible to devise an analytical method so as to achieve the same target project duration, while employing resources lesser than the maximum limits of resource supply? This has led to the current research of defining the resource supply-demand matching problem (RSDMP) and formalizing its mathematical solution.

This chapter intends to propose an analytical RSDMP approach for project scheduling and workface planning that lends effective decision support in determining optimum resource supply limits in association with the shortest total project duration. Thus, this research is capable of analytically identifying the theoretical optimum limit of resource supply that results in the shortest project duration, which is accomplished through applying mathematical optimization techniques (e.g., mathematical branch-and-cut and gradient descent optimization method). The theoretical formulation for matching resource supply and demand is defined first based on literature review.

In the following sections, a critical review of state-of-the-art resource-based scheduling research is provided. The RSDMP is defined in contrast with the established resource-based scheduling problems, including resource leveling, resource allocation, and time-cost/time-resource tradeoff. Further, the RSDMP scheduling approach is formalized which consists of a mathematical model, a two-stage optimization approach, and a resource-activity interaction table. The resulting optimum plan is resource-loaded, practically feasible, and workface executable. An example adapted from a textbook is used to demonstrate the effectiveness of the approach. A case study based on a turnaround project is presented to demonstrate its application in practical settings. Conclusions are drawn at the end of this chapter.

2.2 Literature review

In this section, an overview of state-of-the-art project scheduling problems and solution techniques is given. The purpose is to lay the groundwork for defining and solving the resource supply-demand matching problem (RSDMP), which is built upon existing project scheduling research in the construction domain. Previous resource-based project scheduling research has revolved around three resource loading problems, namely: resource leveling problem (RLP), resource-constrained project scheduling problem (RCPSP), and time-cost tradeoff problem (TCTP) (Karaa and Nasr 1986; Brucker et al. 1999). Over the past few decades, researchers have proposed three general categories of solution methods in order to tackle resource-constrained scheduling problems, namely: (i) mathematical programming models, (ii) heuristic rules and (iii) evolutionary-algorithms. The advantages and disadvantages of each category of solution method are discussed along with each problem definition.

2.2.1 Resource leveling problem (RLP)

The RLP is concerned with how to postpone the start times of noncritical activities such that the project resource demand profile is leveled out, while keeping the original project duration resulting from CPM, as illustrated in Figure 2.1. Hiring, firing, and rehiring resources on a short-term basis can be prohibitively expensive and practically infeasible. Noncritical activities are shifted within its available total floats (Figure 2.1). The peaks and valleys in resource usage profile are leveled as a result, while the total project duration (T) remains unchanged.

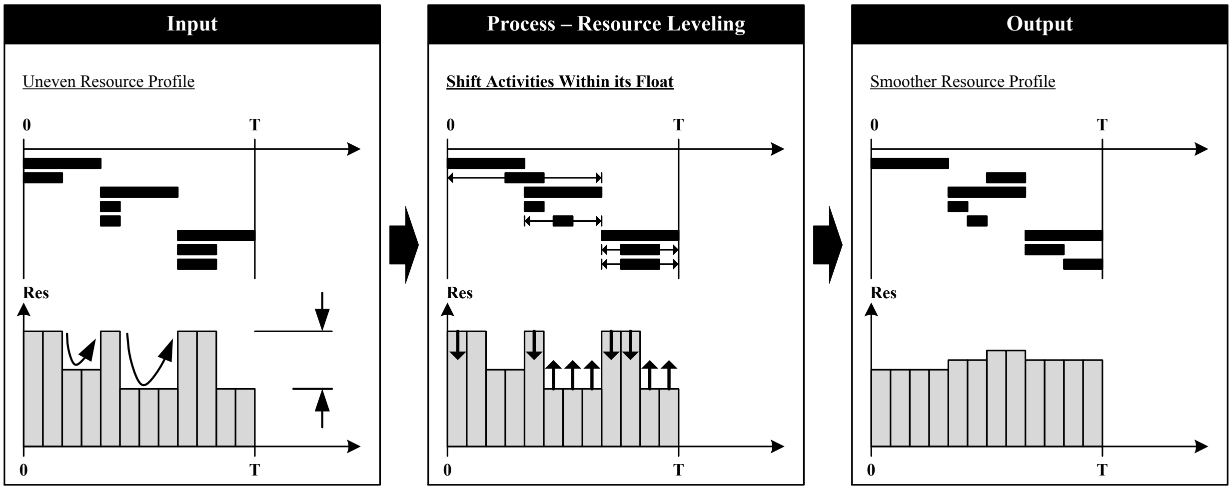


Figure 2.1: Resource leveling problem (RLP)

Mathematical programming models define the objective function subjected to satisfying a set of constraints given in mathematical equations (Winston 2003). Easa (1989) proposed a constrained programming model to minimize the total absolute deviation between actual and desirable resource utilization rates. Based on the resource leveling mathematical models, researchers further considered splitting activities in formulations (Son and Mattila 2004; Hariga and El-Sayegh 2011). The mathematical approach does not always guarantee the generation of feasible solutions as the combinatorial explosion inherent in solving a nondeterministic polynomial-time (NP-hard) problem is likely to be encountered when applying this technique to a project of practical size and complexity. To improve computing efficiency, Rieck et al. (2012) proposed constraint relaxation techniques for facilitating the branch-and-bound enumeration. In general, a unique optimum solution can be identified in deterministic time if it is feasible to solve the problem and the optimum solution exists.

Heuristic rules are a set of proposed rules used to decide activity priorities in resource-based scheduling. Noncritical activities in the project network are scheduled on the basis of such priorities. The heuristic rule approach guarantees that feasible solutions can be generated (Harris 1990). Harris (1978), Martínez and Ioannou (1993) proposed the minimum moment approach to level the resources. Son and Skibniewski (1999) integrated four proposed heuristic rules with simulated annealing to improve solution optimality. Hiyassat (2001) enhanced the minimum moment method for leveling multiple resources. Christodoulou et al. (2010) proposed the entropy maximization technique to level resources by considering activity stretching. However, the solution resulting from the heuristic rule approach is not guaranteed to converge at optimum.

An evolutionary-algorithm based approach randomly generates initial solutions. The solutions are generally encoded with a set of activity priorities. A schedule is constructed on the basis of a particular set of activity priorities. The schedules are then examined to ensure both technological and resource constraints are satisfied, through a simulated evolutionary process which is analogous to trial-and-error, but more efficient because of the guidance by evolution-inspired mechanisms. The fitness of solution is calculated based on evaluating the objective function. The schedule with the best fitness is searched and identified as the optimal solution. To increase the diversity of solutions, Hossein Hashemi Doulabi et al. (2011) implemented genetic algorithms and proposed local search heuristics and repair mechanisms in consideration of activity splitting. The optimized resource-leveled schedules with the same fitness were presented as a Pareto front in order to aid decision makers (Leu et al. 2000). However, the computing time can be nondeterministic and theoretical foundations are still weak to guarantee that the obtained solution converges at a global optimum (Blum and Roli 2003).

In brief, the RLP generally deals with resources that are not limited in supply (such as unskilled laborers; bulk materials), while the total project duration is fixed. In reality, a construction project is driven by limited resources (such as skilled laborers). The maximum resource supply limit throughout the project is always imposed.

2.2.2 Resource-constrained project scheduling problem (RCPSP)

The RCPSP deals with how to prioritize competing activities and allocate limited resources such that extension to the original total project duration can be kept to a minimum under fixed resource availability limit being imposed, as illustrated in Figure 2.2. The objective is to sequence execution of activities such that the resource demand aggregated from all activities at any time point is kept below the resource supply limit imposed for the project. Certain activities need to be delayed in order to acquire resources as required at a later time. The original project time is commonly extended as a result.

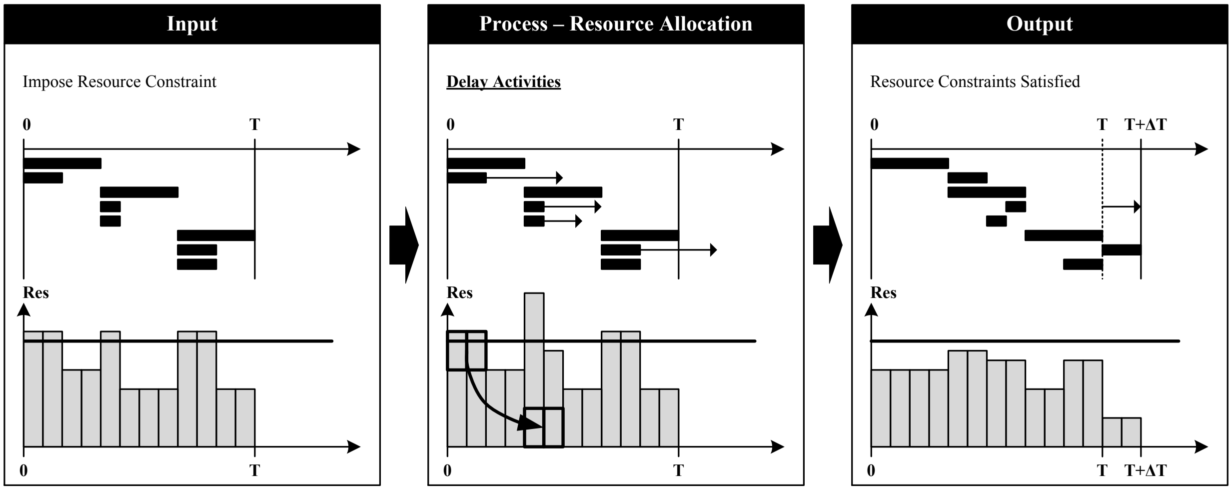


Figure 2.2: Resource-constrained project scheduling problem (RCPSP)

The mathematical modeling approach solved by integer linear programming techniques were widely used to formulate RCPSP mathematical model (Pritsker et al. 1969; Karaa and Nasr 1986), and it was proved to be effective and efficient at scheduling a project with limited resources (Hall 1980). The objective function was generally set as minimizing total project duration (Brucker et al. 1999). One of the major pitfalls was the combinatorial explosion problems likely to be encountered (Koulinas et al. 2014). Computers might not have sufficient memory to handle the large number of decision variables (Patterson 1984; Sprecher 2000). Researchers had thus focused on reducing the number of decision variables by tightening the bounds with respect to the feasible earliest start and latest finish times of activities, and reducing the solution search space by suggesting heuristic rules for branch-and-bound/branch-and-cut algorithms, so as to reduce the computing time required for reaching the optimality (Mingozzi et al. 1998; Patterson and Huber 1974; Dorndorf et al. 2000; Möhring et al. 2003). As such, the theoretical optimum solution can be iteratively determined if the mathematical model is solvable.

Heuristic rules have been suggested to establish activity priorities among candidate activities in addressing RCPSP (e.g., Boctor 1990; Finke 2008). Ready-to-start activities are scheduled on the basis of priorities in securing limited resources when available resources are insufficient. For example, Primavera P3 used to set activity priorities according to the minimum slack heuristic rule; while Primavera P6 defines five levels of activity priority in connection with attributes to each activity (Harris 2012). Lu and Li (2003) prioritized activities by work content and allocated limited resources to activities according to the earliest-ready-first-serve rule. Wongwai and Malaikrisanachalee (2011) applied a heuristic approach to allocate multiple-skilled labor resources to substitute for particular resources that were not available or not sufficient for a project. The generated schedule, which is associated with one unique combination of activity priorities and resource quantities, is not guaranteed to be the optimum in terms of minimizing total project duration. On the other hand, the exhaustive examination of combinations would incur substantial computing resources and time if the feasible ranges of available resources were wide (Zhang et al. 2006). By taking advantage of computer power, uncertainties in activity priority and resource availability can be assessed as part of simulation input modeling. Simulation runs were executed and sensitivity analysis was performed in order to examine all feasible resource combinations (AbouRizk and Shi 1994; Zhang and Li 2004; Zhang et al. 2006a; Lee et al. 2010; Chen et al. 2012). Padilla and Carr (1991) proposed equations to calculate activity priorities as simulation model inputs. McCahill and Bernold (1993) proposed a resource-oriented simulation approach to model resource workflows and performed sensitivity analysis to make decisions on resource supply. Leu and Hung (2002) considered uncertainties in executing activities. Park et al. (2005) built system dynamics simulation models to investigate project performances in regard to time, cost, and resource use. Despite tedious and time-consuming modeling processes, solutions generated by heuristic rule based approaches can be practically feasible, but do not lead to the optimum.

Evolutionary-algorithm based techniques applied to solve RCPSP include genetic algorithm, particle swarm optimization, ant-colony optimization, and shuffled frog-leaping optimization (Liao et al. 2011). Zhang et al. (2005, 2006b), and Lu et al. (2008) utilized particle swarm optimization to minimize total project duration under resource break constraints. Kim (2009) embedded the elitist roulette wheel selection operator in genetic algorithms in order to reduce the computing time. Kim and Ellis (2010) proposed elitist genetic algorithm in both serial and parallel scheduling fashions. The evolutionary-algorithm based formulations remain relatively weak in the theoretical foundation of optimization (Blum and Roli 2003; Pidd 2009).

2.2.3 Time-cost tradeoff problem (TCTP)/Multimode resource-constrained project scheduling problem (MRCPSP)

The time-cost tradeoff problem (TCTP) decides how to crash critical activities by increasing direct costs in an attempt to shorten critical path and reduce indirect cost, eventually resulting in the lowest total project cost (Figure 2.3). TCTP focuses on deciding the best mode for activity execution in crashing activity time. The direct cost on a crash scenario is generally higher than the normal scenario as additional resources are employed, while a project's indirect cost can be reduced as a result of shortening critical path. In the end, total project cost is minimized. The heuristic rule based approaches are commonly applied for solving the classic TCTP (e.g., activity duration is crashed according to the cost slope of a critical activity). The criticality theorem (Ahuja et al. 1994) and linear programming technique (Tang 1999) were also applied to solve for TCTP.

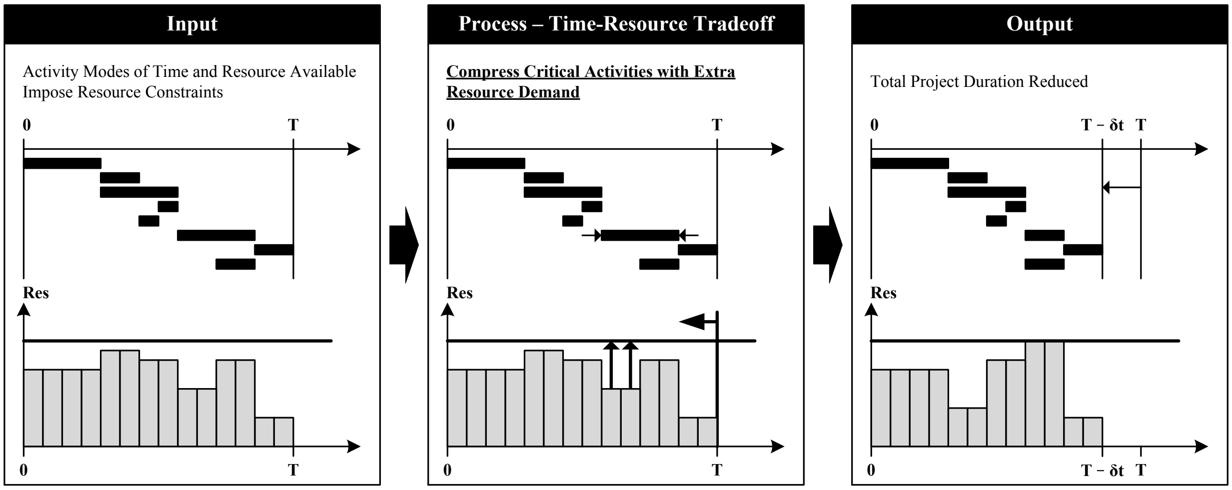


Figure 2.3: Multimode resource-constrained project scheduling problem (MRCPSP)

In recent decades, TCTP has been integrated with RCPSP. Activity crash and normal scenarios are defined with resource requirements explicitly specified. This integrated resource-time tradeoff problem is generally termed as multimode resource-constrained project scheduling problem (MRCPSP) in literature. The MRCPSP is intended to minimize total project duration or cost by selecting the best activity method from multiple options defined for each activity under the fixed resource availability constraints being imposed (Vanhoucke and Debels 2007), as illustrated in Figure 2.3.

Mathematical models have been proposed to solve MRCPSP analytically. Talbot (1982) proposed an integer linear programming formulation in an attempt to decide on completion times and execution modes of individual activities. To enhance computational efficiency, heuristic rules have been proposed to reduce the solution search space. For example, Patterson et al. (1989) proposed the enumeration type of branch-and-bound method, which was enhanced by Sprecher and Drexl (1998) in an attempt to search for the solution in relation to the precedence tree. Zhu et al. (2006) introduced bound-and-cut procedures, aiming to reduce the number of tree nodes. Demeulemeester et al. (2000) presented the depth-first branch-and-bound method in consideration of bottleneck resources. Though the MRCPSP model is more difficult to solve mathematically than RLP and RCPSP models, research has shown that theoretical optimum solutions can be determined on case study problems.

Evolutionary-algorithm based approaches have been developed to solve the MRCPSP. Each potential solution encodes a set of priorities and execution modes corresponding with each activity. Genetic algorithms were implemented to generate the optimal schedule as presented by Hartmann (2001). Alcaraz et al. (2003) proposed penalty functions to screen infeasible solutions. Peng and Wang (2009) considered the resource cost in formulating the fitness function. Lova et al. (2009) further proposed hybrid genetic algorithm for improving computing performance. The ant-colony optimization (Ng and Zhang 2008; Li and Zhang 2013) and leapfrog optimization (Ashuri and Tavakolan 2015) were also proposed. Better solutions can be sought, but the solutions generally cannot be considered theoretical optimums.

Additionally, previous research endeavors have attempted to solve both RCPSP and RLP simultaneously. For example, Tam and Dissanayake (1998) proposed heuristic rules, named as ranked positional weight method, to prioritize activities for resource allocation and leveling. Hegazy (1999) suggested the heuristic rule based double moment approach to level and allocate resources. Koulinas and Anagnostopoulos (2012, 2013) proposed a hyperheuristic algorithm consisting of eleven low-level heuristic rules to swap activity priorities. Simultaneously solving RCPSP, RLP and TCTP/MRCPSP using a mathematical model (Menesi and Hegazy 2014) and evolutionary-algorithms, such as genetic algorithms (Heon Jun and El-Rayes 2011; Ghoddousi et al. 2013) and a strength Pareto evolutionary approach (Hu and Flood 2012), were reported in literature.

2.2.4 Definition of resource supply-demand matching problem (RSDMP)

To produce resource-loaded schedules, previous research endeavors have tackled RLP, RCPSP, and TCTP/MRCPSP problems separately or in an integrative fashion, through applying mathematical programming models, heuristic rules or evolutionary-algorithms.

Nonetheless, to the best knowledge, the resource supply-demand matching problem (RSDMP) being addressed for project scheduling and workface planning has yet to be formalized, which is recapitulated as follows: How can we identify the optimum limits of resource supply within the resource availability ranges in project scheduling such that all the activities in the project can be executed and the whole project can be completed in the shortest project duration, without violating technological and resource availability constraints?

Herein, the RSDMP mathematical programming model is developed as the major academic contribution, which is illustrated in Figure 2.4. The resource supply limits are initially specified as a range with lower and upper boundaries. The model is intended to identify the optimum strategy for shifting and delaying activities and determine the optimum resource supply limit between lower and upper boundaries.

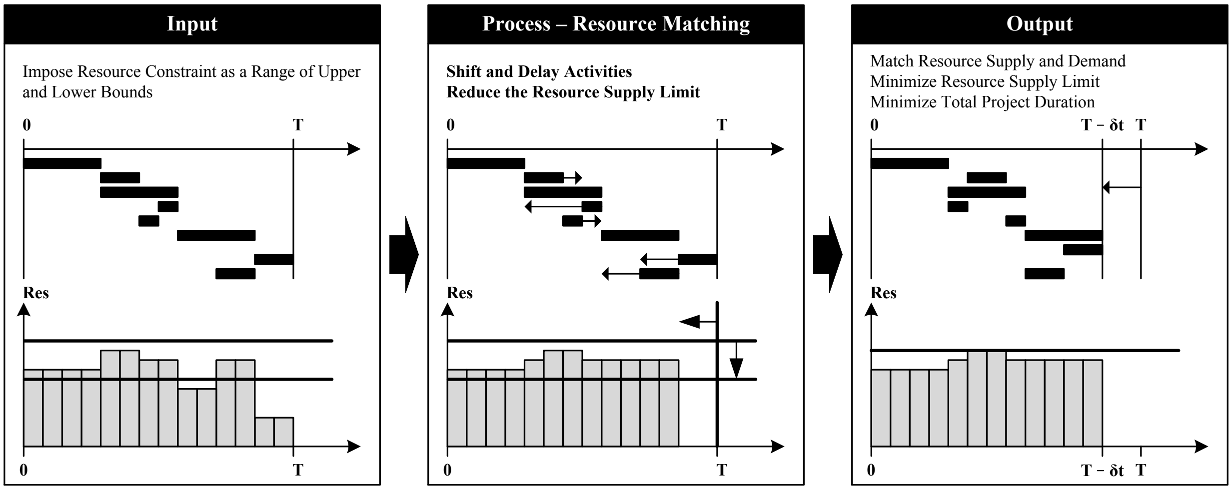


Figure 2.4: Resource supply-demand matching problem (RSDMP)

2.3 RSDMP mathematical model

The RSDMP mathematical model, based on integer linear programming, is composed of objective function, technological constraints and resource constraints. The model assumes that the resource demands of individual activities remain unchanged during their executions. No activity splitting or interruption is allowed. The decision variables of the proposed mathematical model are $x_{\mathrm{Act}}^{\mathrm{t}}$, $x_{\mathrm{Proj}}^{\mathrm{t}}$ and R_{Res}. The decision variables $x_{\mathrm{Act}}^{\mathrm{t}}$ and $x_{\mathrm{Proj}}^{\mathrm{t}}$ are binary variables, which indicate the activity completion time and project completion time, respectively. The decision variable R_{Res} determines the optimum resource supply. Note that the RSDMP mathematical formulation is built upon the zero-one programming strategy commonly applied in the operations research and management science domains (Pritsker et al. 1969; Hall 1980).

2.3.1 Objective function

The objective function is exclusively defined to address RSDMP, is expressed as Equation (2.1). As depicted in Figure 2.5, arrows illustrate the three objectives of optimization in the context of activity bar-chart and resource usage histogram.

$$\text{minimize} \quad f = \sum_{\mathrm{Act}} \sum_{\mathrm{t}=0}^{\mathrm{T}} (\alpha_{\mathrm{Act}}^{\mathrm{t}} \mathrm{t} x_{\mathrm{Act}}^{\mathrm{t}}) + \sum_{\mathrm{t}=0}^{\mathrm{T}} (\beta_{\mathrm{Proj}}^{\mathrm{t}} \mathrm{t} x_{\mathrm{Proj}}^{\mathrm{t}}) + \sum_{\mathrm{Res}} \gamma_{\mathrm{Res}} R_{\mathrm{Res}} \tag{2.1}$$

where f = objective function; $\alpha_{\mathrm{Act}}^{\mathrm{t}}$ = relative importance of completion time of particular activity at Time t; $\beta_{\mathrm{Proj}}^{\mathrm{t}}$ = relative importance of completion time of the project at Time t; γ_{Res} = relative importance of supply quantity for particular resource; t = time unit, from start time 0 to end time T; $x_{\mathrm{Act}}^{\mathrm{t}}$ = binary variable, 1 represents an activity completes at Time t, or 0 otherwise; $x_{\mathrm{Proj}}^{\mathrm{t}}$ = binary variable, 1 represents the project completes at time t, or 0 otherwise; R_{Res} = supply of particular resource.

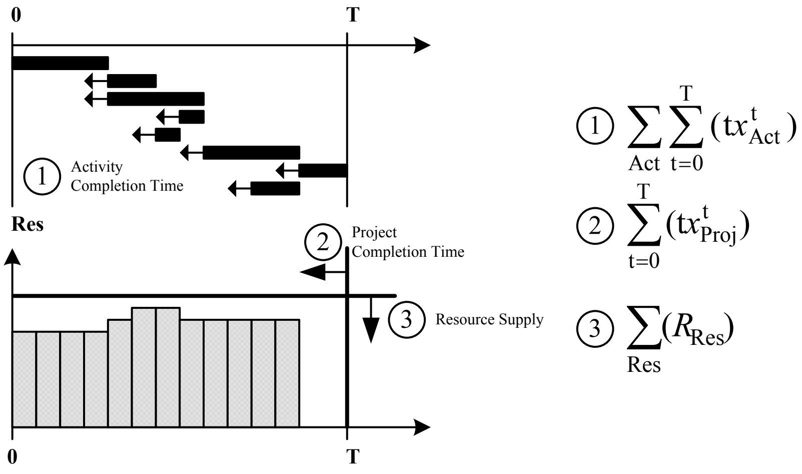


Figure 2.5: RSDMP objective function

The objective function is composed of three parts. The parameters $\{\alpha_{\mathrm{Act}}^{\mathrm{t}}, \beta_{\mathrm{Proj}}^{\mathrm{t}}, \gamma_{\mathrm{Res}}\}$ denote the relative importance (or weight) (Kandil et al. 2010, Li 1996, Rardin 1998, Heon Jun and El-Rayes 2011) of (i) activity completion times, (ii) project completion time, and (iii) resource supply, respectively. $\sum_{\mathrm{Act}}\sum_{\mathrm{t=0}}^{\mathrm{T}}(\alpha_{\mathrm{Act}}^{\mathrm{t}}\mathrm{t}x_{\mathrm{Act}}^{\mathrm{t}})$ is associated with minimizing activity completion time, by multiplying (i) the binary variable $(x_{\mathrm{Act}}^{\mathrm{t}})$ which indicates activity completion status, (ii) the corresponding Time t bounded between 0 and T, and (iii) the corresponding weight $\alpha_{\mathrm{Act}}^{\mathrm{t}}$. T can be estimated by multiplying the project duration without resource availability constraints by an extension factor. If the factor is too small, T is not large enough to cover the optimum project duration; thus the optimization fails to converge at the shortest project duration and the optimization needs to be repeated by setting a larger T. On the other hand, if T is set to be too large, the computing time required to arrive at the optimum can substantially increase. Similarly, $\sum_{\mathrm{t=0}}^{\mathrm{T}}(\beta_{\mathrm{Proj}}^{\mathrm{t}}\mathrm{t}x_{\mathrm{Proj}}^{\mathrm{t}})$ is associated with minimizing project completion time, by multiplying (i) the binary variable $(x_{\mathrm{Proj}}^{\mathrm{t}})$ which indicates project completion status at Time t, (ii) the corresponding Time t bounded between 0 and T, and (iii) the corresponding weight $\beta_{\mathrm{Proj}}^{\mathrm{t}}$. $\sum_{\mathrm{Res}}\gamma_{\mathrm{Res}}R_{\mathrm{Res}}$ is corresponded to optimizing resource supply R_{Res} for all resource types, by multiplying (i) the resource availability and (ii) the corresponding weight γ_{Res}. Note the weight parameter of γ_{Res} can be interpreted as the unit rate of utilizing a particular resource.

2.3.2 Technological constraints

Technological constraints refer to precedence relationships that must be observed among all the activities, and are visually depicted as arrow connections in an activity-on-node network. Equation (2.2) expresses the technological constraint. For each precedence relationship, the completion time of the current activity must be less than the completion time of its successor(s) minus the duration of current activity (d_{Suc}). Note, d_{Suc} is equal to 0 if the successor is project complete, referring to Equation (2.3).

$$\sum_{\mathrm{t=0}}^{\mathrm{T}}[(\mathrm{t}x_{\mathrm{Act}}^{\mathrm{t}})]_{\mathrm{Pred}} \le \sum_{\mathrm{t=0}}^{\mathrm{T}}[(\mathrm{t}-d_{\mathrm{Suc}})x_{\mathrm{Act}}^{\mathrm{t}}]_{\mathrm{Suc}} \text{, for activity-to-activity precedence relationship} \quad (2.2)$$

$$\sum_{\mathrm{t=0}}^{\mathrm{T}}(\mathrm{t}x_{\mathrm{Act}}^{\mathrm{t}}) \le \sum_{\mathrm{t=0}}^{\mathrm{T}}(\mathrm{t}x_{\mathrm{Proj}}^{\mathrm{t}}) \text{, for activity-to-project precedence relationship} \quad (2.3)$$

where d_{Suc} = duration of successor.

Equations (2.4) and (2.5) dictate that only one completion time is allowed for each activity and the project, respectively. The summation of all the binary variables must be equal to 1. Equations (2.6) and (2.7) declare all the binary variables which denote the time points on which one activity or the project is completed.

$$\sum_{\mathrm{t=0}}^{\mathrm{T}}x_{\mathrm{Act}}^{\mathrm{t}}=1 \text{, for all activities} \quad (2.4)$$

$$\sum_{\mathrm{t=0}}^{\mathrm{T}}x_{\mathrm{Proj}}^{\mathrm{t}}=1 \text{, for the project} \quad (2.5)$$

$$x_{\mathrm{Act}}^{\mathrm{t}}=\{0,1\} \quad (2.6)$$

$$x_{\mathrm{Proj}}^{\mathrm{t}} = \{0, 1\} \tag{2.7}$$

Figure 2.6 shows an example for expressing the technological constraints mathematically. A finish-to-start relationship is imposed between Activity I and Activity J. Activity I is the predecessor of Activity J, while Activity J is the successor of Activity I. The duration of Activities I and J is 2 and 4 time units, respectively.

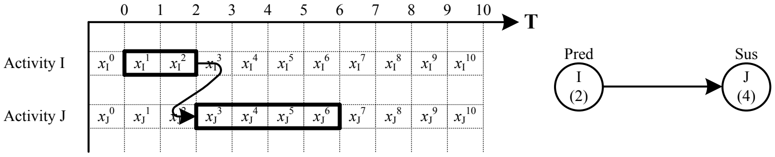


Figure 2.6: Illustration of technological constraint

The decision variables $x_{\mathrm{I}}^{\mathrm{t}}$ and $x_{\mathrm{J}}^{\mathrm{t}}$ are initialized from Time 0 to Time 10. To maintain the precedence relationship, Activity J must be completed $(x_{\mathrm{J}}^{\mathrm{t}})$ only after Activity I is completed $(x_{\mathrm{I}}^{\mathrm{t}})$. The lag time between the completion times of Activity I and Activity J must be greater than or equal to 4 time units (i.e., d_{J} the duration on Activity J). As such, if x_{I}^{2} is equal to 1 (Activity I completes at Time 2), the only possible completion times of Activity J are $\{x_{\mathrm{J}}^{6}, x_{\mathrm{J}}^{7}, x_{\mathrm{J}}^{8}, x_{\mathrm{J}}^{9}, x_{\mathrm{J}}^{10}\}$. Thus, the inequality is expressed as Equation (2.8). To indicate that Activities I and J are completed at Time 2 and Time 6, respectively, after optimization, the values of binary variables x_{I}^{2} and x_{J}^{6} are determined as 1, while others are equal to 0.

All the time variables represent the time point. The time variable t is counted from Time 0. As such, the technological constraints that maintain the relationships between project start and starting activities are required. The optimization results are determined relative to the origin on the timeline, i.e., project start, at Time 0.

$$\sum_{t=0}^{10}(\mathrm{t}x_{\mathrm{I}}^{\mathrm{t}}) \leq \sum_{t=0}^{10}(\mathrm{t}-4)x_{\mathrm{J}}^{\mathrm{t}} \text{, for Activity I and Activity J precedence relationship} \tag{2.8}$$

2.3.3 Resource constraints

The resource constraints are defined and expressed as Equations (2.9) and (2.10). Equation (2.9) guarantees that the resource demand aggregated from activities at particular time point is less than the maximum resource supply over the project time period. Equation (2.10) defines resource supply as a range of lower bound and upper bound.

$$\sum_{\mathrm{Act}} \sum_{\mathrm{t=t}}^{\mathrm{t+d_{Act}}} (r_{\mathrm{ActRes}} x_{\mathrm{Act}}^{\mathrm{t}}) \leq R_{\mathrm{Res}} \text{, for all resource types, for all time points} \tag{2.9}$$

$$lb_{\mathrm{Res}} \leq R_{\mathrm{Res}} \leq ub_{\mathrm{Res}} \text{, for all resource types} \tag{2.10}$$

where r_{ActRes} = resource demand of an activity; $\mathrm{d}_{\mathrm{Act}}$ = duration of current activity; lb_{Res} = lower bound of resource supply; and ub_{Res} = upper bound of resource supply.

For instance, Activities I and J require 4 and 5 resource units, respectively (Figure 2.7), of which the quantities of resource supply are [2 – 10] units. At Time t, the resource constraint (Equation 2.9) is checked after examining (i) if the completion time of Activity I is between Time t and Time (t+2), and (ii) if the completion time of Activity J is between Time t and Time (t+4). If activity completion time is within the time ranges ($\mathrm{t+d_{Act}}$), the resource demand of a particular activity is counted at Time t.

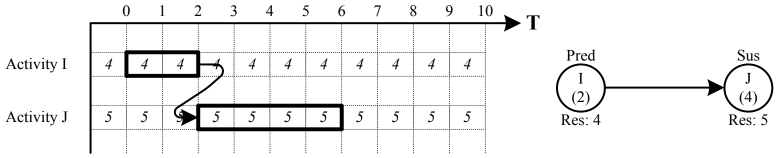


Figure 2.7: Illustration of resource constraint

In this example, Activity I completes at Time 2 and Activity J completes at Time 6. At Time 1, four resource units are required to execute Activity I, as its completion time (Time 2) is within the examined time range (from Time 1 to Time 3). However, Activity J requires no resource at Time 1 since it is not completed within the examined time range (from Time 1 to Time 5). Equation (2.11) shows the expanded mathematical expression of resource constraint at Time 1. The resource constraints are similarly defined on other time point from Time 2 to Time 10. Furthermore, Equation (2.12) defines the resource supply limit as a range of lower and upper boundaries according to the assumed resource availability constraints on the project.

$$\sum_{t=1}^{1+2}(4x_{\mathrm{I}}^{\mathrm{t}})+\sum_{t=1}^{1+4}(5x_{\mathrm{J}}^{\mathrm{t}})\le R_{\mathrm{Res}}\text{ , for Time 1} \tag{2.11}$$

$$2\le R_{\mathrm{Res}}\le 10 \tag{2.12}$$

2.4 Two-stage optimization approach

The optimization approach for workface planning is composed of two stages. The first stage is to determine the optimum project duration and the optimum resource supply by setting the parameters $\{\alpha_{\mathrm{Act}}^{\mathrm{t}},\beta_{\mathrm{Proj}}^{\mathrm{t}},\gamma_{\mathrm{Res}}\}$ as $\{0,\beta_{\mathrm{Proj}}^{\mathrm{t}},\gamma_{\mathrm{Res}}\}$. Given the analytical solutions resulting from the first stage, the second stage is designed to minimize the activity completion times by denoting the parameters $\{\alpha^{t}_{\mathrm{Act}}, \beta^{t}_{\mathrm{Proj}}, \gamma_{\mathrm{Res}}\}$ as $\{\alpha^{t}_{\mathrm{Act}}, 0, 0\}$.

2.4.1 Stage 1: Determine the shortest project duration and the leanest resource supply

In the objective function, $\alpha^{t}_{\mathrm{Act}}$ is set as zero to optimize project duration and resource supply. The parameter $\beta^{t}_{\mathrm{Proj}}$ can be interpreted as the indirect cost per time unit to be incurred on the project; while γ_{Res} can be interpreted as the direct cost (crew resources) per unit. Thus, the project scheduling and resource planning process underlying Stage 1 optimization can be related to the practical context of making the optimum cost budgeting decision.

$\beta^{t}_{\mathrm{Proj}}$ and γ_{Res} are elegantly assigned as relative ratios in the objective function, instead of absolute cost rates (dollars per time unit or per resource unit). For example, $\beta^{t}_{\mathrm{Proj}} = 1$ and $\gamma_{\mathrm{Res}} = 1$, which indicates comparable cost rates for indirect cost and direct resource cost; thus, equal weights are assigned on the indirect cost (project duration) and the direct cost (resource supply) in optimization. When $\beta^{t}_{\mathrm{Proj}} = 100$ and $\gamma_{\mathrm{Res}} = 1$, this indicates that much higher weight is placed on shortening total project duration than providing the leanest resources. On the flip side, when $\gamma_{\mathrm{Res}} = 100$ and $\beta^{t}_{\mathrm{Proj}} = 1$, streamlining resources far outweighs shortening project duration in optimization, thus the results would produce lower direct cost (less resource supply).

2.4.2 Stage 2: Identify the earliest activity finish times

In the objective function, the parameters $\beta^{t}_{\mathrm{Proj}}$ and γ_{Res} are set as zero to optimize activity completion times. This is relevant to the decision making process of field operations at workface level. This stage of optimization analysis is intended to complete each activity at the earliest opportunity so as to maximize the cushion against potential delays during project execution. Note this is analogous to the strategy of defining total float in classic critical path method scheduling.

The final output is the formulated optimum schedule features: (i) the optimum project duration with the optimum resource supply, and (ii) the optimum activity completion times.

2.5 Resource-activity interaction table

Detailed data on the workflows of individual craft persons can be presented by use of a refined resource-activity interaction table. Given the optimum RSDMP solution as derived from the two-stage optimization approach, the table can be used to clearly communicate optimum resource workflows at workface level. The two heuristic rules for resource allocation, defined by Lu and Li (2003), are: (i) work content rule and (ii) the earliest-ready-first-serve rule, as explained below:

- The work content rule is applied to prioritize activities for execution. The work content of an activity is calculated by multiplying its duration and quantities of leading resource as required. The larger the work content, the higher the activity priority in obtaining resources to execute the work.

- The earliest-ready-first-serve rule is applied to prioritize individual resources to be assigned to the prioritized activity. The work is allocated to the resource which has the earliest ready-to-serve (RTS) time. This is intended to distribute the work uniformly to all the available resources.

The data structure of the resource-activity interaction table is discussed by use of an example given in the next section.

2.6 Example case study

The proposed RSDMP scheduling approach is illustrated with an example adapted from a textbook (Ahuja et al. 1994). The objective of this case study is to demonstrate, implement, and verify the RDSMP mathematical model, the two-stage optimization approach, and the resource-activity interaction table.

The example project consists of nine activities and involves two types of resources (Resource A and Resource B). The activity network is shown in Figure 2.8. Activity precedence relationships are defined. The resource demand as required for executing each activity is tabulated in Table 2.1. The resource supply limits of Resource A and Resource B are given in ranges as [3 – 5] and [2 – 5] units, respectively. T is explicitly specified as 20 time units as the time period for analysis. The decision variables $x_{\mathrm{Act}}^{\mathrm{t}}, x_{\mathrm{Proj}}^{\mathrm{t}}$ and R_{Res} are declared as $\{x_{\mathrm{Start}}^{0},...,x_{\mathrm{Start}}^{20}, x_{\mathrm{A}}^{0},...,x_{\mathrm{A}}^{20}, x_{\mathrm{B}}^{0},...,x_{\mathrm{C}}^{0},...,x_{\mathrm{I}}^{20}\}$, $\{x_{\mathrm{Proj}}^{0},...,x_{\mathrm{Proj}}^{20}\}$ and $\{R_{\mathrm{ResA}}, R_{\mathrm{ResB}}\}$.

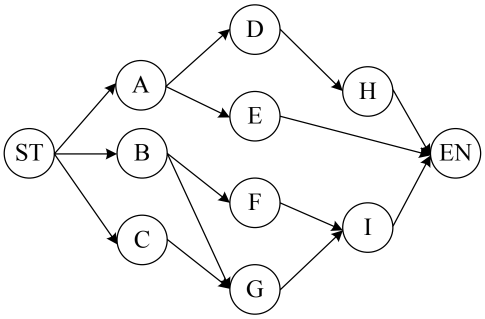


Figure 2.8: Activity network of example case study

Table 2.1. Activity-resource requirements (r_{ActRes}) of example case study

Activity	Duration	Resource A (ResA)	Resource B (ResB)
A	2	1	0
B	3	1	0
C	5	2	0
D	4	0	2
E	4	2	2
F	3	2	1
G	6	1	3
H	2	2	1
I	3	0	1

2.6.1 RSDMP mathematical formulations

The objective function is expressed as Equation (2.13).

$$\begin{aligned}\text{minimize}\quad f = {}& \alpha_{\mathrm{Act}}^{\mathrm{t}} \times [(0)x_{\mathrm{Start}}^{0} + ... + (20)x_{\mathrm{Start}}^{20} + (0)x_{\mathrm{A}}^{0} + ... + (20)x_{\mathrm{A}}^{20} + ... + (20)x_{\mathrm{I}}^{20}] + \\ & \beta_{\mathrm{Proj}}^{\mathrm{t}} \times [(0)x_{\mathrm{Proj}}^{0} + (1)x_{\mathrm{Proj}}^{1} + ... + (20)x_{\mathrm{Proj}}^{20}] + \gamma_{\mathrm{Res}} \times [(R_{\mathrm{ResA}} + R_{\mathrm{ResB}})]\end{aligned} \tag{2.13}$$

Technological constraints define activity precedence relationships. For example, the precedence relationship between Activities A and D is given by Equation (2.14). The constraints are also defined to ensure one completion time for project start, Activities A, B, C, D, E, F, G, H, I, and project complete. For example, Equation (2.15) constrains Activity A to complete at one time point. Equation (2.16) declares the decision variables $x_{\mathrm{Act}}^{\mathrm{t}}$ and $x_{\mathrm{Proj}}^{\mathrm{t}}$ as binary variables, of which the lower bound and upper bound are defined as 0 and 1, respectively.

$$[(0)x_{\mathrm{A}}^{0}+(1)x_{\mathrm{A}}^{1}+(2)x_{\mathrm{A}}^{2}+\ldots+(20)x_{\mathrm{A}}^{20}]-[(-4)x_{\mathrm{D}}^{0}+(-3)x_{\mathrm{D}}^{1}+(-2)x_{\mathrm{D}}^{2}+\ldots+(16)x_{\mathrm{D}}^{20}]\leq 0 \tag{2.14}$$

$$x_{\mathrm{A}}^{0}+x_{\mathrm{A}}^{1}+x_{\mathrm{A}}^{2}+\ldots+x_{\mathrm{A}}^{20}=1 \tag{2.15}$$

$$0\leq x_{\mathrm{Start}}^{0},x_{\mathrm{Start}}^{1},\ldots,x_{\mathrm{A}}^{0},x_{\mathrm{A}}^{1},\ldots,x_{\mathrm{Proj}}^{20}\leq 1 \tag{2.16}$$

The resource constraints are specified with respect to each time point from Time 1 to Time T, and for Resources A and B. For instance, Equation (2.17) denotes that the aggregated demand of Resource A must be less than or equal to its resource limit at Time 1, while Equation (2.18) denotes that the aggregated demand of Resource B must be less than or equal to its resource supply limit at Time 1. Equations (2.19) and (2.20) are the resource constraints for Resources A and B at Time 2, respectively. In addition, Equation (2.21) defines the lower and upper bounds of Resource A's supply limit as 3 and 5 units, respectively, while Equation (2.22) defines the lower and upper bounds of Resource B's supply limit as 2 and 5 units, respectively.

$$\begin{aligned}
&\text{At Time 1:}\\
&(2)x_{\mathrm{A}}^{1}+(2)x_{\mathrm{A}}^{2}+(1)x_{\mathrm{B}}^{1}+(1)x_{\mathrm{B}}^{2}+(1)x_{\mathrm{B}}^{3}+(2)x_{\mathrm{C}}^{1}+(2)x_{\mathrm{C}}^{2}+\ldots+(2)x_{\mathrm{C}}^{5}+\\
&(0)x_{\mathrm{D}}^{1}+(0)x_{\mathrm{D}}^{2}+\ldots+(0)x_{\mathrm{D}}^{4}+(2)x_{\mathrm{E}}^{1}+(2)x_{\mathrm{E}}^{2}+\ldots+(2)x_{\mathrm{E}}^{4}+(2)x_{\mathrm{F}}^{1}+(2)x_{\mathrm{F}}^{2}+(2)x_{\mathrm{F}}^{3}+\\
&(1)x_{\mathrm{G}}^{1}+(1)x_{\mathrm{G}}^{2}+\ldots+(1)x_{\mathrm{G}}^{6}+(2)x_{\mathrm{H}}^{1}+(2)x_{\mathrm{H}}^{2}+(0)x_{\mathrm{I}}^{1}+(0)x_{\mathrm{I}}^{2}+(0)x_{\mathrm{I}}^{3}-R_{\mathrm{ResA}}\leq 0
\end{aligned} \tag{2.17}$$

$$\begin{aligned}&\text{At Time 1}:\\&(0)x_{\mathrm{A}}^{1}+(0)x_{\mathrm{A}}^{2}+(0)x_{\mathrm{B}}^{1}+(0)x_{\mathrm{B}}^{2}+(0)x_{\mathrm{B}}^{3}+(0)x_{\mathrm{C}}^{1}+(0)x_{\mathrm{C}}^{2}+\ldots+(0)x_{\mathrm{C}}^{5}+\\&(2)x_{\mathrm{D}}^{1}+(2)x_{\mathrm{D}}^{2}+\ldots+(2)x_{\mathrm{D}}^{4}+(2)x_{\mathrm{E}}^{1}+(2)x_{\mathrm{E}}^{2}+\ldots+(2)x_{\mathrm{E}}^{4}+(1)x_{\mathrm{F}}^{1}+(1)x_{\mathrm{F}}^{2}+(1)x_{\mathrm{F}}^{3}+\\&(3)x_{\mathrm{G}}^{1}+(3)x_{\mathrm{G}}^{2}+\ldots+(3)x_{\mathrm{G}}^{6}+(1)x_{\mathrm{H}}^{1}+(1)x_{\mathrm{H}}^{2}+(1)x_{\mathrm{I}}^{1}+(1)x_{\mathrm{I}}^{2}+(1)x_{\mathrm{I}}^{3}-R_{\mathrm{ResB}}\leq 0\end{aligned}\tag{2.18}$$

$$\begin{aligned}&\text{At Time 2}:\\&(2)x_{\mathrm{A}}^{2}+(2)x_{\mathrm{A}}^{3}+(1)x_{\mathrm{B}}^{2}+(1)x_{\mathrm{B}}^{3}+(1)x_{\mathrm{B}}^{4}+(2)x_{\mathrm{C}}^{2}+(2)x_{\mathrm{C}}^{3}+\ldots+(2)x_{\mathrm{C}}^{6}+\\&(0)x_{\mathrm{D}}^{2}+(0)x_{\mathrm{D}}^{3}+\ldots+(0)x_{\mathrm{D}}^{5}+(2)x_{\mathrm{E}}^{2}+(2)x_{\mathrm{E}}^{3}+\ldots+(2)x_{\mathrm{E}}^{5}+(2)x_{\mathrm{F}}^{2}+(2)x_{\mathrm{F}}^{3}+(2)x_{\mathrm{F}}^{4}+\\&(1)x_{\mathrm{G}}^{2}+(1)x_{\mathrm{G}}^{3}+\ldots+(1)x_{\mathrm{G}}^{7}+(2)x_{\mathrm{H}}^{2}+(2)x_{\mathrm{H}}^{3}+(0)x_{\mathrm{I}}^{2}+(0)x_{\mathrm{I}}^{3}+(0)x_{\mathrm{I}}^{4}-R_{\mathrm{ResA}}\leq 0\end{aligned}\tag{2.19}$$

$$\begin{aligned}&\text{At Time 2}:\\&(2)x_{\mathrm{A}}^{2}+(2)x_{\mathrm{A}}^{3}+(1)x_{\mathrm{B}}^{2}+(1)x_{\mathrm{B}}^{3}+(1)x_{\mathrm{B}}^{4}+(2)x_{\mathrm{C}}^{2}+(2)x_{\mathrm{C}}^{3}+\ldots+(2)x_{\mathrm{C}}^{6}+\\&(0)x_{\mathrm{D}}^{2}+(0)x_{\mathrm{D}}^{3}+\ldots+(0)x_{\mathrm{D}}^{5}+(2)x_{\mathrm{E}}^{2}+(2)x_{\mathrm{E}}^{3}+\ldots+(2)x_{\mathrm{E}}^{5}+(2)x_{\mathrm{F}}^{2}+(2)x_{\mathrm{F}}^{3}+(2)x_{\mathrm{F}}^{4}+\\&(1)x_{\mathrm{G}}^{2}+(1)x_{\mathrm{G}}^{3}+\ldots+(1)x_{\mathrm{G}}^{7}+(2)x_{\mathrm{H}}^{2}+(2)x_{\mathrm{H}}^{3}+(0)x_{\mathrm{I}}^{2}+(0)x_{\mathrm{I}}^{3}+(0)x_{\mathrm{I}}^{4}-R_{\mathrm{ResB}}\leq 0\end{aligned}\tag{2.20}$$

$$3\leq R_{\mathrm{ResA}}\leq 5\tag{2.21}$$

$$2\leq R_{\mathrm{ResB}}\leq 5\tag{2.22}$$

2.6.2 Two-stage optimization approach

The above mathematical model for Stage 1 can be readily solved by setting the parameters $\{\alpha_{\mathrm{Act}}^{\mathrm{t}},\beta_{\mathrm{Proj}}^{\mathrm{t}},\gamma_{\mathrm{Res}}\}$ as $\{0,\beta_{\mathrm{Proj}}^{\mathrm{t}},\gamma_{\mathrm{Res}}\}$. Given the values of $x_{\mathrm{Proj}}^{\mathrm{t}}$ and R_{Res} as derived from the analytical solutions, Stage 2 optimization is followed by denoting the parameters $\{\alpha_{\mathrm{Act}}^{\mathrm{t}},\beta_{\mathrm{Proj}}^{\mathrm{t}},\gamma_{\mathrm{Res}}\}$ as $\{\alpha_{\mathrm{Act}}^{\mathrm{t}},0,0\}$. In this case study, the values of parameters $\{\alpha_{\mathrm{Act}}^{\mathrm{t}},\beta_{\mathrm{Proj}}^{\mathrm{t}},\gamma_{\mathrm{Res}}\}$ are assumed as $\{1,1,1\}$.

The computer software systems developed for solving linear integer programming formulations can be adopted. The optimizers generally implement branch-and-bound algorithms to enumerate theoretical optimum solution, such as MATLAB (MathWorks 2014) and CPLEX (IBM 2014) optimizers. The MATLAB version 2014 is chosen in the current research as it has been found effective to produce optimal solutions of complex problems (Savelsbergh 1994; Nemhauser and Wolsey 1999). Note the input-to-output processing in MATLAB for analytically solving the mathematical programming models by use of the standard matrix and vector formulations will be discussed in Chapter 3. In current case study, the resulting values of decision variables $\{x_{\text{Start}}^{0}, x_{\text{A}}^{2}, x_{\text{B}}^{3}, x_{\text{C}}^{5}, x_{\text{D}}^{6}, x_{\text{E}}^{13}, x_{\text{F}}^{9}, x_{\text{G}}^{11}, x_{\text{H}}^{13}, x_{\text{I}}^{14}, x_{\text{Proj}}^{14}, R_{\text{ResA}}, R_{\text{ResB}}\}$ are determined as $\{1,1,1,1,1,1,1,1,1,1,1,4,5\}$, while the values of other decision variables are generated as 0. Figure 2.9 shows the optimum schedule with the corresponding resource usage histogram. The leanest supply for Resources A and B is fixed as 4 and 5 units, respectively. The total project duration is 14 time units.

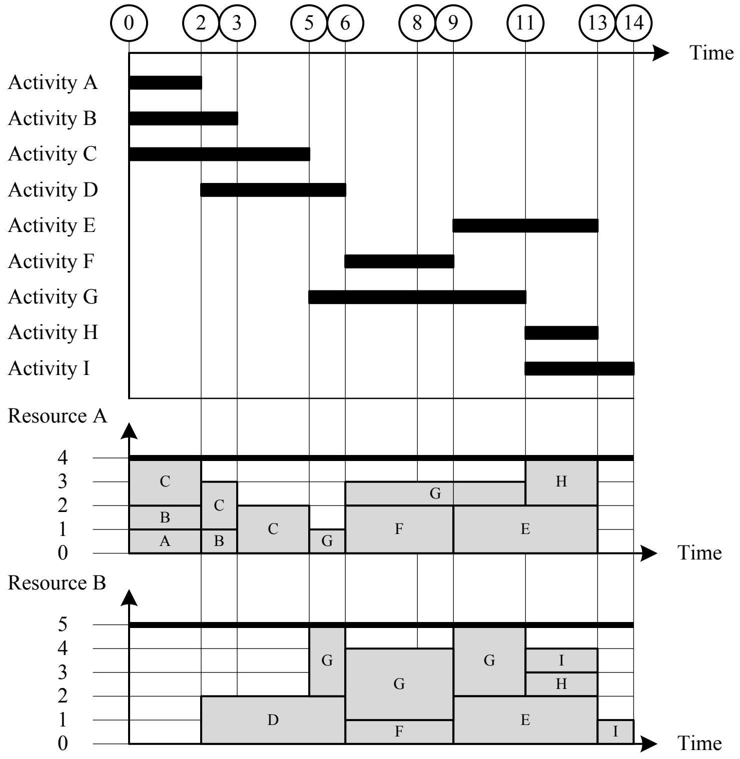


Figure 2.9: Optimum schedule for example case study (RDSMP approach)

2.6.3 Resource-activity interaction table

Figure 2.10 shows the data structure of the resource-activity interaction table. The current activity is denoted in Row (Cur.Act.). The early finish times of its predecessor activities are entered in Row (Pre.Act.EFT). Columns (1) and (2) represent resource identifier and resource name. Column (3) initializes the ready-to-serve (RTS) time of each available resource (i.e., 4 units for Resource A; 5 units of Resource B). Column (4) represents the end-of-service (EOS) time of each individual resource. Columns (a), (b) and (c) keep track of resource-activity interactions with respect to the current activity being executed. Column (a) updates the ready-to-serve (RTS) time of each individual resource according to the finish times of previously processed activities. Column (b) flags resource utilization (1 means utilized, 0 otherwise). Column (c) keeps idling time of each utilized resource prior to the start time of the current activity. The earliest start time and earliest finish time of the current activity are entered in Row (EST) and Row (EFT), respectively.

Cur.Act.			C			B			A			D			G			F			E			H			I			
Pre.Act EFT			0			0			0			2			3 5			3			2			6			9 11			
(1)	(2)	(3)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(4)
1	ResA1	0	0	1	0	5			5			5			5			5	1	1	9			9	1	2	13			13
2	ResA2	0	0	1	0	5			5			5			5			5			5	1	4	13			13			13
3	ResA3	0	0			0	1	0	3			3			3			3	1	3	9	1	0	13			13			13
4	ResA4	0	0			0			0	1	0	2			2	1	3	11			11			11	1	0	13			13
5	ResB1	0	0			0			0			0	1	2	6			6	1	0	9	1	0	13			13			13
6	ResB2	0	0			0			0			0	1	2	6			6			6	1	7	13			13			13
7	ResB3	0	0			0			0			0			0	1	5	11			11			11	1	0	13			13
8	ResB4	0	0			0			0			0			0	1	5	11			11			11			11	1	0	14
9	ResB5	0	0			0			0			0			0	1	5	11			11			11			11			11
EST			0			0			0			2			5			6			9			11			11			
EFT			5			3			2			6			11			9			13			13			14			

Direction to read →

Figure 2.10: Resource-activity interaction table for the example case study

The optimum supply of Resource A and Resource B are 4 and 5 units, respectively. Columns (1) and (2) declare IDs (1 – 4) and names (ResA1 – ResA4) of Resource A, and IDs (5 – 9) and names (ResB1 – ResB5) of Resource B. The RTS times of all resources are initialized as 0 (Column 3). According to the analytical solution, Activities A, B, and C start at Time 0. In the present case, both Resources A and B are taken as the leading resources. Thus, Activity C owns the largest work content (5 × 2 = 10 res-time units), followed by Activity B (3 res-time units) and Activity A (2 res-time units), in accordance with the work content rule. Hence, Activity C is the first activity to schedule, and its ID is entered in Row (Cur.Act.). The EFT of its predecessor, which is recorded in Row (Pre.Act.EFT), is Time 0. The RTS times of all resources are Time 0 (Column a). With regard to the earliest-ready-first-serve rule, ResA1 and ResA2 are chosen to execute Activity C (Column b). The idling times of ResA1 and ResA2 are 0 time unit, prior to the start time of Activity C (Column c). As such, Activity C starts at Time 0 and completes at Time 5. The EST and EFT are recorded in Row (EST) and Row (EFT), respectively. Next, Activity B is scheduled and is followed by completing Activity A. Before executing Activity B, the RTS times of ResA1 and ResA2 are Time 5 since Activity C completes at Time 5. Therefore, the RTS times of all resources, except for ResA1 and ResA2, still remain at Time 0. Both Activity B and Activity A require 1 unit of Resource A to execute the work. On the basis of the earliest-ready-first-serve rule, ResA3 and ResA4 are assigned to execute Activities B and A, respectively. The detailed data on individual resource workflows for Activities D, G, F, E, H and I are presented and visualized (Figure 2.10). The final end-of-service times of individual resources are given in Column (4).

It is worth mentioning that the activities are completed at the time points as derived in the analytical solution, and resource supply satisfies resource demand at each time unit over the project period. As such, the feasibility of the optimum schedule and the validity of the proposed RSDMP mathematical model are verified. In addition, next section provides a cross-validation of the proposed RSDMP solution against solutions resulting from applying a simulation based approach and an evolutionary-algorithm based optimization approach on the case study example. Then, a case study based on an oil refinery turnaround project is presented to demonstrate its applications in practical settings.

2.7 Cross-validation against simulation and evolutionary optimization solutions

This section provides a cross-validation of the proposed RSDMP solution against solutions resulting from a simulation based approach and an evolutionary-algorithm based optimization approach based on the case study example.

A simulation model for the example case study is built using a discrete-event simulation platform, named as SDESA (Lu et al., 2008). In the resource pool of the simulation model, 5 units of Resource A and 5 units of Resource B are initialized. Figure 2.11 shows the simulated resource-constrained schedule, and Figure 2.12 gives the detailed schedule results represented in the resource-activity interaction table. It shows that the project is completed at Time 15 by utilizing 5 units of Resource A and 5 units of Resource B. In contrast with the RDSMP solution, the project duration is 1 time unit longer while 1 extra unit of Resource A is involved.

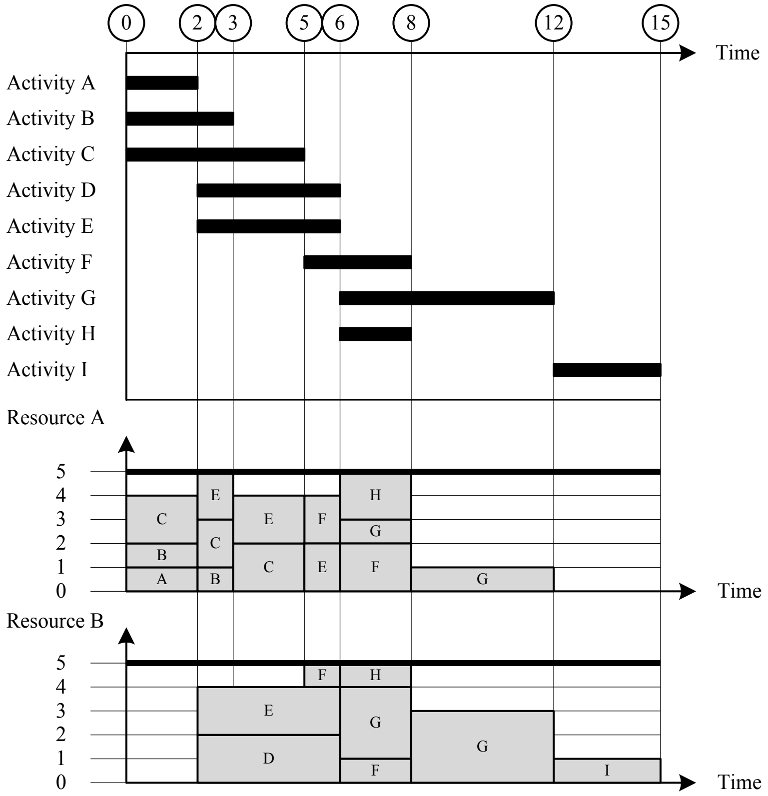


Figure 2.11: Optimum schedule for example case study (simulation approach)

Cur.Act.			C			B			A			E			D			F			G			H			I			
Pre.Act EFT			0			0			0			2			2			3			3 5			6			8 12			
(1)	(2)	(3)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(4)
1	ResA1	0	0	1	0	5			5			5			5			5	1	0	8			8			8			8
2	ResA2	0	0	1	0	5			5			5			5			5			5	1	1	12			12			12
3	ResA3	0	0			0	1	0	3			3			3			3	1	2	8			8			8			8
4	ResA4	0	0			0			0	1	0	2	1	0	6			6			6			6	1	0	8			8
5	ResA5	0	0			0			0			0	1	2	6			6			6			6	1	0	8			8
6	ResB1	0	0			0			0			0	1	2	6			6			6	1	0	12			12			12
7	ResB2	0	0			0			0			0	1	2	6			6			6	1	0	12			12			12
8	ResB3	0	0			0			0			0			0	1	2	6			6	1	0	12			12			12
9	ResB4	0	0			0			0			0			0	1	2	6			6			6	1	0	8			8
10	ResB5	0	0			0			0			0			0			0	1	5	8			8			8	1	4	15
EST			0			0			0			2			2			5			6			6			12			
EFT			5			3			2			6			6			8			12			8			15			

Direction to read →

Figure 2.12: Resource-activity interaction table for example case study (simulation approach)

An evolutionary optimization engine (particle swarm optimization) is integrated in SDESA simulation platform, which can be used to optimize the schedule in regard to the shortest project duration. With the same settings in the resource pool (5 units of Resource A and 5 units of Resource B), the optimization process was invoked to shorten project duration by adjusting relative priority rankings of activities. Figure 2.13 shows the resulting optimum schedule. Note the project duration is reduced to 14 time units given 5 units of Resource A and 5 units of Resource B are employed. Detailed schedule results are given in the resource-activity interaction table (Figure 2.14).

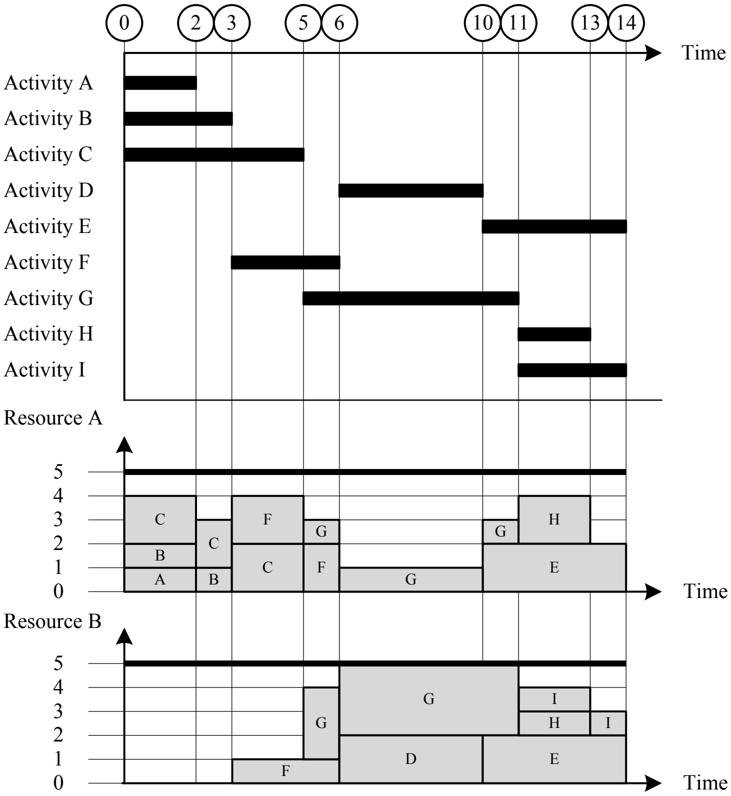


Figure 2.13: Optimum schedule for example case study (evolutionary approach)

Cur.Act.			C			B			A			F			G			D			E			H			I			
Pre.Act EFT			0			0			0			3			3 5			2			2			10			6 11			
(1)	(2)	(3)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(4)
1	ResA1	0	0	1	0	5			5			5			5			5			5	1	5	14			14			14
2	ResA2	0	0	1	0	5			5			5			5			5			5	1	5	14			14			14
3	ResA3	0	0			0	1	0	3			3			3	1	2	11			11			11			11			11
4	ResA4	0	0			0			0	1	0	2	1	1	6			6			6			6	1	5	13			13
5	ResA5	0	0			0			0			0	1	3	6			6			6			6	1	5	13			13
6	ResB1	0	0			0			0			0	1	3	6			6	1	0	10	1	0	14			14			14
7	ResB2	0	0			0			0			0			0	1	5	11			11			11	1	0	13			13
8	ResB3	0	0			0			0			0			0	1	5	11			11			11			11	1	0	14
9	ResB4	0	0			0			0			0			0	1	5	11			11			11			11			11
10	ResB5	0	0			0			0			0			0			0	1	6	10	1	0	14			14			14
EST			0			0			0			3			5			6			10			11			11			
EFT			5			3			2			6			11			10			14			13			14			

Direction to read →

Figure 2.14: Resource-activity interaction table for example case study (evolutionary approach)

For this small case project, the optimum schedule from the proposed RDSMP identifies 4 units of Resource A and 5 units of Resource B to be employed in order to complete the project in 14 time units.

The computer used for conducting above cross-validations has the following specifications: processor: Intel Core i7-4770 CPU, 3.40 GHz; memory: 16.0 GB; system type: 64-bit operating system, x64-based processor. It is found that the theoretical optimum solution can be reached within 5 seconds by implementing the proposed RDSMP approach (Stage 1 and Stage 2 combined).

2.8 Industrial plant shutdown project

A three-month oil refinery turnaround project is executed in Alberta Canada. The preventive, predictive and corrective maintenance work is planned in order to upgrade existing facilities including the reactor, the regenerator, and the overhead system. The scope of this project consists of (i) replacing the four elbows in the reactor; (ii) removing existing head and cyclone assemblies; (iii) installing new head and cyclone assemblies; and (iv) completing refractory and tie-in electrical instrumentation, piping and platforming. The scope of the present case study is narrowed down to the reactor upgrading portion of this turnaround project.

As the industrial plant is suspended for construction, oil is not produced during the turnaround period. Substantial economic loss would be incurred if the project were delayed. One common cause for turnaround project delay is attributed to the fact that skilled labor resources are not sufficient to execute planned maintenance activities (O'Connor and Tucker 1986; Siddiqui and Rafiuddin 2012). As such, the turnaround project requires stringent task-sequencing control due to technological feasibility, while also entailing detailed workflow planning of highly limited skilled laborers (Lenahan 2006). Planners define the turnaround activities in the finest granularities (e.g., time unit is an hour instead of a day). The resource supply of a crew mix, factoring in the site's spatial and safety requirements, is roughly estimated to match the project demand based on experiences in handling similar projects in the past.

The project work breakdown information, including activity name, activity duration, activity precedence relationships, and resource demand required by each activity, is summarized in Appendix A. This project is planned for approximately 200 hours. In total, there are 107 activities and 19 types of resources planned. The resource supply limits are defined in Table 2.2. In this case study, the focus is on formulating the optimum baseline schedule for workface planning purpose, which features the shortest project duration and optimum resource supply limits subject to all the technological and resource availability constraints. Practical factors such as delay due to clarifying engineering drawings with the designer; delayed material supply due to bad weather; and labor supply shortage due to preemptive demand from other areas of the same project or different projects under the same contractor will present additional constraints to update the baseline schedule resulting from the current research. Addressing those factors may also involve the use of other techniques relevant to project control and risk analysis. This is out of the scope of the current work, but outlines promising research directions to pursue down the path.

Table 2.2. Resource supply of turnaround project

Resources identifier	Estimate	Optimum
A	0 – 20	14
B	0 – 10	9
C	0 – 2	1
D	0 – 7	6
E	0 – 10	6
F	0 – 10	6
G	0 –6	6
H	0 – 5	2
I	0 – 2	2
J	0 – 2	2
K	5 – 15	7
L	0 – 1	1
M	0 – 1	1
N	0 – 1	1
O	0 – 4	2
P	0 – 5	2
Q	0 – 4	1
R	0 – 2	1
S	0 – 2	1

The proposed RSDMP scheduling approach was applied. The decision variables of the RSDMP mathematical model in regard to activity completion times, the project completion time and resource supply were declared as $\{x_{\text{Start}}^{0},\ldots,x_{\text{Start}}^{200},x_{001}^{0},\ldots,x_{001}^{200},\ldots,x_{107}^{200}\}$, $\{x_{\text{Proj}}^{0},\ldots,x_{\text{Proj}}^{200}\}$ and $\{R_{\text{A}},R_{\text{B}},\ldots,R_{\text{S}}\}$, respectively. The mathematical model consists of 1 objective function, 128 technological constraints, and 3,800 resource constraints (19 resources × 200 time units), 109 equations to constrain one activity/project completion time, 21,910 equations (109 decision variables for activity/project completion time × 201 time units) for declaring the binary variables corresponding with activity/project completion times, and 19 equations for defining the resource supply limits. The optimum solution is generated by using MATLAB version 2014. The optimum solution emerged in 30 seconds computer time. The shortest project duration is 173 hours. Table 2.3 shows activity and project completion times in terms of hours after project starts. The leanest resource supply is determined, as tabulated in Table 2.2. The two-stage optimization approach was implemented. Though the detailed resource-activity interaction table is not included in this chapter due to length limitation, it can be readily constructed by readers based on the analytical solution provided.

Table 2.3. Analytical solutions for turnaround project

Activity identifier	Time	Activity identifier	Time	Activity identifier	Time	Activity identifier	Time
1	50	31	72	61	50	91	134
2	1	32	82	62	147	92	137
3	9	33	102	63	82	93	5
4	13	34	40	64	51	94	4
5	22	35	46	65	57	95	1
6	18	36	76	66	61	96	10
7	32	37	58	67	172	97	10
8	42	38	77	68	65	98	5
9	10	39	87	69	71	99	11
10	52	40	102	70	77	100	13
11	1	41	92	71	77	101	3
12	2	42	60	72	83	102	2
13	3	43	91	73	83	103	6
14	4	44	62	74	173	104	8
15	42	45	64	75	89	105	13
16	20	46	92	76	89	106	16
17	5	47	102	77	5	107	142
18	6	48	112	78	17	108	173
19	10	49	66	79	95		
20	9	50	106	80	95		
21	12	51	106	81	101		
22	14	52	122	82	101		
23	62	53	107	83	18		
24	62	54	131	84	107		
25	30	55	132	85	119		
26	18	56	171	86	112		
27	22	57	42	87	122		
28	28	58	152	88	125		
29	40	59	142	89	128		
30	34	60	30	90	131		

On applications of practical size and complexity, the proposed RSDMP scheduling approach can be taken as an effective feasibility check on the preset target project duration subject to tight resource supply limits. For example, if T was set to be 100 hours or supply limits for key resources (e.g., boilermakers, pipefitters) were set at very low levels, the model would not have converged to any feasible solution. As such, infeasibility warning can be immediately conveyed to planners and follow-up actions can be recommended, such as reassessing target duration and resource supply limits before redoing the analysis. On the other hand, if the upper limit for pipefitters is set on the high side (oversupply), the optimum resource supply limit for pipefitters can be determined so as to avoid unnecessary waste in resource utilization, as demonstrated in the case study.

2.9 Conclusions

This chapter develops a quantitative RSDMP approach for matching resource supply and resource demand to facilitate project scheduling and workface planning. It addresses how to formulate the optimum schedule with the shortest project duration and leanest resource supply, so as to plan the workflow of individual craft persons while matching the resource supply and demand for the project. As a result of the RSDMP scheduling analysis, the plan obtained is resource-loaded, practically feasible, and workface executable, while also featuring the shortest total project duration with the leanest resource supply under the boundaries of resource supply limit being evaluated by the site planner in consideration of the site’s spatial and safety requirements. The RSDMP approach holds the potential to immediately impact and advance the state-of-the-art in scheduling research and the current practice of construction workface planning. The next chapter modifies the developed RSDMP approach for determining the optimum quantities of resource supply for particular time periods in order to formulate the project schedules with time-dependent resource constraints.

CHAPTER 3: ZERO-ONE PROGRAMMING APPROACH TO DETERMINE OPTIMUM RESOURCE SUPPLY UNDER TIME-DEPENDENT RESOURCE CONSTRAINT[3]

3.1 Introduction

Skilled labor is the critical resource to any construction project, but generally is highly limited and availabilities vary for particular time periods. At the planning stage, the determination of resource supply quantities is largely dependent on the experience of project managers, project schedulers, and field superintendents, without any analytical decision support. In practice, it is generally stipulated in the contractual documents that the schedule be developed based on the critical path method (CPM) in order to guide activity and project executions (AACE 2010). However, CPM becomes convoluted if the schedule is resource-constrained (Fondahl 1991). The current CPM-based scheduling tools, such as Primavera P6, do not provide functionalities to analyze the optimum resource supply in meeting resource demand for particular time periods (Harris 2008, 2013). Little scheduling-related research has yet attempted to address time-dependent resource availability constraints commonly encountered during project execution.

Quantities of resource supply are generally determined based on the aggregated demand of activities, which can vary at different stages of project execution. The quantity of each resource must be assigned within the practical range in consideration of the spatial and safety restrictions on site. A case of assigning skilled trade resources, namely boilermakers and pipefitters, to an

---

[3] This chapter has been published in the journal of computing in civil engineering, ASCE. 10.1061/(ASCE)CP.1943-5487.0000498, 04015028.

industrial project is considered. Figure 3.1 shows the activity network. Table 3.1 summarizes activity durations and activity-resource requirements. Three practical decision making scenarios in relation to resource scheduling can be considered:

1. How many resources should be allocated to the project if at most ten boilermakers [0 – 10] and five pipefitters [0 – 5] are available?

2. How many resources should be allocated if [1 – 4] boilermakers and [2 – 3] pipefitters are available?

3. How many resources should be allocated if [1 – 4] boilermakers and [2 – 3] pipefitters are available from the project start time, but the available quantities change to [0 – 10] boilermakers and [0 – 5] pipefitters after Time 30?

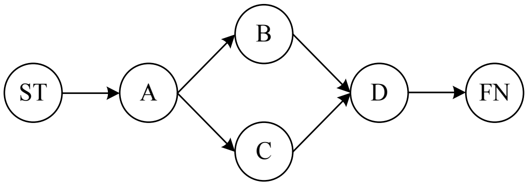


Figure 3.1: Activity network

Table 3.1: Activity and resource requirements

Activity	Duration	Resource	
		Boilermaker	Pipefitter
A	25	2	2
B	20	2	1
C	10	3	2
D	25	3	0

This research work focuses on the determination of optimum resource quantities between the specified resource availability boundaries, so as to formulate the optimum schedule under time-dependent resource availability constraints. The proposed resource scheduling methodology is developed by modifying the resource supply-demand matching problem (RSDMP) approach, as presented in the previous chapter. As such, the resulting optimum schedule shortens total project duration while streamlining resource supply for each specific time period.

In the following sections, literature on resource-constrained project scheduling problems in connection with the time-dependent resource constraints is critically reviewed. The mathematical model along with the two-stage solution framework is presented for the new problem's definition. An example is given to illustrate the calculation procedure. The turnaround project serves as a test case to demonstrate method application and computing efficiency. Conclusions of the present work are drawn by discussing theoretical limitations and potential benefits to construction scheduling practitioners.

3.2 Literature review

The critical path method (CPM) has found widespread use in construction project scheduling. However, the classic CPM has limitations when coping with resource constraints on a construction project. For example, in solving the resource-constrained project scheduling problem (RCPSP), the finite quantities of available resources can significantly change the activity execution sequence. As a result, the project network model underlying CPM analysis may not be a valid representation, while the completion times for both an activity and the project can become irrelevant and misleading (Fondahl 1991). In general, researchers have applied four categories of methodologies in order to tackle RCPSP, namely: (i) heuristic rule; (ii) evolutionary-algorithm; (iii) simulation; and (iv) mathematical modeling approaches.

The heuristic rule relies on a list of priorities to sequence the processing of candidate activities when resource availability on a project is finite (Boctor 1990; Finke 2008). For example, the scheduling software system of Primavera P3 sets the activity priorities based on the minimum slack heuristic rule. The later Primavera P6 defines five levels of activity priority in connection with the attributes of each activity and allows for the variations of resource availability limits in different time periods (Harris 2008, 2013). Lu and Li (2003) prioritized activities based on the work content of the primary resource and allocated limited resources to activities according to the earliest-ready-first-serve rule. The proposed heuristic method was intended to reduce the idling time of individual resources, but not to minimize the total project time. Wongwai and Malaikrisanachalee (2011) suggested heuristic rules to allocate resources by considering substitute resources, which allows for the use of available multiskilled resources to substitute for the resources that are needed but not available. In short, one of the major drawbacks in applying heuristic approaches is that the generated schedule is not guaranteed to be the optimum in terms of total project duration or resource supply.

Evolutionary-algorithms are stochastic methods for searching optimum solutions. The population of solutions is randomly initialized. The feasibility of solutions is assessed by examining if the generated schedule satisfies the technological and resource constraints. The populations are continuously evolved based on reproduction mechanisms (Elbeltagi et. al 2005). The near-optimum solution is determined based on its fitness. This process entails a large number of iterations (generations) in order to evaluate a large quantity of feasible solutions. The evolutionary-algorithms have been proven to be an effective computer-based approach for generating near-optimum solutions within a reasonable time frame. Leu et al. (2000) pointed out that the advantage of using genetic algorithms is that multiple optimum schedules can be generated to benefit decision makers. Zhang et al. (2005), Lu et al. (2008) proposed the use of particle swarm optimization to minimize project duration by changing activity priority. They treated the resource availability limit as a constant that would remain unchanged during the optimization process. Zhang et al. (2006) further integrated activity break constraints in optimizing the schedule. They divided a preemptive activity into subunits that would not be scheduled when resources required are unavailable; activity priority was assigned for each subunit to facilitate particle swarm optimization. Kim and Ellis (2008) proposed elitist genetic algorithm to generate optimum schedules in both serial and parallel fashions. Hegazy (1999) applied genetic algorithms to allocate resources along with leveling the resource use profile. To select the optimum activity execution mode among multiple resource-time tradeoff options under resource availability constraints, Ng and Zhang (2008), Li and Zhang (2013) proposed the ant-colony optimization approach and Ashuri and Tavakolan (2013) developed a leapfrog optimization approach. Simultaneously solving of resource allocation, leveling and time-cost tradeoff problems by applying genetic algorithms (Heon Jun and El-Rayes 2011; Ghoddousi et al. 2013) or a strength Pareto evolutionary approach (Hu and Flood 2012) were also attempted. In spite of the effectiveness and efficiency in solving practical project and resource scheduling problems, evolutionary-algorithms remain relatively weak in theoretical foundations.

Discrete event simulation is a commonly applied technique to account for operational details and model dynamic resource workflows (such as waiting or queuing). In analyzing the impact of resource availability constraint, researchers have applied simulation modeling and conducted sensitivity analysis based on the two-point estimates of resource supply limits. The simulation runs are generally executed for evaluating all likely scenarios in order to determine the optimum resource supply (AbouRizk and Shi 1994; Zhang and Li 2004; Zhang et al. 2006; Lee et al. 2010; Chen et al. 2012). Padilla and Carr (1991) proposed the use of equations to calculate activity priorities as simulation model input for resource allocation. McCahill and Bernold (1993) developed a resource-based simulation approach to model resource workflows and predict production rates. AbouRizk and Shi (1994) attempted to evaluate a large quantity of resource combinations and comparing feasible alternatives through simulation modeling. Leu and Hung (2002) considered uncertainties in executing activities subject to specified resource availability limits. Hegazy and Kassab (2003) proposed the use of genetic algorithms to initialize the potential solutions (resource combinations), and determined the optimum resource supply based on simulation outputs. Zhang and Li (2004) proposed heuristic rules to guide the allocation of available resources for executing activities. The heuristic rules were applied and embedded in the simulation engine. Park et al. (2005) built system dynamics simulation models in order to investigate project performances in regard to time, cost and resource use; resource supply quantities were adjusted in each simulation scenario. Zhang et al. (2006) proposed a simulation-based optimization architecture, and observed that the exhaustive examination of combinations would incur substantial computing resources and time if feasible ranges of available resources were wide. Lu et al. (2008) integrated discrete event simulation with particle swarm optimization, so as to evaluate the optimum resource supply for the project. In brief, simulation models are case-dependent, tedious to build and update, and not oriented towards reaching theoretical optimums. Besides, model building, verification and validation require construction planners to have sufficient simulation knowledge and computer programming skills.

Mathematical modeling approaches generally consist of defining objective functions, subject to satisfying a set of constraints. Use of linear programming to generate non-resource-constrained schedule is well established (Tang 1999). The objective function is to minimize the project completion time. The constraints are set based on activity precedence relationships. However, resources are indispensable for executing construction activities while limited resource availability can significantly extend total project duration. Therefore, mathematical models have been enhanced to incorporate resource availability constraints (Rieck et al. 2012). Pritsker et al. (1969) proposed the use of integer linear programming models to schedule a project subject to limited resources. They devised a unique modeling strategy by utilizing binary variables to represent time points on which each activity is completed. With the advent of computers, solutions to resource-constrained scheduling problems of practical size and complexity can be efficiently identified based on Pritsker's modeling strategy (Hall 1980). Doersch and Patterson (1977) modified Pritsker's mathematical model to maximize the net present value of the project. In construction engineering and management domain, Menesi and Hegazy (2014) applied constraint programming to simultaneously solving resource allocation, resource leveling and time-cost tradeoff problems. Megow et al. (2011) applied integer linear mathematical model to formulate a resources-constrained and leveled schedule for an industrial plant turnaround project. They assumed that the resource availability remained unchanged throughout the project period.

The determination of optimum resource supply quantities for different periods of the project duration has yet to be addressed.

Based on the literature review, the formulation and solution of a mathematic optimization model aiming to identify an optimum project schedule under time-dependent resource availability constraints are yet to be formalized.

3.3 Modified RSDMP mathematical model

The RSDMP mathematical model is modified by extending the modeling strategy as presented in previous chapter. The mathematical model consists of an objective function, decision variables and constraints on the values of decision variables (Winston 2003). In previously developed mathematical models (such as Pritsker et al. 1969; Hall 1980), the objective function is generally given to minimize project completion time, with activity start/completion times being the decision variables and the resource availability limit generally set as a constant. In contrast, the proposed RSDMP model generalizes an objective function intended to optimize three critical construction planning factors in an integrative fashion, namely: activity completion times, project completion time, and resource supply for particular time periods. For each specific time period, resource availability can be given as a range (a lower bound and an upper bound). The time-dependent resource availability constraints are imposed to maintain the balance between resource demand and supply in particular time periods. Furthermore, a two-stage solution framework is devised to align with critical decision making processes in current practices of project scheduling and workface planning.

3.3.1 Decision variables

The decision variables of the proposed mathematical model are declared as $x_{\mathrm{Act}}^{\mathrm{t}}, x_{\mathrm{Proj}}^{\mathrm{t}}, R_{\mathrm{Res}}^{\mathrm{tp}}$. The subscripts "Act" and "Res" indicate the names of activity and resource. The superscripts "t" and "tp" indicate "time point" and "time period", respectively.

3.3.2 Objective function

The proposed objective function is expressed as Equation (3.1). The parameters $\alpha_{\mathrm{Act}}, \beta_{\mathrm{Proj}}, \gamma_{\mathrm{Res}}^{\mathrm{tp}}$ indicate the relative importance (or weight) of (i) activity completion time; (ii) project completion time; and (iii) resources supply for particular time periods, respectively.

$$\text{minimize} \quad f = \sum_{\mathrm{Act}} \sum_{\mathrm{t=0}}^{\mathrm{T}} (\alpha_{\mathrm{Act}} \mathrm{t} x_{\mathrm{Act}}^{\mathrm{t}}) + \sum_{\mathrm{t=0}}^{\mathrm{T}} (\beta_{\mathrm{Proj}} \mathrm{t} x_{\mathrm{Proj}}^{\mathrm{t}}) + \sum_{\mathrm{Res}} \sum_{\mathrm{tp}} (\gamma_{\mathrm{Res}}^{\mathrm{tp}} R_{\mathrm{Res}}^{\mathrm{tp}}) \tag{3.1}$$

where f = objective function; α_{Act}= relative importance of activity completion time; β_{Proj}= relative importance of project completion time; $\gamma_{\mathrm{Res}}^{\mathrm{tp}}$ = relative importance of supply quantity for particular resource at time period tp; t= time unit, from start time 0 to end time T; $x_{\mathrm{Act}}^{\mathrm{t}}$=binary variable, 1 represents an activity completes at time t, or 0 otherwise; $x_{\mathrm{Proj}}^{\mathrm{t}}$= binary variable, 1 represents the project completes at time t, or 0 otherwise; $R_{\mathrm{Res}}^{\mathrm{tp}}$= resource supply at time period tp.

$\sum_{\mathrm{Act}}\sum_{\mathrm{t}=0}^{\mathrm{T}}(\alpha_{\mathrm{Act}}\mathrm{t}x_{\mathrm{Act}}^{\mathrm{t}})$ is intended for minimizing activity completion time, by multiplying (i) the binary variable $(x_{\mathrm{Act}}^{\mathrm{t}})$, which indicates activity completion status; (ii) the corresponding time t bounded between 0 and T; and (iii) the corresponding weight α_{Act}. Similarly, $\sum_{\mathrm{t}=0}^{\mathrm{T}}(\beta_{\mathrm{Proj}}\mathrm{t}x_{\mathrm{Proj}}^{\mathrm{t}})$ is to minimize project completion time by multiplying (i) the binary variable $(x_{\mathrm{Proj}}^{\mathrm{t}})$ which indicates project completion status at the associated time t, (ii) the corresponding time t bounded between 0 and T, and (iii) the corresponding weight β_{Proj}. $\sum_{\mathrm{Res}}\sum_{\mathrm{tp}}(\gamma_{\mathrm{Res}}^{\mathrm{tp}}R_{\mathrm{Res}}^{\mathrm{tp}})$ is intended to optimize resource supply $R_{\mathrm{Res}}^{\mathrm{tp}}$ for all resource types by multiplying the resource availability at time period tp and the corresponding weight $\gamma_{\mathrm{Res}}^{\mathrm{tp}}$. The weight parameter of $\gamma_{\mathrm{Res}}^{\mathrm{tp}}$ can be interpreted as the unit rate of utilizing a particular resource at a particular time period tp.

The three weight parameters $\{\alpha_{\mathrm{Act}},\beta_{\mathrm{Proj}},\gamma_{\mathrm{Res}}^{\mathrm{tp}}\}$ are generally defined to indicate the relative importance for different criteria in multiobjective optimizations (Li 1996; Rardin 1998; Kandil et al. 2010; Heon Jun and El-Rayes 2011; Mathwork 2014). As for cost analysis on typical construction projects, the indirect cost is generally estimated as fixed portion (field office, crane installation, utility installation such as power, water, washroom) plus variable portion (utility usage, salaries and allowances for administrative staff, project management staff such as superintendent, scheduler/planner, quality and safety personnel)—which can be estimated as a constant rate (dollar/time unit) throughout the project period (Hegazy 2002). On the other hand, the direct cost (particularly labor cost) is more complicated to estimate and more difficult to control, which is not held constant but varies considerably in different time periods. Nevertheless, the parameters β_{Proj} and $\gamma_{\text{Res}}^{\text{tp}}$ can be set as relative ratios as well as absolute unit rates. The scaling and normalization of minimization components are only relevant in the case of applying relative ratios, which dependent on subjective preferences and project-specific constraints.

In order to shed light on the implications of the weight parameters in the context of project scheduling and workface planning in practice, a two-stage solution framework is proposed, as follows:

Stage 1: Determine the shortest project duration $x_{\text{Proj}}^{\text{t}}$ and the optimum quantity to supply each type of resource over a specific time period $R_{\text{Res}}^{\text{tp}}$.

In the objective function, α_{Act} is set as zero $(\alpha_{\text{Act}} = 0)$. Thus, the objective is to optimize project duration and resource supply. The parameter β_{Proj} can be interpreted as the indirect cost per time unit to be incurred on the project; while $\gamma_{\text{Res}}^{\text{tp}}$ can be interpreted as the direct cost (crew resources) per unit for particular time periods. In a practical application context, the Stage 1 objective is essentially to minimize the total project cost by identifying the optimum combination of total project duration and resource supply settings for different time periods during the project duration. Thus, the project scheduling and resource planning process underlying Stage 1 optimization can be related to the practical context of making the cost budgeting decision by project management.

The following three scenarios of setting the parameters β_{Proj} and $\gamma_{\text{Res}}^{\text{tp}}$ as relative ratios are as follows:

(i) When β_{Proj} and $\gamma_{\text{Res}}^{\text{tp}}$ are of the same order of magnitude and close to one another (for example, $\beta_{\text{Proj}} = 1$ and $\gamma_{\text{Res}}^{\text{tp}} = 1$), the optimization will arrive at a resource-constrained schedule achieving the optimum tradeoff between the indirect cost (in terms of shortening total project duration) and the direct cost (in terms of providing sufficient resources).

(ii) When β_{Proj} is greater than $\gamma_{\text{Res}}^{\text{tp}}$ by orders of magnitude (for example, $\beta_{\text{Proj}} = 100$ and $\gamma_{\text{Res}}^{\text{tp}} = 1$), this indicates that much higher weight is placed on shortening total project duration against providing the leanest resources. The Stage 1 optimization is thus more inclined toward identifying a resource-constrained schedule with the shortest total project duration. This scenario applies to the industrial turnaround project scheduling as the refinery plant shutdown incurs a high daily cost of production loss, which is taken as the major portion of project indirect cost. As such, completing the project in the shortest project duration governs the optimization objective.

(iii) When $\gamma_{\text{Res}}^{\text{tp}}$ is greater than β_{Proj} by orders of magnitude, lowering the direct cost by streamlining resources outweighs shortening project duration and thus governs the optimization objective function. This generally applies to the practical scenario of employing expensive crews with specialized equipment and materials.

Stage 2: Given the optimized schedule resulting from Stage 1, fine-tune activity finish times to identify earliest finish times $x_{\text{Act}}^{\text{t}}$.

After the values of decision variables $R_{\text{Res}}^{\text{tp}}$ and $x_{\text{Proj}}^{\text{t}}$ are determined from Stage 1 optimization, the values are fixed as constants for Stage 2 optimization. Stage 2 optimization is more relevant to the decision making process by field superintendents who plan for the earliest possible start and finish times on each activity. Thus, this stage of optimization analysis is intended to complete each activity at the earliest opportunity so as to maximize the cushion against potential delays during project execution. Note this is analogous to the strategy of defining total float in classic critical path method scheduling.

As such, $\{\alpha_{\text{Act}}, \beta_{\text{Proj}}, \gamma_{\text{Res}}^{\text{tp}}\}$ in the objective function is set as $\{1, 0, 0\}$ in Stage 2. Only α_{Act} is switched on in Stage 2 optimization $(\alpha_{\text{Act}} = 1)$ and the optimization is initialized based on the results obtained in Stage 1.

The final output is the optimum RSDMP schedule formulated under time-dependent resource constraints and ready for execution in the field. The optimum schedule features (i) the optimum project duration with the optimum resource supply (leading to the minimum total project cost), and (ii) the earliest activity completion times.

3.3.3 Technological constraints

Technological constraints are imposed in order to maintain activity precedence relationships, expressed as Equation (3.2). The completion time of the current activity must be less than the completion time of its successor(s) minus its duration (d_{Suc}). However, d_{Suc} is equal to 0 if the successor is project complete, referring to Equation (3.3). Equations (3.4) and (3.5) maintain that only one completion time is allowed for each activity and the project, respectively. The time points, at which an activity or the project is completed, are denoted by binary variables, given as Equations (3.6) and (3.7).

$$\sum_{\mathrm{t}=0}^{\mathrm{T}}[(\mathrm{t}x_{\text{Act}}^{\mathrm{t}})]_{\text{Pred}} \le \sum_{\mathrm{t}=0}^{\mathrm{T}}[(\mathrm{t}-d_{\text{Suc}})x_{\text{Act}}^{\mathrm{t}}]_{\text{Suc}}, \quad \text{for each activity-to-activity precedence relationships} \tag{3.2}$$

$$\sum_{\mathrm{t}=0}^{\mathrm{T}}[(\mathrm{t}x_{\text{Act}}^{\mathrm{t}})]_{\text{Pred}} \le \sum_{\mathrm{t}=0}^{\mathrm{T}}[(\mathrm{t}x_{\text{Proj}}^{\mathrm{t}})]_{\text{Suc}}, \quad \text{for each activity-to-project precedence relationships} \tag{3.3}$$

$$\sum_{\mathrm{t}=0}^{\mathrm{T}} x_{\text{Act}}^{\mathrm{t}} = 1, \text{ for all activities} \tag{3.4}$$

$$\sum_{\mathrm{t}=0}^{\mathrm{T}} x_{\text{Proj}}^{\mathrm{t}} = 1, \text{ for the project} \tag{3.5}$$

$$x_{\text{Act}}^{\mathrm{t}} = \{0,1\} \tag{3.6}$$

$$x_{\text{Proj}}^{\mathrm{t}} = \{0,1\} \tag{3.7}$$

where d_{Suc} = duration of successor.

3.3.4 Time-dependent resource constraints

The time-dependent resource availability constraints are expressed with respect to time point t and time period tp. The constraints are imposed as Equations (3.8) and (3.9). Equation (3.8) guarantees the aggregated resource demand from activities being processed at time point t are less than available quantities for a particular time period tp. Equation (3.9) defines the boundaries (lower bound $lb_{\mathrm{Res}}^{\mathrm{tp}}$ and upper bound $ub_{\mathrm{Res}}^{\mathrm{tp}}$) of the resource availability limit.

$$\sum_{\mathrm{t=t}}^{\mathrm{t}+d_{\mathrm{Act}}} (r_{\mathrm{ActRes}}^{\mathrm{t}} x_{\mathrm{Act}}^{\mathrm{t}}) \leq R_{\mathrm{Res}}^{\mathrm{tp}} \text{ , for all resource types, for all time points} \tag{3.8}$$

$$lb_{\mathrm{Res}}^{\mathrm{tp}} \leq R_{\mathrm{Res}}^{\mathrm{tp}} \leq ub_{\mathrm{Res}}^{\mathrm{tp}} \text{, for all resource types, for all time periods} \tag{3.9}$$

where d_{Act} = duration of current activity; $r_{\mathrm{ActRes}}^{\mathrm{t}}$ = resource demand of activity; $lb_{\mathrm{Res}}^{\mathrm{tp}}$ = lower bound of resource quantity available during time period tp; $ub_{\mathrm{Res}}^{\mathrm{tp}}$ = upper bound of resource quantity available during time period tp.

3.3.5 Vector and matrix representations

The representation of the linear integer programming model in vector and matrix forms provides standardized input for computers to generate feasible solutions (Winston 2003). Vectors ***f***, ***x***, ***b***, ***b***$\boldsymbol{b}_{\mathbf{eq}}$, ***lb***, and ***ub***, and matrices **A** and $\mathbf{A}_{\mathbf{eq}}$ are defined. Equation (3.10) is the objective function factoring in the decision variable *x*; Equations (3.11) and (3.12) are sets of inequality and equality equations, respectively; Equation (3.13) specifies the lower and upper bounds of variable *x*. Commonly used software systems for mathematical programming optimization include MATLAB (MathWorks 2014) and CPLEX (IBM 2014). The formulations of matrix and vector for RSDMP model are further elaborated by use of a small example case study given in Appendix B.

$$\underset{\boldsymbol{x}}{\text{minimize}} \quad \boldsymbol{f}^{\mathbf{T}}\boldsymbol{x} \tag{3.10}$$

$$\mathbf{A}\boldsymbol{x} \leq \boldsymbol{b} \tag{3.11}$$

$$\mathbf{A}_{\mathbf{eq}}\boldsymbol{x} = \boldsymbol{b}_{\mathbf{eq}} \tag{3.12}$$

$$\boldsymbol{lb} \leq \boldsymbol{x} \leq \boldsymbol{ub} \tag{3.13}$$

The modified RSDMP mathematical model proposed in this study adds to the existing body of knowledge in regard to the formulation and solution of resource-scheduling problems based on linear integer mathematical programming, in consideration of time-dependent resource availability constraints with practical implications in the construction field. In the subsequent section, a case study is used to illustrate the calculation procedure of applying this new RSDMP approach.

3.4 Example case study

The modified RSDMP approach is implemented in order to determine the optimum resource supply quantities for the project defined in Figure 3.1 and Table 3.1. The parameter T is explicitly specified as 100 time units and three scenarios are considered:

1. [0 – 10] boilermakers and [0 – 5] pipefitters are available;
2. [1 – 4] boilermakers and [2 – 3] pipefitters are available;

3. [1 – 4] boilermakers and [2 – 3] pipefitters are available from Time 0 (project start time), [0 – 10] boilermakers and [0 – 5] pipefitters are available after Time 30.

In the 1st and 2nd scenarios, the time period is analyzed from Time 0 to Time 100. In the 3rd scenario, two time periods are specified as (i) Time 0 to Time 30, and (ii) Time 30 to Time 100.

3.4.1 Scenario 1: [0 – 10] boilermakers and [0 – 5] pipefitters available from Time 0 to Time 100

To determine the optimum resource quantities of boilermakers and pipefitters, two decision variables R_{BM}^{0-100} and R_{PF}^{0-100} are defined, respectively. In this scenario, the resource quantity for each trade remains constant from project start time to project end time. The mathematical model is expressed in Equations (3.14) to (3.23).

Equation (3.14) defines the objective function. Technological constraint in regard to the precedence relationships between Activity A and Activity B is shown in Equation (3.15). The mathematical equations for Activities Start and A, Activities A and C, Activities B and D, and Activities C and D are similar. Equation (3.16) guarantees each activity (Activity A, for example) can only be completed at one time point. Also, the decision variable $x_{\mathrm{Act}}^{\mathrm{t}}$ is defined as a binary variable (Equation 3.17).

The time-dependent resource constraints for boilermakers and pipefitters are expressed. For example, the aggregated resource demand of boilermakers (Equation 3.18) and pipefitters

(Equation 3.19) at Time 1 must be less than the available supply. At Time 2, the aggregated resource demand of boilermakers (Equation 3.20) and pipefitters (Equation 3.21) must be less than the availability limit. Equations (3.22) and (3.23) define the ranges of resource availability for boilermakers and pipefitters, respectively.

$$\begin{aligned}&\text{minimize} \quad f = \\ &\alpha_{\text{Act}} \times [(0)x_{\text{Start}}^{0} + (1)x_{\text{Start}}^{1} + \ldots + (100)x_{\text{Start}}^{100} + (0)x_{\text{A}}^{0} + \ldots + (100)x_{\text{A}}^{100} + \ldots + (100)x_{\text{D}}^{100}] + \\ &\beta_{\text{Proj}} \times [(0)x_{\text{Proj}}^{0} + (1)x_{\text{Proj}}^{1} + \ldots + (100)x_{\text{Proj}}^{100})] + \gamma_{\text{Res}}^{\text{tp}} \times [(R_{\text{BM}}^{0-100} + R_{\text{PF}}^{0-100})]\end{aligned} \tag{3.14}$$

$$[(0)x_{\text{A}}^{0} + (1)x_{\text{A}}^{1} + (2)x_{\text{A}}^{2} + \ldots + (100)x_{\text{A}}^{100}] - [(-20)x_{\text{B}}^{0} + (-19)x_{\text{B}}^{1} + (-18)x_{\text{B}}^{2} + \ldots + (80)x_{\text{B}}^{100}] \le 0 \tag{3.15}$$

$$x_{\text{A}}^{0} + x_{\text{A}}^{1} + x_{\text{A}}^{2} + \ldots + x_{\text{A}}^{100} = 1 \tag{3.16}$$

$$0 \le x_{\text{Start}}^{0}, x_{\text{Start}}^{1}, \ldots, x_{\text{Start}}^{100}, x_{\text{A}}^{0}, x_{\text{A}}^{1}, \ldots, x_{\text{Proj}}^{100} \le 1 \tag{3.17}$$

$$\begin{aligned}&\text{At Time } 1, \\ &(2)x_{\text{A}}^{1} + (2)x_{\text{A}}^{2} + \ldots + (2)x_{\text{A}}^{25} + (2)x_{\text{B}}^{1} + (2)x_{\text{B}}^{2} + \ldots + (2)x_{\text{B}}^{20} + \\ &(3)x_{\text{C}}^{1} + (3)x_{\text{C}}^{2} + \ldots + (3)x_{\text{C}}^{10} + (3)x_{\text{D}}^{1} + (3)x_{\text{D}}^{2} + \ldots + (3)x_{\text{D}}^{25} - R_{\text{BM}}^{0-100} \le 0\end{aligned} \tag{3.18}$$

$$\begin{aligned}&\text{At Time } 1, \\ &(2)x_{\text{A}}^{1} + (2)x_{\text{A}}^{2} + \ldots + (2)x_{\text{A}}^{25} + (1)x_{\text{B}}^{1} + (1)x_{\text{B}}^{2} + \ldots + (1)x_{\text{B}}^{20} + \\ &(2)x_{\text{C}}^{1} + (2)x_{\text{C}}^{2} + \ldots + (2)x_{\text{C}}^{10} - R_{\text{PF}}^{0-100} \le 0\end{aligned} \tag{3.19}$$

$$\begin{aligned}&\text{At Time } 2, \\ &(2)x_{\text{A}}^{2} + (2)x_{\text{A}}^{3} + \ldots + (2)x_{\text{A}}^{26} + (2)x_{\text{B}}^{2} + (2)x_{\text{B}}^{3} + \ldots + (2)x_{\text{B}}^{21} + \\ &(3)x_{\text{C}}^{2} + (3)x_{\text{C}}^{3} + \ldots + (3)x_{\text{C}}^{11} + (3)x_{\text{D}}^{2} + (3)x_{\text{D}}^{3} + \ldots + (3)x_{\text{D}}^{26} - R_{\text{BM}}^{0-100} \le 0\end{aligned} \tag{3.20}$$

$$\begin{aligned}&\text{At Time } 2, \\ &(2)x_{\text{A}}^{2} + (2)x_{\text{A}}^{3} + \ldots + (2)x_{\text{A}}^{26} + (1)x_{\text{B}}^{2} + (1)x_{\text{B}}^{3} + \ldots + (1)x_{\text{B}}^{21} + \\ &(2)x_{\text{C}}^{2} + (2)x_{\text{C}}^{3} + \ldots + (2)x_{\text{C}}^{11} - R_{\text{PF}}^{0-100} \le 0\end{aligned} \tag{3.21}$$

$$0 \le R_{\text{BM}}^{0-100} \le 10 \tag{3.22}$$

$$0 \le R_{\text{PF}}^{0-100} \le 5 \tag{3.23}$$

The above mathematical model for Stage 1 is readily solvable by applying a linear integer programming solver program. It minimizes the objective function by setting the parameters

$\{\alpha_{\mathrm{Act}}, \beta_{\mathrm{Proj}}, \gamma_{\mathrm{Res}}^{\mathrm{tp}}\}$ as $\{0,1,1\}$. The variables $x_{\mathrm{Proj}}^{\mathrm{t}}$ (project completion time) and $R_{\mathrm{Res}}^{\mathrm{tp}}$ (quantity of each resource over each period) are determined. In Stage 2, the objective is to minimize individual activity completion times (Activity Start, A, B, C and D) by setting weight parameters $\{\alpha_{\mathrm{Act}}, \beta_{\mathrm{Proj}}, \gamma_{\mathrm{Res}}^{\mathrm{tp}}\}$ as $\{1,0,0\}$, with $x_{\mathrm{Proj}}^{\mathrm{t}}$ and $R_{\mathrm{Res}}^{\mathrm{tp}}$ initialized as the optimum values derived in Stage 1 (Equations 3.24 to 3.26).

$$x_{\mathrm{Proj}}^{\mathrm{t}} = 1 \tag{3.24}$$

$$R_{\mathrm{BM}}^{0-100} = lb_{\mathrm{BM}}^{0-100} = ub_{\mathrm{BM}}^{0-100} \tag{3.25}$$

$$R_{\mathrm{PF}}^{0-100} = lb_{\mathrm{PF}}^{0-100} = ub_{\mathrm{PF}}^{0-100} \tag{3.26}$$

The MATLAB version 2014 is chosen to automatically search for the optimum solution by use of branch-and-bound algorithms. Further details of the branch-and-bound heuristic rules defined in MATLAB can be referred to in Savelsbergh (1994), Nemhauser and Wolsey (1999), MathWorks (2014). Appendix B discusses the input-to-output processing in MATLAB for analytically solving the mathematical programming models by use of the standard matrix and vector formulations. After the optimization, the values of decision variables $\{x_{\mathrm{Start}}^{0}, x_{\mathrm{A}}^{25}, x_{\mathrm{B}}^{45}, x_{\mathrm{C}}^{35}, x_{\mathrm{D}}^{70}, x_{\mathrm{Proj}}^{70}, R_{\mathrm{BM}}^{0-100}, R_{\mathrm{PF}}^{0-100}\}$ are determined as $\{1,1,1,1,1,1,5,3\}$, while the other decision variables are all equal to 0. The optimized schedule and corresponding resource usage histogram are shown in Figure 3.2. As a result, rather than allocating 10 boilermakers and 5 pipefitters based on experience, the analytical procedure concludes that 5 boilermakers and 3 pipefitters should be assigned from Time 0 to Time 70 in order to complete the project at Time 70.

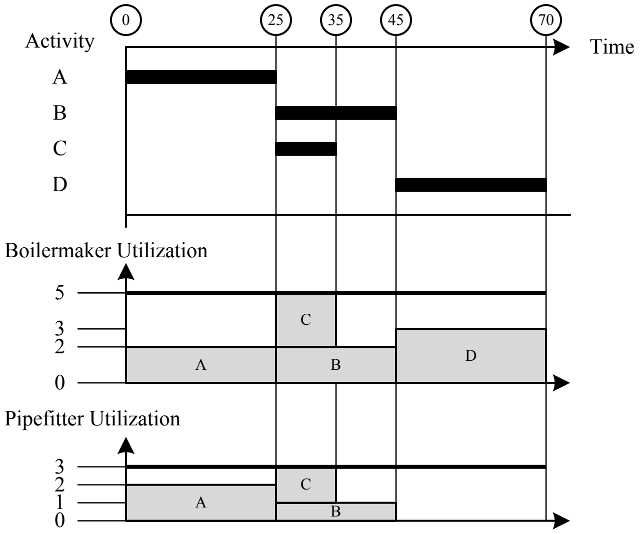


Figure 3.2: Schedule and resource usage histogram for Scenario 1

3.4.2 Scenario 2: [1 – 4] boilermakers and [2 – 3] pipefitters available from Time 0 to Time 100

In Scenario 2, the availability boundaries for boilermakers and pipefitters are narrowed down to [1 – 4] and [2 – 3], respectively. Compared to Scenario 1, the values of parameters $\{lb_{\mathrm{BM}}^{0-100}, ub_{\mathrm{BM}}^{0-100}, lb_{\mathrm{PF}}^{0-100}, ub_{\mathrm{PF}}^{0-100}\}$ change to $\{1,4,2,3\}$. After the optimization, the decision variables $\{x_{\mathrm{Start}}^{0}, x_{\mathrm{A}}^{25}, x_{\mathrm{B}}^{55}, x_{\mathrm{C}}^{35}, x_{\mathrm{D}}^{80}, x_{\mathrm{Proj}}^{80}, R_{\mathrm{BM}}^{0-100}, R_{\mathrm{PF}}^{0-100}\}$ are determined as $\{1,1,1,1,1,1,3,2\}$, while the other decision variables are equal to 0. The optimized schedule and resource usage histogram are formulated, shown in Figure 3.3. The project duration is lengthened by 10 time units in contrast with Scenario 1. Because there are insufficient boilermakers and pipefitters provided to execute Activities B and C at the same time, Activity B is delayed until sufficient resources are available after completing Activity C. In order to complete the project on time at Time 80, 3 boilermakers and 2 pipefitters should be provided.

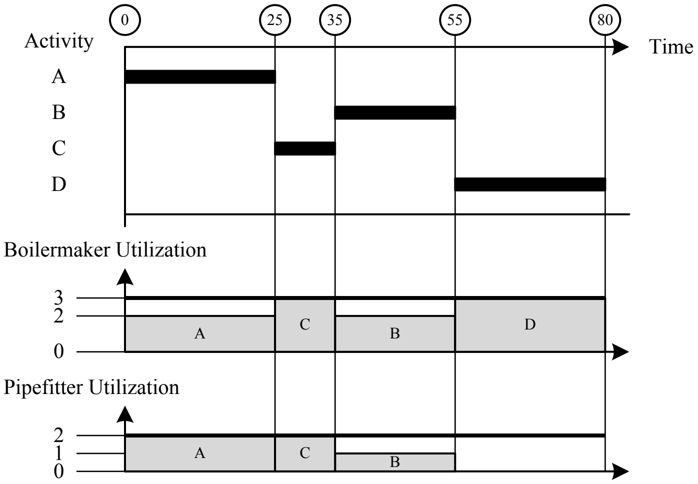


Figure 3.3: Schedule and resource usage histogram for Scenario 2

3.4.3 Scenario 3: [1 – 4] boilermakers and [2 – 3] pipefitters available from Time 0 to Time 30; [0 – 10] boilermakers and [0 – 5] pipefitters available from Time 30 to Time 100

The time-dependency of resource availability constraints can be interpreted as the changes in the likely range of resource availability over different time periods in the project duration. The question being addressed is: how many resources should be allocated if [1 – 4] boilermakers and [2 – 3] pipefitters are available from the project start time, but available resource quantities change to [0 – 10] for boilermakers and [0 – 5] for pipefitters from Time 30 until the project end time?

In comparison with previous two scenarios, the RSDMP mathematical model formulated in the current scenario defines the decision variables $R_{\mathrm{Res}}^{\mathrm{tp}}$ for two different time periods, i.e., (i) Time 0 to Time 30; and (ii) Time 30 to Time 100. The variables are declared as

$\{R_{\text{BM}}^{0-30}, R_{\text{PF}}^{0-30}, R_{\text{BM}}^{30-100}, R_{\text{PF}}^{30-100}\}$. The parameters $\{lb_{\text{BM}}^{0-30}, lb_{\text{PF}}^{0-30}, lb_{\text{BM}}^{30-100}, lb_{\text{PF}}^{30-100}\}$ are set as $\{1,2,0,0\}$, while $\{ub_{\text{BM}}^{0-30}, ub_{\text{PF}}^{0-30}, ub_{\text{BM}}^{30-100}, ub_{\text{PF}}^{30-100}\}$ set as $\{4,3,10,5\}$.

Equation (3.27) is the objective function. Technological constraints are identical to the previous two cases. The equations of resource constraints are similar to the previous scenarios, but $\{R_{\text{BM}}^{0-30}, R_{\text{PF}}^{0-30}, R_{\text{BM}}^{30-100}, R_{\text{PF}}^{30-100}\}$ are considered with respect to particular time periods. For instance, the resource constraint in regard to the boilermakers at Time 1 is expressed in Equation (3.28), of which the decision variable R_{BM}^{0-30} is involved. The mathematical equation corresponds to Time 31, on the other hand, is expressed as Equation (3.29), in which only the decision variable R_{BM}^{30-100} is considered.

$$\begin{aligned}
&\text{minimize} \quad f = \\
&\alpha_{\text{Act}} \times [(0)x_{\text{Start}}^{0} + \ldots + (100)x_{\text{Start}}^{100} + (0)x_{\text{A}}^{0} + \ldots + (100)x_{\text{A}}^{100} + \ldots + (100)x_{\text{D}}^{100}] + \\
&\beta_{\text{Proj}} \times [(0)x_{\text{Proj}}^{0} + \ldots + (100)x_{\text{Proj}}^{100})] + \gamma_{\text{Res}}^{\text{tp}} \times [(R_{\text{BM}}^{0-30} + R_{\text{BM}}^{30-100} + R_{\text{PF}}^{0-30} + R_{\text{PF}}^{30-100})]
\end{aligned} \tag{3.27}$$

$$\begin{aligned}
&\text{At Time 1,} \\
&(2)x_{\text{A}}^{1} + (2)x_{\text{A}}^{2} + \ldots + (2)x_{\text{A}}^{25} + (2)x_{\text{B}}^{1} + (2)x_{\text{B}}^{2} + \ldots + (2)x_{\text{B}}^{20} + \\
&(3)x_{\text{C}}^{1} + (3)x_{\text{C}}^{2} + \ldots + (3)x_{\text{C}}^{10} + (3)x_{\text{D}}^{1} + (3)x_{\text{D}}^{2} + \ldots + (3)x_{\text{D}}^{25} - R_{\text{BM}}^{0-30} \le 0
\end{aligned} \tag{3.28}$$

$$\begin{aligned}
&\text{At Time 31,} \\
&(2)x_{\text{A}}^{31} + (2)x_{\text{A}}^{32} + \ldots + (2)x_{\text{A}}^{55} + (2)x_{\text{B}}^{31} + (2)x_{\text{B}}^{32} + \ldots + (2)x_{\text{B}}^{50} + \\
&(3)x_{\text{C}}^{31} + (3)x_{\text{C}}^{32} + \ldots + (3)x_{\text{C}}^{40} + (3)x_{\text{D}}^{31} + (3)x_{\text{D}}^{32} + \ldots + (3)x_{\text{D}}^{55} - R_{\text{BM}}^{30-100} \le 0
\end{aligned} \tag{3.29}$$

After the optimization, the values of decision variables $\{x_{\text{Start}}^{0}, x_{\text{A}}^{25}, x_{\text{B}}^{45}, x_{\text{C}}^{40}, x_{\text{D}}^{70}, x_{\text{Proj}}^{70}, R_{\text{BM}}^{0-30}, R_{\text{PF}}^{0-30}, R_{\text{BM}}^{30-100}, R_{\text{PF}}^{30-100}\}$ are determined as $\{1,1,1,1,1,1,2,2,5,3\}$, while the other decision variables are equal to 0. The optimum schedule and resource usage histogram are shown in Figure 3.4. The project duration is 70 time units. The leanest supply quantities are 2 boilermakers and 2 pipefitters from Time 0 to Time 30. After Time 30, 5 boilermakers and 3 pipefitters should be assigned. Because available quantities of boilermakers and pipefitters are insufficient to execute Activities B and C in parallel at Time 25, only Activity B is allowed to start while Activity C is delayed. Owing to extra resources becoming available at Time 30, Activities B and C are able to be executed at the same time. As a result, 5 boilermakers and 3 pipefitters should be provided from Time 30 to Time 70, so as to complete the project at Time 70.

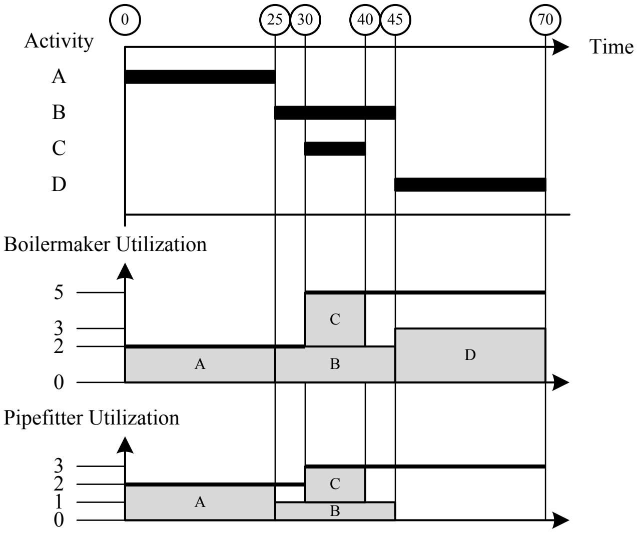


Figure 3.4: Schedule and resource usage histogram for Scenario 3

The optimum results show that 2 boilermakers should be provided, rather than 3 boilermakers, from Time 0 to Time 30. If the number of boilermakers increases to 3 units, which is the minimum activity-resource requirement of an individual activity on the project (in this case, Activities C and D each require 3 boilermakers), there would be one extra boilermaker idling from Time 0 to Time 30. This demonstrates the potential of applying the proposed RSDMP approach to avoid undersupply and oversupply of resources over different time periods of the project duration.

3.4.4 Significance of Stage 2 optimization

In Stage 2, the parameter α_{Act} is switched on to schedule activity completion times as early as possible. Without Stage 2 optimization, the activity completion times generated from Stage 1 may not be the earliest possible values. For example, the parameters $\{\beta_{\text{Proj}}, \gamma_{\text{Res}}^{\text{tp}}\}$ are set as $\{100,1\}$ in Scenario 1. Figure 3.5 shows the resulting optimum schedule along with the resource usage histogram. The project completion time (Time 70) and resource supply (5 boilermakers and 3 pipefitters) remain unchanged. However, the start and completion times of Activity C are on Time 31 and Time 41, respectively, in contrast with Time 25 and Time 35 as in Figure 3.2. As a result, Stage 2 optimization allows Activity C to have 6 time units float. In construction practice, activities are generally planned to start at the earliest time in order to own the greatest amount of float to absorb any potential delay during activity execution. Therefore, Stage 2 optimization is essential.

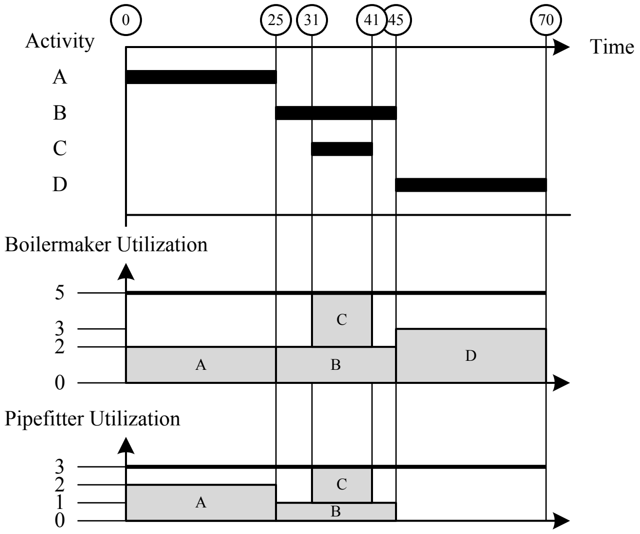


Figure 3.5: Schedule and resource usage histogram for Scenario 1 without Stage 2 optimization

3.4.5 Tradeoff between resource supply and project time

If the importance of streamlining resource supply (associated with reducing project direct cost in the objective function) outweighs attaining earlier project completion times (associated with reducing project indirect cost), a heavier weight should be assigned to $\gamma_{\text{Res}}^{\text{tp}}$. For example, the parameters $\{\beta_{\text{Proj}}, \gamma_{\text{Res}}^{\text{tp}}\}$ are set as $\{1,100\}$ in Scenario 1, all other parameters held unchanged. The resulting optimum schedule and resource usage histogram are shown in Figure 3.6. The resource quantities of boilermakers and pipefitters are reduced to 3 and 2 units, respectively. However, the project duration is lengthened by 10 time units. It proves that the optimization result could be significantly altered, depending scheduling priorities in practical settings.

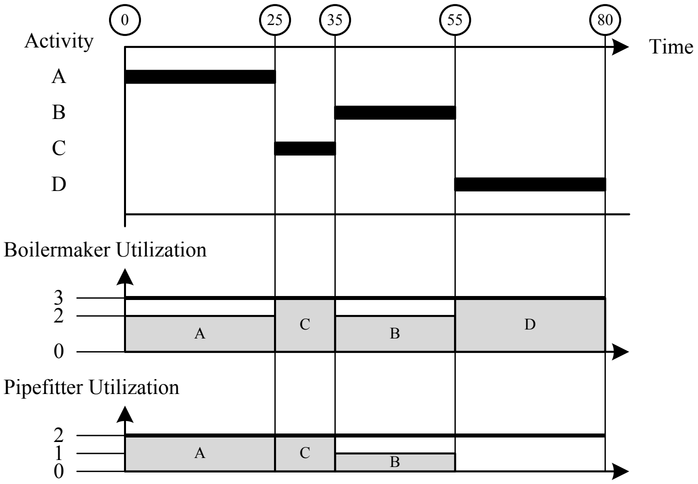


Figure 3.6: Schedule and resource usage histogram subjects to $\{\beta_{\text{Proj}}, \gamma_{\text{Res}}^{\text{tp}}\} = \{1,100\}$

3.4.6 Setting optimization parameters as absolute unit rates

To demonstrate the application of cost optimization, the total direct cost per resource unit for each particular time period is postulated in Table 3.2, and the indirect cost of the project is assumed as \$10/time unit. The cost rates are fictitious, and only used to demonstrate cost calculation. For example, \$100 (total direct cost for a boilermaker) and \$90 (total direct cost for a pipefitter) are budgeted for employing one boilermaker and one pipefitter from Time 0 to Time 30, respectively. From Time 30 to Time 100, \$220 and \$210 are budgeted for boilermaker and pipefitter (in this case, the unit cost of boilermaker is reduced from \$3.3/time unit to \$3.1/time unit; while the unit cost of pipefitter remains unchanged as \$3/time unit).

Table 3.2: Total direct cost per resource unit for particular time periods

Resources	Total direct cost @ Time 0 – 30	Total direct cost @ Time 30 – 100
Boilermaker	\$100/Boilermaker	\$220/Boilermaker
Pipefitter	\$90/Pipefitter	\$210/Pipefitter

Equation (3.30) is the objective function. The value of parameters β_{Proj} is 10, while the values of parameters $\{\gamma_{\mathrm{BM}}^{0-30}, \gamma_{\mathrm{PF}}^{0-30}, \gamma_{\mathrm{BM}}^{30-100}, \gamma_{\mathrm{PF}}^{30-100}\}$ are $\{100, 90, 220, 210\}$. In this optimization scenario, following Stage 1 optimization $(\alpha_{\mathrm{Act}} = 0)$ and Stage 2 optimization $(\alpha_{\mathrm{Act}} = 1)$, the values of decision variables $\{x_{\mathrm{Start}}^{0}, x_{\mathrm{A}}^{25}, x_{\mathrm{B}}^{45}, x_{\mathrm{C}}^{55}, x_{\mathrm{D}}^{80}, x_{\mathrm{Proj}}^{80}, R_{\mathrm{BM}}^{0-30}, R_{\mathrm{PF}}^{0-30}, R_{\mathrm{BM}}^{30-100}, R_{\mathrm{PF}}^{30-100}\}$ are determined as $\{1,1,1,1,1,1,2,2,3,2\}$. The resulting optimum schedule and resource usage histogram are shown in Figure 3.7. The resulting total project cost is \$2,260 (direct cost: \$1,460=2×100+2×90+3×220+2×210; indirect cost: \$800=10×80).

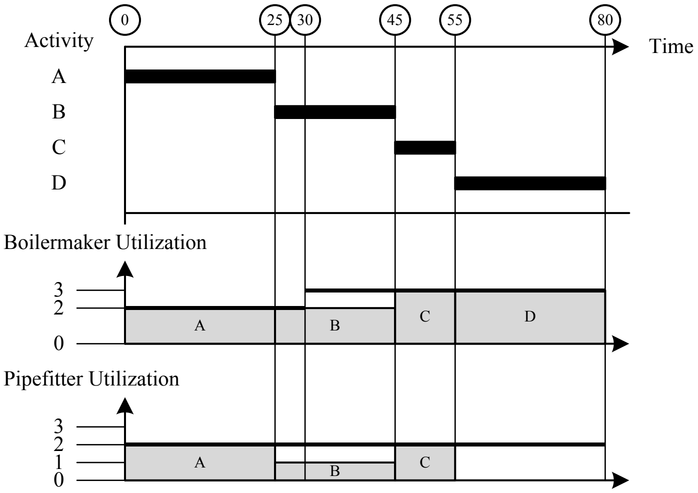


Figure 3.7: Schedule and resource usage histogram for Scenario 3
$\{\beta_{\mathrm{Proj}}, \gamma_{\mathrm{BM}}^{0-30}, \gamma_{\mathrm{PF}}^{0-30}, \gamma_{\mathrm{BM}}^{30-100}, \gamma_{\mathrm{PF}}^{30-100}\} = \{10, 100, 90, 220, 210\}$

$$\begin{aligned}
&\text{minimize} \quad f = \\
&\alpha_{\mathrm{Act}} \times [(0)x_{\mathrm{Start}}^{0} + \ldots + (100)x_{\mathrm{Start}}^{100} + (0)x_{\mathrm{A}}^{0} + \ldots + (100)x_{\mathrm{A}}^{100} + \ldots + (100)x_{\mathrm{D}}^{100}] + \\
&\beta_{\mathrm{Proj}} \times [(0)x_{\mathrm{Proj}}^{0} + \ldots + (100)x_{\mathrm{Proj}}^{100})] + \\
&[(\gamma_{\mathrm{BM}}^{0-30} \times R_{\mathrm{BM}}^{0-30}) + (\gamma_{\mathrm{BM}}^{30-100} \times R_{\mathrm{BM}}^{30-100}) + (\gamma_{\mathrm{PF}}^{0-30} \times R_{\mathrm{PF}}^{0-30}) + (\gamma_{\mathrm{PF}}^{30-100} \times R_{\mathrm{PF}}^{30-100})]
\end{aligned} \tag{3.30}$$

In contrast with the schedule resulting from Scenario 3 (Figure 3.4) which sets the parameters $\{\beta_{\text{Proj}}, \gamma_{\text{Res}}^{\text{tp}}\}$ as $\{1,1\}$, the project cost can be determined using the same unit costs given in Table 3.2, namely: total cost equal to \$2,810 (direct cost: \$2,110=2×100+2×90+5×220+3×210; indirect cost: \$700=10×70).

A time-cost tradeoff can be observed from the two optimization scenarios: when the two weights are set as relative ratios in Scenario 3 of the present case, the optimization leads to 70 time units of project duration and \$2,810 total cost; if the weights are set as absolute rates (dollars per time unit for β_{Proj}; dollars per resource unit for $\gamma_{\text{Res}}^{\text{tp}}$), the optimization generates a schedule solution with 80 time units of project duration and \$2,260 total cost.

3.4.7 Significance of proposed resource scheduling approach

Without the modified RSDMP resource scheduling approach, the project can be broken down into subprojects for scheduling analysis according to the time periods associated with corresponding resource availability constraints. For instance, in Scenario 3, the project is divided into two portions: (i) one subproject must be completed in 30 time units, followed by (ii) the other subproject to perform all uncompleted activities. Activity A is executed before Time 30. However, Activities B or C cannot be scheduled as part of the 1st subproject as its duration would overrun project end (Time 30). Therefore, both Activities B and C are scheduled after Time 30 in the 2nd subproject (Figure 3.8). As a result, the total project completion time is delayed by 5 time units. In contrast, the developed approach overcomes this drawback by scheduling one single project under time-dependent resource constraints. The following section demonstrates its practical application to the turnaround project.

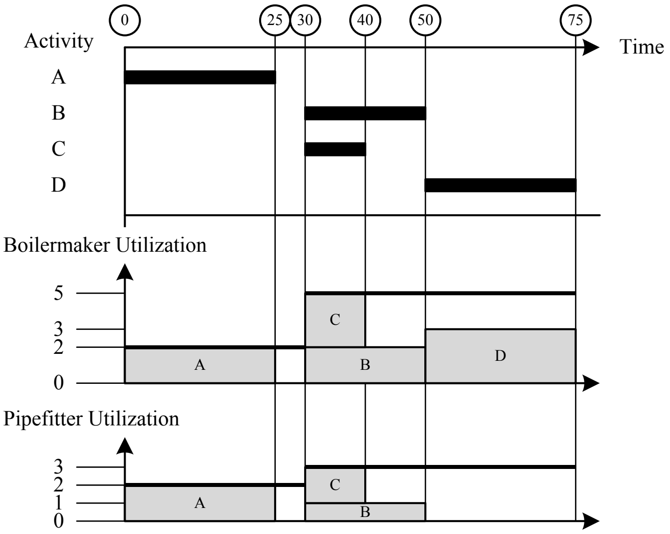


Figure 3.8: Schedule analyses for two separate subprojects

3.5 Industrial turnaround scheduling application

As mentioned in previous chapter, the three-month industrial turnaround project is planned to upgrade existing oil refinery facilities including the reactor, the regenerator, and the overhead system. The project scope for the present case study is narrowed down to the reactor work package. The work content of this project consists of (i) replacing the four elbows in the reactor; (ii) removing the existing head and cyclone assemblies; (iii) installing new head and cyclone assemblies; and (iv) completing refractory and tie-in electrical instrumentation, piping and platforming.

As the industrial plant operation is suspended for maintenance, oil is not produced during the turnaround period. The plant owner would incur substantial economic loss if the project is delayed. To ensure the project will be completed on time, the contract stipulates that activities must be executed in accordance with a reliable resource-constrained project schedule.

This project is planned to take approximately 200 hours. There are a total of 107 activities. It involves 19 types of resources (mainly skilled labor resources) to execute this work package (Appendix A). The resource availability must fall within the lower and upper boundaries as specified by experienced project managers, project schedulers and field superintendents. In current scenario, the resource supply is re-accessed after 100 hours. Thus, the optimum resource quantities are determined for two consecutive 100-hour time periods.

The decision variables in regard to activity completion times, project completion time, and resource supply quantities are declared as $\{x_{\mathrm{Start}}^{0},\ldots,x_{\mathrm{Start}}^{200},x_{001}^{0},\ldots,x_{001}^{200},\ldots,x_{107}^{200}\}$, $\{x_{\mathrm{Proj}}^{0},x_{\mathrm{Proj}}^{1},\ldots,x_{\mathrm{Proj}}^{200}\}$ and $\{R_{\mathrm{A}}^{0-100},R_{\mathrm{B}}^{0-100},\ldots,R_{\mathrm{S}}^{0-100},R_{\mathrm{A}}^{100-200},R_{\mathrm{B}}^{100-200},\ldots,R_{\mathrm{S}}^{100-200}\}$, respectively.

The dimensions of matrices and vectors are summarized in Table 3.3. Those dimensions indicate the complexity of the problem. For the current problem, the model consists of 21,947 decision variables, and 3,928 equations to define technological and time-dependent resource constraints. The computer used for conducting optimization analysis has the following specifications: processor: Intel Core i7-4770 CPU, 3.40 GHz; memory: 16.0 GB; System type: 64-bit operating system, x64-based processor. The computing time to complete the two-stage optimization analysis is 34.48 seconds. It is emphasized that the processing time is dependent on numerous factors, including: the complexity and size of the problem, selected heuristic rules for branching and bounding processes, matrix and vector formulations, desirable solution accuracy, and computer power. For further information of computing efficiency in the context of solving resource-based scheduling problems, readers are referred to Möhring et al. (2003); Jiang and Shi (2005); Zhu et al. (2006); Menesi and Hegazy (2014). In short, compared with other iterative evolutionary-algorithms, given projects of larger size, the proposed RSDMP methodology is analytical in nature and holds high potential to remain computationally efficient and arrive at solutions in a finite time frame (in minutes or hours).

Table 3.3: Dimensions of the matrix/vector

Matrix/Vector	Dimension
$\boldsymbol{x}$	1 × 21947
$\boldsymbol{f}$	1 × 21947
$\mathbf{A}$	3928 × 21947
$\mathbf{A}_{\mathbf{eq}}$	109 × 21947
$\boldsymbol{b}$	3928 × 1
$\boldsymbol{b}_{\mathbf{eq}}$	109 × 1
$\boldsymbol{lb}$	1 × 21947
$\boldsymbol{ub}$	1 × 21947

An optimum solution for the current case study is generated using MATLAB version 2014. The total project duration is 173 hours. Resource quantities estimated by experienced field schedulers in the partner company and optimized by the proposed computer-based approach are contrasted in Table 3.4. It is emphasized that optimum resource quantities are determined based on the original range estimates of resource supply estimated by experienced project managers, project schedulers and field superintendents in the partner company. Instead of a rough estimate based on experience, this research work provides an analytical RSDMP method to evaluate the leanest supply of critical construction resources. This case study has proved the effectiveness of the proposed resource-based scheduling methodology to formulate resource-constrained project schedule under time-dependent resource availability constraint in practical settings.

Table 3.4: Resource supply

Identifier	Resource	Estimated @ Time 0 – 100	Estimated @ Time 100 – 200	Optimized @ Time 0 – 100	Optimized @ Time 100 – 200
A	Boilermaker	5 – 12	0 – 20	12	13
B	Boilermaker welder	2 – 12	0 – 10	8	9
C	MSG80 3600 ton	0 – 1	0 – 2	1	0
D	Rigger	0 – 7	0 – 7	6	0
E	Scaffolder	0 – 10	0 – 10	6	0
F	Iron worker	0 – 10	0 – 10	6	0
G	Sterling-130 ton crane	0 – 5	0 – 6	5	1
H	Technical	0 – 5	0 – 5	2	1
I	Inspection	0 – 2	0 – 2	2	1
J	Complex process operator	0 – 2	0 – 2	2	0
K	Refractory	0 – 15	0 – 15	7	7
L	Liquid penetrant inspection	0 – 1	0 – 1	1	1
M	X-ray	0 – 1	0 – 1	0	1
N	PAUT inspection	0 – 1	0 – 1	0	1
O	Painter	0 – 4	0 – 4	0	2
P	Pipefitter	0 – 5	0 – 5	2	2
Q	Pipefitter welder	0 – 3	0 – 3	1	1
R	Inspector	0 – 2	0 – 3	1	1
S	Supervisor	0 – 2	0 – 2	1	1

3.6 Conclusions

In practice, the resource supply quantities allocated to a construction project over different time periods are subjectively estimated based on experience. In connection with the practical need to specify feasible ranges of resource supply for project execution over different time periods, an innovative RSDMP approach is modified and proposed to formulate resource-constrained schedules under time-dependent resource availability constraints. The resulting optimum schedule is ready for execution in the field and features the optimum project duration with the optimum resource supply along with the earliest activity completion times, so as to avoid undersupply and oversupply of resources for particular time periods. The major limitation of the proposed RSDMP approach lies in the fact that the combinatorial explosion problem is likely to be encountered and the solution may not converge to the global optimum in the definitive time frame when the project network is large and highly complicated. This problem can be alleviated by using numerous branching and bounding techniques developed from related research. Nevertheless, the RSDMP approach provides quantitative decision support for formulating reliable project schedules. The next chapter introduces the schedule assessment approach for evaluating the budget sufficiency and resource utilization in relation to the control budget and resource schedule. The performance metrics as derived from RSDMP and Primavera P6 schedules are compared.

CHAPTER 4: QUANTITATIVE ASSESSMENT OF BUDGET SUFFICIENCY AND RESOURCE UTILIZATION FOR RESOURCE-CONSTRAINED PROJECT SCHEDULES[4]

4.1 Introduction

In current practice, the control budget and resource schedule are separately developed at different stages in project planning. During the conceptual planning stage, the amount of control budget is estimated based on the preliminary study of project work scope (Peurifoy and Oberlender 2013), commonly by referencing industry-wide or company-specific benchmark data (Bernold and AbouRizk 2010). As per the Association for Advancement of Cost Engineering definition (AACE 2011), the cost estimates for concept screening and feasibility study of process piping projects are classified as Class 5 and Class 4 estimates, with the associated accuracy range being [–50%, +100%] and [–30%,+50%], respectively.

In general, the control budget for project delivery is the budgeted unit available for performing the total work of a project within a particular time frame. The budgeted unit can be measured in worker-hours (i.e., wh) or monetary value (Ahuja et al. 1994). It is commonly given as budgeted worker-hours when delivering a labor-intensive construction project. After the amount has been approved during the procurement stage, the control budget serves as a baseline for providing resources to deliver the construction project. As defined by AACE (2011), Class 3, Class 2, and Class 1 cost estimates are performed for quantifying the budgeted unit based on the detailed

---

[4] This chapter has been published in the journal of construction engineering and management, ASCE. 10.1061/(ASCE)CO.1943-7862.0001106, 04016003.

quantity take-off of the work scope and deliverables, with the associated accuracy range being [–20%,+30%], [–15%,+20%], and [–10%,+15%], respectively.

The bulk of the control budget is used for deploying resources (mainly manpower and equipment) to perform construction activities (Hegazy 2002; Hinze 2008). Part of the control budget is also reserved as contingency in order to address the uncertain work scope in bidding and to cover unanticipated work in the execution stage (Pinker and Larson 2003; Construction Specifications Institute 2011; Gould and Joyce 2013). The Project Management Institute (2013) emphasizes that the contingency reserve must be allocated for mitigating responses to situations that are generally unexpected in the early planning stage. The amount of contingency reserve is estimated based on historical data and personal experience (Barraza and Bueno 2007; Xie et al. 2012). In short, the control budget needs to be sufficient to allow for executing activities while reserving a certain level of contingency in order to deliver the project on time and within budget.

During the course of project planning, the project schedule evolves progressively over different stages of project development in granularity of definition, presenting crucial information to relevant stakeholders. During the conceptual planning stage, Level 0, Level 1, Level 2, and Level 3 schedules are commonly formulated as per the AACE definition (AACE 2006): the project schedules formulated at Level 0, 1, 2, 3 without resource constraints show the major milestones, major activities, major subactivities, and critical path network, respectively.

Once the project is awarded to the contractor, a detailed Level 4, or even Level 5 project schedules needs to be developed based upon the Level 0, 1, 2, 3 schedules (Griffith 2005, AACE

2010), aimed for guiding resource allocation in the field (Fondahl 1991; Lu and Li 2003; Kim and De la Garza 2003; De la Garza and Kim 2005). According to the AACE definition (AACE 2006), Level 4 and Level 5 schedules are generally formulated under resource constraints in order to plan activities to be accomplished by the project workforce. The schedulers generally work with segments of the total schedule at more detailed scheduling levels. It is worth mentioning that Level 4 and Level 5 schedules in terms of two or three weeks look-ahead planning is closely aligned with the common definition of workface planning (CII 2013; COAA 2014), intended to facilitate daily or hourly job assignment to individual craft persons on site.

A resource-constrained project schedule can be obtained by use of commercial scheduling software systems such as Primavera P6 (Harris 2008, 2012) or innovative resource scheduling optimization techniques resulting from research. To formulate a valid resource-constrained project schedule, the resources as required by individual activities are loaded while resource supply limits are also imposed on the current project. The resource-loaded activities are rescheduled subject to both technological and resource constraints, so as to ensure the aggregated resource units required by activities at any particular time are less than the resource supply limits. Guided by the resource-constrained schedule, resources are deployed to carry out the daily work in the construction field.

Primavera P6 is generally specified as the tool for resource scheduling on industrial shutdown and maintenance projects (commonly referred to as turnaround) in the real world. The resource leveling functionalities in Primavera P6 can produce a feasible turnaround schedule, conducive to estimating crew size and resource usage during particular time periods. Nevertheless, the difficulty of using Primavera P6's resource scheduling functionality is how to control activity sequence: upon imposing resource constraints, the activity sequence of the Primavera P6 schedule can change. In the generation of the resource-constrained project schedule by use of Primavera P6, seasoned schedulers strive to manage and maintain the stability of activity execution sequence―which is followed in the original project schedule without resource loading.

The assessment of budget sufficiency and resource utilization for a formulated resource-constrained project schedule is crucial to the successful delivery of a construction project. During the detailed planning and workface planning stages, such assessment is commonly made based on experiences instead of analytical metrics. Thus, this chapter addresses the following critical questions from resource scheduling perspectives:

1. How sufficient is the control budget for executing the formulated project schedule (namely, a Level 4/5 project schedule)?

2. How efficiently will the deployed resources be utilized when executing the formulated project schedule?

In this research, a novel schedule assessment approach is proposed based on defining budget sufficiency metrics and resource utilization metrics, so as to assess multiple alternatives of resource-constrained project schedules in a straightforward but objective fashion.

The remainder of this chapter is organized as follows. A critical review in connection with evaluation of budget sufficiency and resource utilization from project scheduling perspectives is given. Metrics for resource-constrained schedule assessment are then proposed. Next, a simple project is used to demonstrate how to implement and verify the proposed metrics on multiple alternative schedules, which are derived from practical scheduling approach (Primavera P6) and resource-based scheduling optimization approaches [RSDMP (resource supply-demand matching problem) approaches, as introduced in previous chapters], respectively. The refinery plant turnaround project is also analyzed in order to demonstrate application in practical settings, prior to drawing conclusions on the present research.

4.2 Literature review

In this section, a comprehensive literature review is given in regard to assessing budget sufficiency and resource utilization from project scheduling perspectives.

4.2.1 Budget sufficiency assessment

Previous research on measuring the sufficiency of the control budget based upon a resource-constrained project schedule (Level 4/5 schedule) is limited. Instead, significant research efforts were devoted to two separate streams in order to assist in project planning at different stages, namely, (i) determining the budget for contingency in conceptual planning, and (ii) formulating an executable resource-constrained project schedule in detailed planning or workface planning.

During the conceptual planning stage, the amount of control budget is estimated in consideration of the project scope and project risks. Sufficient contingency reserve provides the flexibility of supplying extra resources to take contingent and mitigating responses (Khamooshi and Cioffi 2013). The contingency reserve is conventionally estimated as a percentage of the baseline budget for performing planned activities on a project (Thompson and Perry 1992; Rothwell 2005; Cioffi and Khamooshi 2009). Allowing for contingency at a proper level is essential to procure the project bid and increase the chances of delivering the project on time and within budget.

Sophisticated techniques were proposed for estimating the contingency in a more reliable manner. For instance, Barraza and Bueno (2007) suggested a simulation approach for determining project contingency, based upon the probability of activity cost overrun. Touran (2010) proposed a mathematical model that calculates the required increase in control budget for a portfolio of projects; the confidence levels of budget sufficiency were established using the probability of a project experiencing cost overrun. Xie et al. (2012) suggested a value-at-risk modeling approach for updating the amount of contingency reserve during the project execution. Khamooshi and Cioffi (2013) developed a unified scheduling method to simulate project cost and contingency reserve based on the confidence level of activity duration.

During the workface planning stage, a detailed schedule with resource constraints (equivalent to Level 4 and 5 schedules as per AACE classifications) is generally required for guiding resource allocation and activity execution (Lu and Li 2003; Kim and De la Garza 2003). Previous research efforts revolve around how to formulate a valid project schedule with resource constraints as such the objectives in terms of minimizing project duration or project cost can be attained. For instance, researchers proposed mathematical formulations and solutions (Siu et al. 2015a, 2015b, 2015c) and evolutionary-algorithms (Lu et al. 2008; Liao et al. 2011) in order to identify a resource-constrained project schedule that represents the optimum solution in terms of the shortest project duration or optimal resource supply limits. To avoid a budget overrun, budgetary constraints were also imposed on project direct and indirect costs in formulating the resource-constrained project schedules (Karaa and Nasr 1986), resulting in feasible schedules with the least project cost that satisfied budgetary limits.

In the majority of previous research endeavors, evaluating resource budget sufficiency and formulating resource-constrained project schedules were dealt with separately. Regardless of the methodology applied, performance metrics have yet to be formalized for simultaneously evaluating the resultant resource-loaded schedules in terms of budget sufficiency and resource utilization. In particular, budget sufficiency metrics will be developed in the current research to fill the gap in the existing body of knowledge, which are based on an effective comparison between a control budget (determined during conceptual planning stage) and a resource budget (derived from a Level 4/5 project schedule during detailed and workface planning stages).

4.2.2 Resource utilization assessment

In current practice, the resource utilization rate is also assessed and closely monitored for an executable resource-constrained project schedule (Level 4 or 5 schedule), so as to avoid undersupply and oversupply of resources.

Resource utilization has been the focal point in studies of operation simulation. The resource utilization is statistically evaluated as the expected proportion of time that the resource stays busy during simulation. Applications of construction operation simulation aimed at improving resource utilization have been widely reported in the literature (Al-Bataineh et al. 2013; Taghaddos et al. 2014). The simulation results are instrumental in identifying underutilized resources in a construction system. To achieve maximum resource efficiency, a sensitivity analysis of resource utilization can be performed for determining the optimum supply of deployed resources (AbouRizk and Shi 1994; Zhang and Li 2004; Chen et al. 2012). Operation simulation modeling is thus capable of measuring resource utilization by tracing the busy state of individual resource units over time. However, the technique is more focused on balancing different types of resources and analyzing the effect of uncertain activity times on resource utilization, instead of formulating a resource-constrained project schedule (Level 4/5 schedule).

Resource-based scheduling research aimed at increasing resource utilization rates is commonly classified as the resource leveling problem, which is formulated in order to minimize the total absolute deviation between actual and desirable resource utilization rates by postponing start times of noncritical activities of a project within available total floats. Previous research proposed specific objective functions for formulating optimum resource-leveled project schedules, such as the minimum moment (Hegazy 1999) and the maximum entropy (Christodoulou et al. 2010). In addition, mathematical modeling (Rieck et al. 2012) and evolutionary-algorithms (Leu et al. 2000; Christodoulou 2005) have also been applied to address resource leveling optimization problems. The result is a project schedule with higher resource utilization rates, while the derived resource demand profile is leveled out. It is worth noting that the interplay between the amount of a control budget and the resulting resource utilization was considered in defining a multiobjective optimization problem by Ashuri and Tavakolan (2015).

This chapter will define straightforward yet effective metrics to quantitatively evaluate budget sufficiency and resource utilization and further characterize the relationship between them, given any feasible resource-loaded project schedule that can be generated by heuristic rules or optimization algorithms. The following section first defines the metrics for quantifying and visualizing budget sufficiency and resource utilization based upon a resource-constrained project schedule.

4.3 Resource-loaded schedule assessment metrics

4.3.1 Budgeted unit

The *budgeted unit* represents the total amount of resource budget typically given in worker-hour (i.e., wh), allowing for the direct cost for executing scheduled activities plus the contingency reserved for unanticipated activities or changes within the project scope.

The total amount of budgeted unit is estimated based on performing quantity takeoff for major work items on the project. The budgeted worker-hour (wh) associated with a work item can be estimated as the quantity of work (in takeoff unit) divided by labor productivity (unit/wh). For example, if the quantity of the work item of pipe handling on site is 27,200 ft and labor productivity is 20 ft/wh, the budgeted unit is calculated as 1,360 wh [=(27,200 ft)/(20 ft/wh)]. As such, the budgeted unit is determined by aggregating worker-hours over all work items (Equation 4.1).

$$\text{Budgeted unit} = \sum\nolimits_{\text{work}} \frac{Q_{\text{work}}}{P} \tag{4.1}$$

where Q_{work} = quantity of specific work item (takeoff unit); and P = productivity (unit/wh)

4.3.2 Deployed unit

The *deployed unit* is the worker-hour (i.e., wh) allocated to execute activities over each particular period of the total project duration, which accounts for total deployment time of labor resources including productive time and nonproductive time such as breaks and idle times. The scheduled resource supply limit (i.e., maximum resource provision quantity for a particular resource for each day or hour) can be visualized as the scheduled resource supply profile over project time. Instead of a constant limit throughout the project duration, a more typical resource supply limit profile characterizes gradual stepwise increase of the resource supply limit from the project start, reaching a plateau halfway of the project, then a gradual reduction till the end of the project. The deployed unit can be visualized as the shaded area under the resource supply profile (Figure 4.1). The deployed unit is estimated by multiplying the quantity of deployed resources with the deployed duration on the project.

Analytically, the deployed unit can be calculated by summarizing the deployed worker-hours over each particular time period of the project duration as given in Equation (4.2). For example, if the resource supply profile as derived from a resource-constrained project schedule is depicted in Figure 4.1, the deployed unit is 888 wh (=32×4+54×4+64×4+48×4+24×4).

$$\text{Deployed unit} = \sum_{\text{Res}} \sum_{\text{tp}} R^{\text{tp}}_{\text{Res(Deployed)}} \times T^{\text{tp}}_{\text{Res(Deployed)}} \tag{4.2}$$

where $R^{\text{tp}}_{\text{Res(Deployed)}}$ = deployed quantity of a resource Res over the time period tp; and $T^{\text{tp}}_{\text{Res(Deployed)}}$ = deployed duration of resource Res over the time period tp

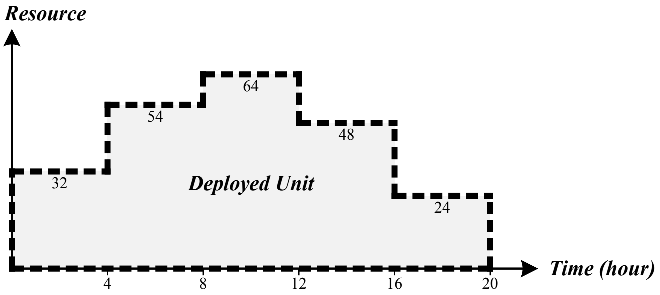


Figure 4.1: Numerical example for calculating deployed unit based on resource supply profile

4.3.3 Scheduled unit

The *scheduled unit* represents the resource demand by scheduled activities according to a resource-constrained project schedule. Total scheduled unit can be also given in worker-hour (i.e., wh) as required for executing all scheduled activities.

The scheduled unit is determined by aggregating resource quantities as required by scheduled activities at each time unit throughout the project duration, based upon the bar chart project schedule (Hinze 2008). The resource demand profile (also called the resource utilization histogram) is commonly generated alongside the activity bar chart for a resource-loaded project schedule. The scheduled unit can be represented by the total area of the resource demand profile, which generally has a more rugged shape than the resource supply profile (Figure 4.2).

Analytically, the scheduled unit in terms of total scheduled worker-hour can be calculated by accumulating the scheduled worker-hours of all labor resources throughout the project time duration (Equation 4.3). For example, if the resource demand profile derived from a resource-constrained project schedule is depicted in Figure 4.2, the scheduled unit is 664 wh (=18×1+30×1+26×1+24×1+44×1+40×1+36×1+34×1+50×1+54×1+56×1+48×1+40×1+36×1+40 ×1+36×1+18×1+14×1+12×1+8×1).

$$\text{Scheduled unit} = \sum_{\text{Res}} \sum_{\text{t}} R^{\text{t}}_{\text{Res(Scheduled)}} \times T^{\text{t}}_{\text{Res(Scheduled)}} \qquad (4.3)$$

where $R^{\text{t}}_{\text{Res(Scheduled)}}$ = required quantities of resource at time point t; and $T^{\text{t}}_{\text{Res(Scheduled)}}$ = required duration of resource at time point t

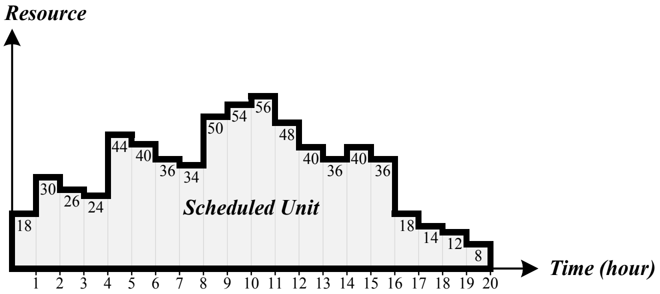


Figure 4.2: Numerical example for calculating scheduled unit based on resource demand profile

4.3.4 Budget sufficiency metrics

Two budget sufficiency metrics, named as *budget sufficiency index* (BSI) and *budget sufficiency variance* (BSV), are defined for a given resource-loaded schedule. The BSI is defined as the ratio of budgeted unit to deployed unit (Equation 4.4). The BSV is defined as the difference between budgeted unit and deployed unit (Equation 4.5).

$$\text{Budget sufficienc y index (BSI)} = \frac{\text{Budgeted unit}}{\text{Deployed unit}} \tag{4.4}$$

$$\text{Budget sufficienc y variance (BSV)} = \text{Budgeted unit} - \text{Deployed unit} \tag{4.5}$$

Note that the definitions of the two budget sufficiency metrics are inspired by the established project control technique of earned value analysis (Anbari 2003). The definition of BSI is analogous to schedule performance index (SPI), which is the ratio of earned value over planned value, while the definition of BSV resembles schedule variance (SV), which is defined as the difference between earned value and planned value. Nonetheless, there is no direct correlation between BSI and SPI, or BSV and SV. The definitions of BSI and BSV are only intended to assess if the control budget is sufficient given any resource-constrained project schedule during the project planning stage.

Figure 4.3 illustrates the definitions of budget sufficiency metrics by superimposing the two graphical shapes denoting budgeted unit and deployed unit. Note that the budgeted unit (in worker-hour) can be represented as the area of a rectangular shape. The BSI is a relative ratio, implying the magnitude of the budgeted unit area exceeding the deployed unit area. The BSV is the absolute difference between budgeted unit and deployed unit, which is actually the amount of budgeted unit set aside for contingency.

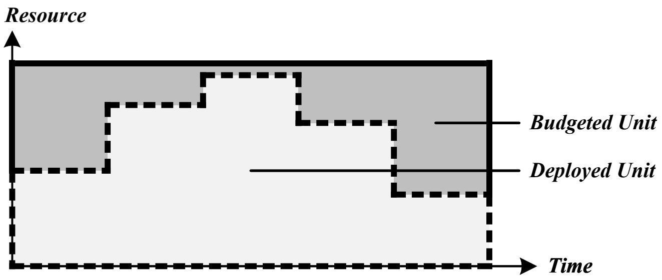


Figure 4.3: Visualization of budget sufficiency by superimposing budgeted unit and deployed unit

A BSI value less than 1 means the amount of budgeted unit is not enough for supplying resources to execute the scheduled activities. A BSI value equal to 1 indicates that the budgeted unit is sufficient for performing planned activities, but there is no contingency available. A BSI value greater than 1 implies that the amount of budgeted unit is not only sufficient for supplying resources to complete the scheduled activities, but also a contingency is available for unexpected work or changes during project execution. Similarly, BSV not only indicates the budget sufficiency but also gives the exact amount of budget (worker-hours) as a contingency (positive value) or shortfall (negative value). In short, BSI and BSV can be used as effective metrics to evaluate budget sufficiency and compare alternative resource-loaded project schedules: the higher BSI value, the higher BSV value, and the more sufficient budget, the more budget reserved contingency.

To demonstrate, assume a budgeted unit of 1,360 wh is available for the current project, which allows 68 resource units (laborers) to work on the project in 20 hours (=68×20). The deployed unit is determined as 888 wh. As per Equations (4.4) and (4.5), BSI and BSV are determined as 153.2% (=1,360/888) and 472 wh (=1,360–888), respectively. The budgeted unit can be visualized as the area of a rectangular shape; by superimposing the budgeted unit area and the deployed unit area, the budget sufficiency can be graphically represented, as shown in Figure 4.4.

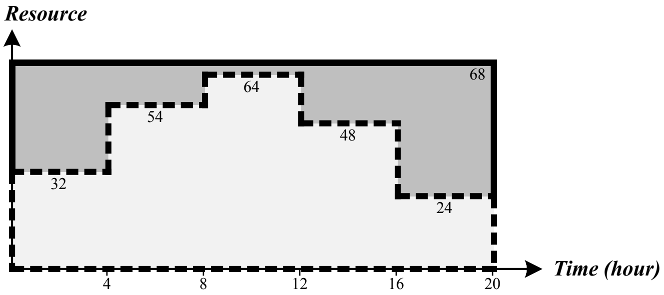


Figure 4.4: Numerical example for calculating budget sufficiency index

4.3.5 Resource utilization metrics

Two resource utilization metrics, named as *resource utilization index* (RUI) and *resource utilization variance* (RUV), are defined based on the scheduled unit and deployed unit. The RUI is the ratio of scheduled unit to deployed unit (Equation 4.6). The RUV is the difference between deployed unit and scheduled unit (Equation 4.7).

$$\text{Resource utilization index (RUI)} = \frac{\text{Scheduled unit}}{\text{Deployed unit}} \tag{4.6}$$

$$\text{Resource utilization variance (RUV)} = \text{Deployed unit} - \text{Scheduled unit} \tag{4.7}$$

The RUI and RUV can be graphically comprehended by superimposing the shapes denoting the deployed unit and scheduled unit respectively (Figure 4.5). The RUI is the relative ratio of the scheduled unit area over the deployed unit area. The RUV is the absolute difference between the deployed unit and the scheduled unit, which represents the nonproductive resource time over the project duration.

RUI and RUV can be used to evaluate how efficiently deployed resources can be utilized if a specific resource-constrained project schedule is executed. The higher RUI value, the lower RUV value, and the higher resource utilization during project execution.

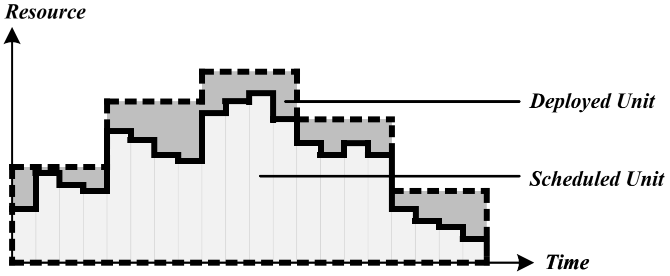


Figure 4.5: Visualization of resource utilization by superimposing scheduled unit and deployed unit

For example, in the demonstration case as shown in Figure 4.6, the deployed unit and scheduled unit are calculated as 888 wh and 664 wh, respectively. As per Equations (4.6) and (4.7), RUI and RUV are determined as 74.8% (=664/888) and 224 wh (=888–664), respectively. The two metrics imply about three-quarters of deployed labor resource time is utilized; as far as scheduled activities are concerned, the balance of one-quarter (equivalent to 224 wh out of the total 888 wh deployed) is deemed nonproductive.

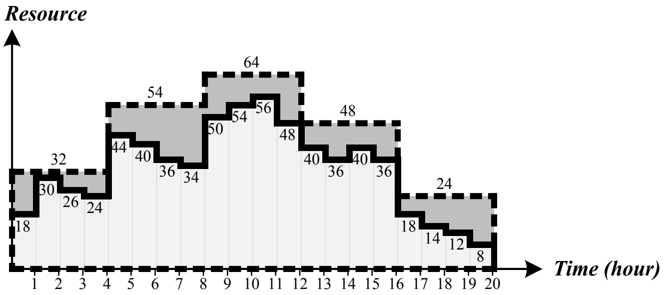


Figure 4.6: Numerical example for calculating resource utilization index

Given the identical project, multiple alternative resource-constrained schedules can be formulated by applying a practical resource scheduling approach (Primavera P6) and newly developed RSDMP approaches. The schedules can then be readily assessed and compared by use of the proposed metrics in terms of budget sufficiency and resource utilization. The Primavera P6 and the optimization scheduling approaches are introduced in the following subsections.

4.3.6 Practical resource scheduling approach (Primavera P6)

The commercial scheduling software system Primavera P6 is marketed by Oracle Inc. and widely used to formulate resource-constrained project schedules (Harris 2008, 2012). In the software system, resource demand by each activity can be defined in consideration of planned activity duration and crew productivity, while resource supply over project duration is specified by users subject to practical constraints on resource availability, complemented by field experience.

The project network is defined by linking activities in accordance with technological constraints. The start and finish times of individual activities are calculated based on the critical path method (CPM) (Kelley and Walker 1959). Resource scheduling by Primavera P6 causes the start times of certain activities to be delayed if available resources at any particular time are overallocated (Harris 2008, 2012). The Primavera P6 schedule is formulated in such a way that the aggregated resource demand as per scheduled activities at a particular time is lower than the corresponding resource supply limit being imposed.

Note that after resource leveling, Primavera P6 produces a feasible resource-constrained project schedule, along with the determination of the scheduled unit. The resulting Primavera P6 schedule provides a basis to further analyze the completion time of project and distributions of the resource budget (Seibert and Evans 1991). The budgeted unit, deployed unit, and scheduled unit, as proposed in this research, can also be readily determined from the Primavera P6 schedule, as illustrated in Figure 4.7.

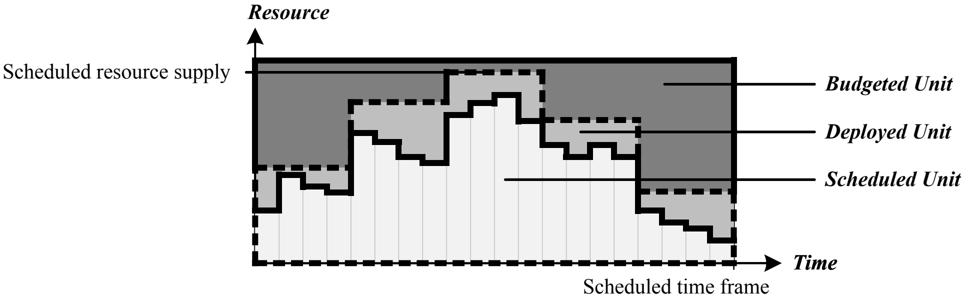


Figure 4.7: Budgeted unit, deployed unit and scheduled unit apply to analyze a resource-constrained project schedule

4.3.7 RSDMP optimization approaches

The resource-based scheduling problem, termed as resource supply-demand matching problem (RSDMP) along with the proposed solution approaches are formalized in previous chapters, in order to mathematically derive optimum resource-constrained project schedules. With regard to resource provisions, the RSDMP schedule can be constrained by constant resource supply limits throughout the project duration or periodic resource supply limits varied over different time periods of the project duration. Note that the objective function of RSDMP is uniquely designed in order to minimize project time duration and resource supply limits simultaneously. The result is an optimum schedule featuring the shortest project duration and optimum resource supply limits.

The RSDMP mathematical model is restated from Equations (4.8) to (4.16). The decision variables are the completion times of activity and project, and the quantities of supplied resources. Equation (4.8) shows the objective function, which minimizes individual activity completion time, project completion time and supplied resources for particular time periods. Equations (4.9) and (4.10) maintain the technological relationships between activities. Equations (4.11) and (4.12) declare the time-dependent resource constraints for ensuring the resource supply matches the resource demand at any project time. Equations (4.13) and (4.14) constrain each individual activity and the whole project to be completed at only one particular time. Equations (4.15) and (4.16) declare the decision variables, which represent the completion times of activity and project, as binary variables.

$$\text{minimize} \quad f = \sum_{\text{Act}} \sum_{\text{t}=0}^{\text{T}} (\alpha_{\text{Act}} \text{t} x_{\text{Act}}^{\text{t}}) + \sum_{\text{t}=0}^{\text{T}} (\beta_{\text{Proj}} \text{t} x_{\text{Proj}}^{\text{t}}) + \sum_{\text{Res}} \sum_{\text{tp}} (\gamma_{\text{Res}}^{\text{tp}} R_{\text{Res}}^{\text{tp}}) \tag{4.8}$$

$$\sum_{\text{t}=0}^{\text{T}} [(\text{t} x_{\text{Act}}^{\text{t}})]_{\text{Pred}} \le \sum_{\text{t}=0}^{\text{T}} [(\text{t} - d_{\text{Suc}}) x_{\text{Act}}^{\text{t}}]_{\text{Suc}} , \tag{4.9}$$

for each activity-to-activity precedence relationships

$$\sum_{\text{t}=0}^{\text{T}} [(\text{t} x_{\text{Act}}^{\text{t}})]_{\text{Pred}} \le \sum_{\text{t}=0}^{\text{T}} [(\text{t} x_{\text{Proj}}^{\text{t}})]_{\text{Suc}} , \tag{4.10}$$

for each activity-to-project precedence relationships

$$\sum_{\text{t}=\text{t}}^{\text{t}+d_{\text{Act}}} (r_{\text{ActRes}}^{\text{t}} x_{\text{Act}}^{\text{t}}) \le R_{\text{Res}}^{\text{tp}} \text{ , for all resource types, for all time points} \tag{4.11}$$

$$lb_{\text{Res}}^{\text{tp}} \le R_{\text{Res}}^{\text{tp}} \le ub_{\text{Res}}^{\text{tp}} \text{, for all resource types, for all time periods} \tag{4.12}$$

$$\sum_{\text{t}=0}^{\text{T}} x_{\text{Act}}^{\text{t}} = 1 \text{, for all activities} \tag{4.13}$$

$$\sum_{t=0}^{T} x_{\mathrm{Proj}}^{\mathrm{t}} = 1, \text{ for the project} \tag{4.14}$$

$$x_{\mathrm{Act}}^{\mathrm{t}} = \{0,1\} \tag{4.15}$$

$$x_{\mathrm{Proj}}^{\mathrm{t}} = \{0,1\} \tag{4.16}$$

where f = objective function; α_{Act}= relative importance of activity completion time; β_{Proj}= relative importance of project completion time; $\gamma_{\mathrm{Res}}^{\mathrm{tp}}$ = relative importance of supply quantity for particular resource at time period tp; t = time unit, from start time 0 to end time T; $x_{\mathrm{Act}}^{\mathrm{t}}$=binary variable with 1 representing an activity completed at time t, or 0 otherwise; $x_{\mathrm{Proj}}^{\mathrm{t}}$= binary variable with 1 representing the project completed at time t, or 0 otherwise; $R_{\mathrm{Res}}^{\mathrm{tp}}$= resource supply at time period tp; d_{Suc}= duration of successor; d_{Act}= duration of current activity; $r_{\mathrm{ActRes}}^{\mathrm{t}}$= resource demand of activity; $lb_{\mathrm{Res}}^{\mathrm{tp}}$ = lower bound of resource quantity available during time period tp; $ub_{\mathrm{Res}}^{\mathrm{tp}}$ = upper bound of resource quantity available during time period tp.

Compared with Primavera P6, the RSDMP approach optimizes the resource supply and project duration in an integrative fashion, significantly reducing the deployed unit of the original Primavera P6 schedule, which is illustrated in Figure 4.8.

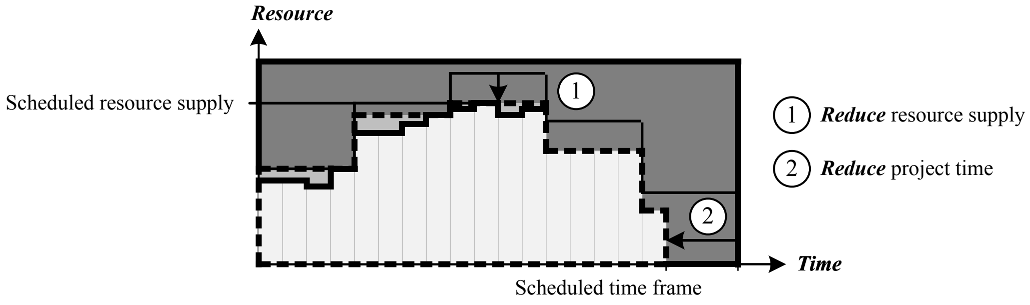


Figure 4.8: Optimization processes by RSDMP against the original Primavera P6 schedule

Built upon the RSDMP mathematical model, three resource scheduling optimization approaches with specific optimization objectives are defined by adjusting the order of magnitude between the parameters β_{Proj} and $\gamma_{\mathrm{Res}}^{\mathrm{tp}}$ which govern the optimization objective, as follows:

(i) RSDMP-P approach

The parameter β_{Proj} is greater than $\gamma_{\mathrm{Res}}^{\mathrm{tp}}$ by orders of magnitude (e.g., $\beta_{\mathrm{Proj}} = 100$ and $\gamma_{\mathrm{Res}}^{\mathrm{tp}} = 1$); this indicates much higher weight is being placed on shortening total project duration against providing the leanest resources.

(ii) RSDMP-R approach

The parameter $\gamma_{\mathrm{Res}}^{\mathrm{tp}}$ is greater than β_{Proj} by orders of magnitude (e.g., $\beta_{\mathrm{Proj}} = 1$ and $\gamma_{\mathrm{Res}}^{\mathrm{tp}} = 100$). This approach provides the optimum results with particular emphasis on streamlining resources over shortening project duration.

(iii) RSDMP-N approach

The parameters β_{Proj} and $\gamma_{\mathrm{Res}}^{\mathrm{tp}}$ are of the same order of magnitude. The optimum solution is provided where both objectives of shortening project duration and streamlining resource supply are optimized to the same extent.

Next, the budget sufficiency and resource utilization are objectively assessed for optimum RSDMP schedules along with the counterpart Primavera P6 schedule for (i) a simple project adapted from textbook and (ii) a case study of the refinery plant turnaround project.

4.4 Example case study

A textbook example (Ahuja et al. 1994) is adapted to demonstrate the proposed schedule assessment approach. The project consists of nine activities. The project involves two resources, i.e., Resource A and Resource B. Activity duration and resource requirements are summarized in Table 4.1.

Table 4.1: Activity duration and resource requirements

Activity	Successor	Duration (hr)	Resource A	Resource B
A	D, E	2	4	1
B	F, G	3	4	0
C	G	5	4	0
D	H	4	3	0
E	–	4	1	0
F	I	3	2	1
G	I	6	2	0
H	–	2	2	1
I	–	3	2	0

It is assumed in the conceptual planning stage, the client requires this project to complete within 24 time units (hours) as per the master schedule (Level 1 schedule). The control budget can be determined based upon the project scope and labor productivity (Equation 4.1). For the current simple case, it is roughly estimated that a crew size of 9 workers including type A and type B will be available to carry out the project over 24 hours, thus resulting in the budgeted unit of 216 wh (namely, 9 × 24 = 216 wh).

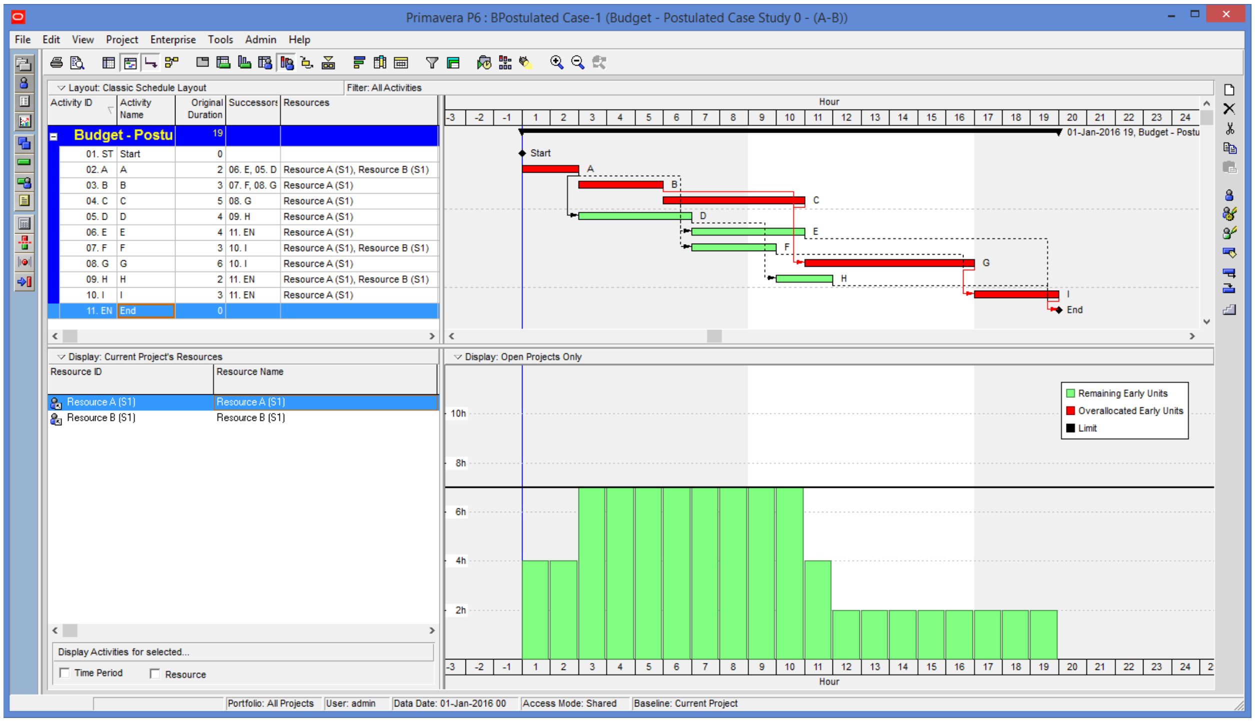
With the budgeted unit specified, two scenarios of providing available resources for executing the project are postulated. In Scenario 1, the quantities of resource supply are constantly provided throughout the project duration. In Scenario 2, the quantities of resource supply are varied with respect to three time periods over the project duration.

4.4.1 Scenario 1

In this scenario, the availability limits of Resource A and Resource B from Time 0 to Time 24 are considered as 7 and 2 units, respectively. Note, the resource provision limits are determined in consideration of the budgeted unit and the estimated project duration.

4.4.1.1 Primavera P6 approach (Scenario 1)

The Primavera P6 schedule is represented in Figure 4.9. According to the scheduling results, 7 units of Resource A and 2 units of Resource B are deployed to execute the project from Time 0 to Time 19. Hence, the deployed units for Resource A and Resource B are calculated as 133 wh (=7×19) and 38 wh (=2×19), respectively (Equation 4.2). The total deployed unit is 171 wh. The scheduled unit is 91 wh [=(4×1+4×1+7×1+7×1+7×1+7×1+7×1+7×1+7×1+7×1+4×1+2×1+2×1+2×1+2×1+2×1+2×1+2×1+2×1)+(1×1+1×1+1×1+1×1+1×1+1×1+1×1)] (Equation 4.3).



Activity ID	Activity Name	Original Duration	Successors	Resources
	Budget - Postu	19		
01. ST	Start	0		
02. A	A	2	06. E, 05. D	Resource A (S1), Resource B (S1)
03. B	B	3	07. F, 08. G	Resource A (S1)
04. C	C	5	08. G	Resource A (S1)
05. D	D	4	09. H	Resource A (S1)
06. E	E	4	11. EN	Resource A (S1)
07. F	F	3	10. I	Resource A (S1), Resource B (S1)
08. G	G	6	10. I	Resource A (S1)
09. H	H	2	11. EN	Resource A (S1), Resource B (S1)
10. I	I	3	11. EN	Resource A (S1)
11. EN	End	0		

Resource ID	Resource Name
Resource A (S1)	Resource A (S1)
Resource B (S1)	Resource B (S1)

Portfolio: All Projects | User: admin | Data Date: 01-Jan-2016 00 | Access Mode: Shared | Baseline: Current Project

Figure 4.9: Primavera P6 schedule (Scenario 1)—showing activity bar chart, resource demand profile, and constant resource supply limits

Based upon the budgeted unit, deployed unit, and scheduled unit, the values of budget sufficiency index (BSI), budget sufficiency variance (BSV), resource utilization index (RUI), and resource utilization variance (RUV) are calculated as follows:

- BSI is 126.3% (=216/171);
- BSV is 45 wh (=216–171);
- RUI is 53.2% (=91/171); and
- RUV is 80 wh (=171–91).

Note that the BSI value (126.3%>1) implies that the amount of budgeted unit is sufficient for scheduling activities and reserving contingency (26.3% of the budgeted unit). The BSV (45 wh) is the exact amount of contingency. The RUI (53.2%) implies that 53.2% of the deployed labor resource time is utilized. The RUV (80 wh) is the nonproductive amount of deployed labor resource time.

4.4.1.2 RSDMP approach (Scenario 1)

The RSDMP-P, RSDMP-R, and RSDMP-N approaches were applied to formulate optimum RSDMP schedules. Figure 4.10 shows the optimum RSDMP-P project schedule with the project duration shortened to 17 hours, in the form of activity bar chart and resource use profile. Note that in order to present the resource-constrained schedule in a clear fashion, individual activities and interactivity sequences are highlighted in the resource use profile. Moreover, 6 resources of type A and 1 resource of type B are to be provided from Time 0 to Time 17. The deployed unit is 119 wh [=(6+1)×17].

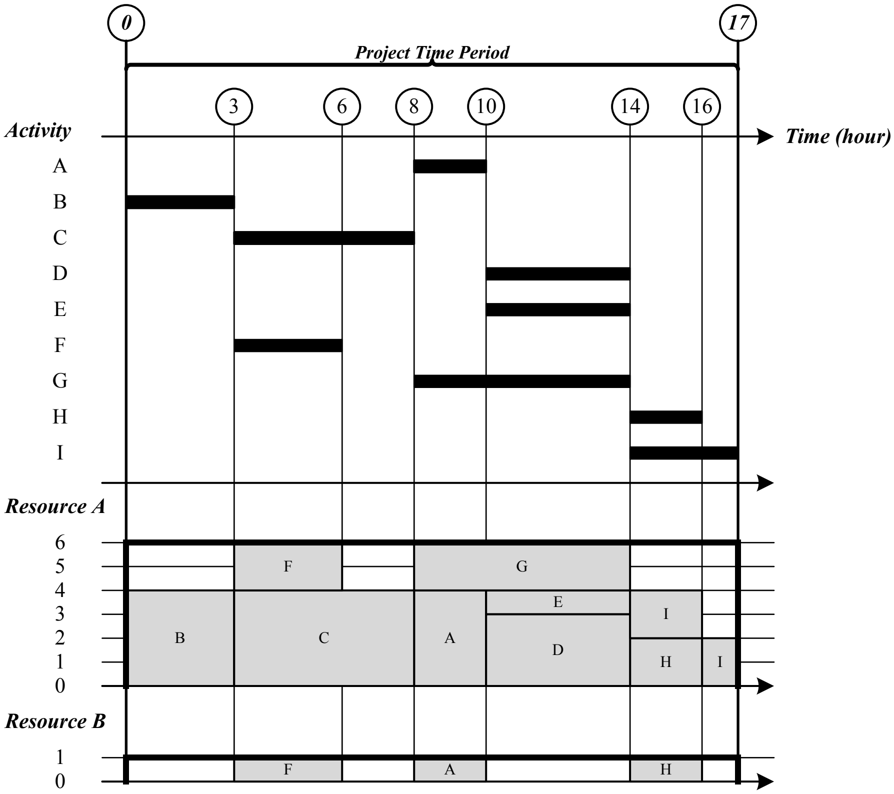


Figure 4.10: RSDMP-P schedule (Scenario 1)—activity bar chart and resource use profile

Figure 4.11 shows the optimum project schedule formulated by RSDMP-R. The project duration is 23 hours. 4 resources of type A and 1 resource of type B are provided from Time 0 to Time 23. The deployed unit is thus 115 wh [=(4+1)×23].

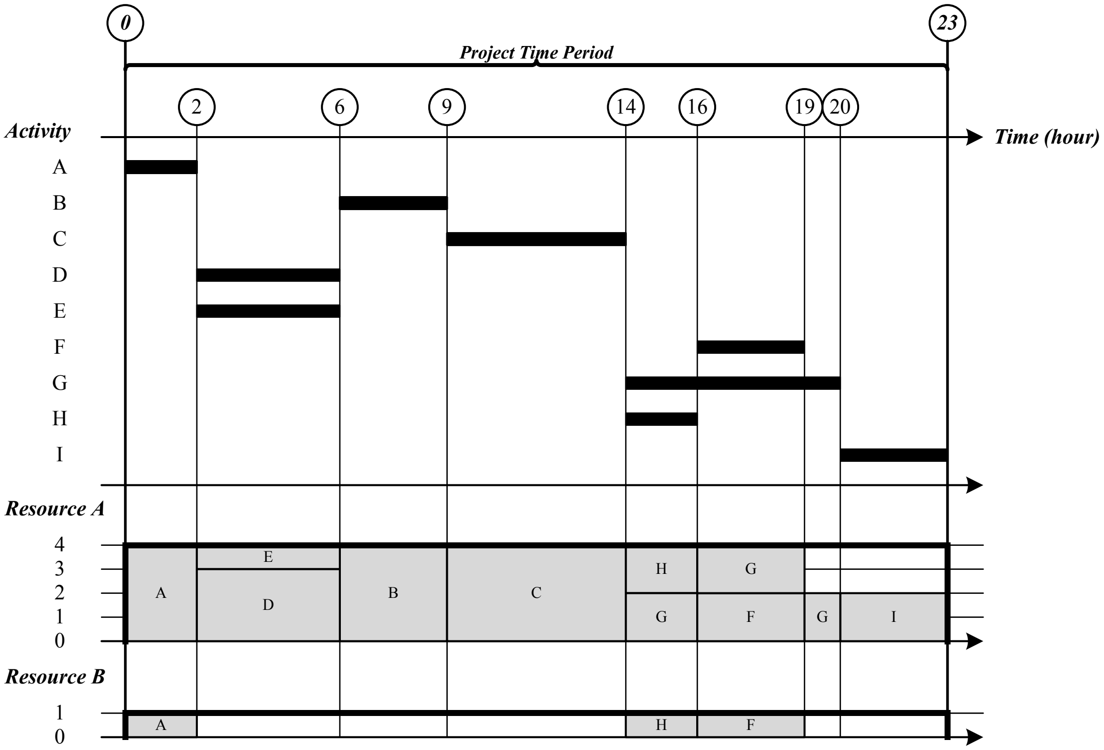


Figure 4.11: RSDMP-R schedule (Scenario 1)—activity bar chart and resource use profile

Figure 4.12 shows the optimum RSDMP-N project schedule. The project duration is 19 hours. The project utilizes 5 resources of type A and 1 resource of type B. The deployed unit is 114 wh [=(5+1)×19]. It is noteworthy that the RSDMP optimization results from three approaches all show streamlined resource supply limits in comparison with the Primavera P6 case (7 resources of type A and 2 resource of type B).

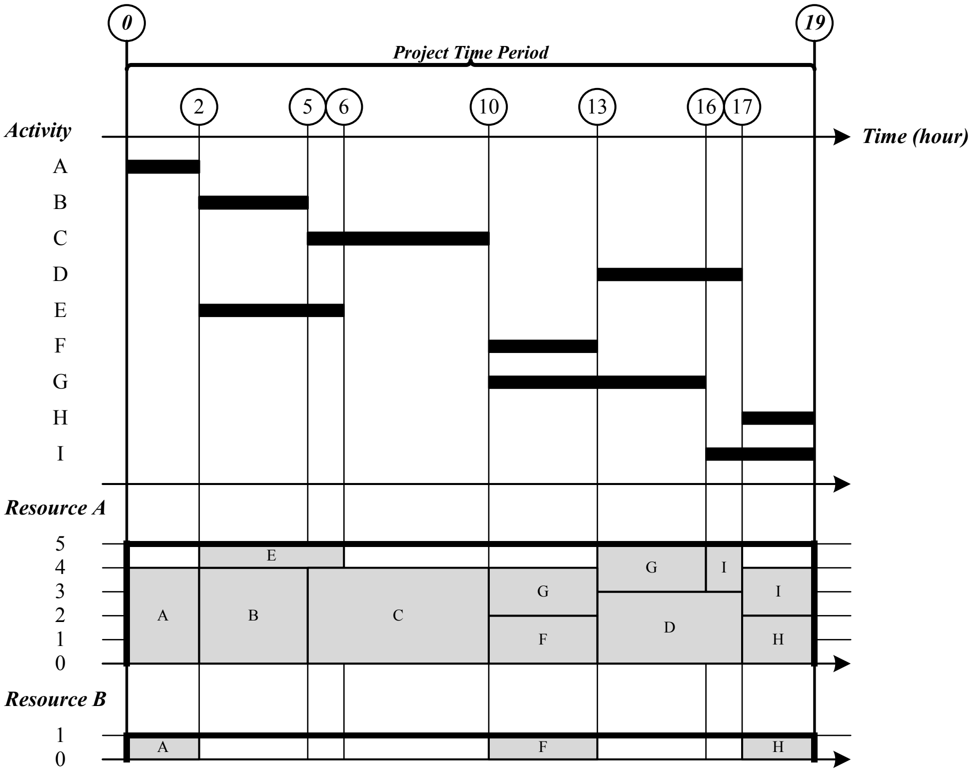


Figure 4.12: RSDMP-N schedule (Scenario 1)—activity bar chart and resource use profile

The values of BSI, BSV, RUI and RUV are derived for the RSDMP schedules, summarized in Table 4.2. All three schedules can be delivered within the 24-hour target project duration. If the shortest project duration is of the highest priority, then the RSDMP-P schedule with 17 hours total project time outperforms the others. If budget sufficiency and resource utilization are set as the top criteria, the RSDMP-N project schedule is chosen because its BSI and RUI values are the highest. It can be also seen that all the three RSDMP optimized schedules outperform the counterpart schedule generated by Primavera P6 in terms of budget sufficiency and resource utilization.

Table 4.2: BSI, BSV, RUI and RUV values derived from Primavera P6 versus RSDMP schedules (Scenario 1)

Index	Primavera P6 (19h-7A-2B)	RSDMP-P (17h-6A-1B)	RSDMP-R (23h-4A-1B)	RSDMP-N (19h-5A-1B)
BSI	126.3%	181.5%	187.8%	189.5%
BSV	45 wh	97 wh	101 wh	102 wh
RUI	53.2%	76.5%	79.1%	79.8%
RUV	80 wh	28 wh	24 wh	23 wh

In particular, Table 4.3 compares BSI, BSV, RUI and RUV as derived from corresponding Primavera P6 and RSDMP-N schedules, showing that RSDMP outperforms Primavera P6 with considerably higher budget sufficiency and resource utilization (the BSI value increases by 61.5%, the BSV value increases by 56 wh, the RUI value increases by 25.9%, and the RUV value decreases by 56 wh). Worth mentioning is that 56 wh of idled resource time (part of deployed unit) in the Primavera P6 schedule are shifted to the contingency in the RSDMP optimized schedule such that the project can be delivered with more contingency against unanticipated activities.

Table 4.3: Comparing BSI, BSV, RUI and RUV on Primavera P6 versus RSDMP-N (Scenario 1)

Index	Primavera P6	RSDMP-N	Difference
BSI	126.3%	189.5%	+61.5%
BSV	45 wh	102 wh	+56 wh
RUI	53.2%	79.8%	+25.9%
RUV	80 wh	23 wh	–56 wh

4.4.2 Scenario 2

In Scenario 2, maximum resource supply limits are considered separately with reference to three consecutive project periods of the 24-hour project duration (Table 4.4), i.e., (i) from Time 0 to Time 8, (ii) from Time 8 to Time 16, and (iii) from Time 16 to Time 24. The resource availability limits of Resource A are varied over the three project periods. The maximum available quantity of Resource B is 2 units throughout the project duration. The budgeted unit remains unchanged as 216 wh [=(6+2)×(8–0)+(8+2)×(16–8)+(7+2)×(24–16)].

Table 4.4: Periodic maximum resource supply limits (Scenario 2)

Time period (start and finish points)	1 (0 – 8)	2 (8 – 16)	3 (16 – 24)
Resource A	6	8	7
Resource B	2	2	2

4.4.2.1 Primavera P6 approach (Scenario 2)

In Primavera P6, the maximum resource availability limits of Resource A and Resource B are imposed with respect to three time periods, as shown in Figure 4.13. The schedule is successfully formulated by Primavera P6. It can be seen from Figure 4.13 that the resource supply can satisfy the resource demand for particular time periods. The project duration is 19 hours. In total, 6 A resources and 2 B resources are utilized during Time period 1; 8 A resources and 2 B resources are employed for Time period 2; 7 A resources and 2 B resources are employed during Time period 3. The deployed unit is 171 wh (=[(6+2)×(8–0)+(8+2)×(16–8)+(7+2)×(19–16)]). Note that the scheduled activity times are identical to Scenario 1.

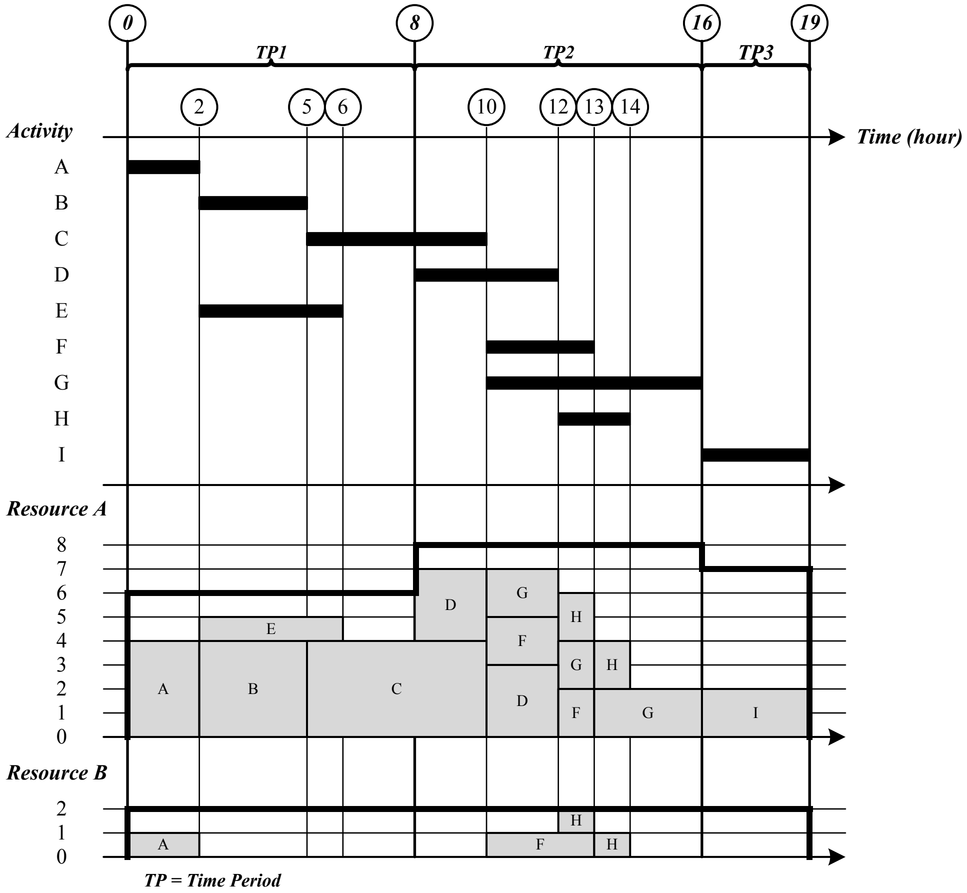


Figure 4.13: Primavera P6 schedule (Scenario 2)—activity bar chart and resource use profile with periodic resource supply limits highlighted

Based upon the budgeted unit (=216 wh), deployed unit (=171 wh), and scheduled unit (=91 wh), the values of BSI, BSV, RUI, and RUV are determined as BSI is 126.3% (=216/171); BSV is 45 wh (=216–171); RUI is 53.2% (=91/171); and RUV is 80 wh (=171–91).

4.4.2.2 RSDMP approach (Scenario 2)

Similar to Scenario 1, the three RSDMP schedules were generated based on various optimization functions. Figure 4.14 shows the optimum RSDMP-P project schedule. The project duration is 17 hours. 6 A resources and 1 B resource are provided during Time periods 1 and 2; while only 2

A resources are provided during Time period 3. The deployed unit is thus 114 wh [=(6+1)×(8–0)+(6+1)×(16–8)+(2+0)×(17–16)]. Note that the activity execution sequences indicated by the RSDMP-P project schedules in Scenarios 1 and 2 (Figures 4.10 and 4.14) are identical. In comparison with Scenario 1, where constant resource supply limits are applied over the total project duration, 4 A resources and 1 B resource can be actually saved for Time period 3 in Scenario 2 where the resource supply limits are periodically defined.

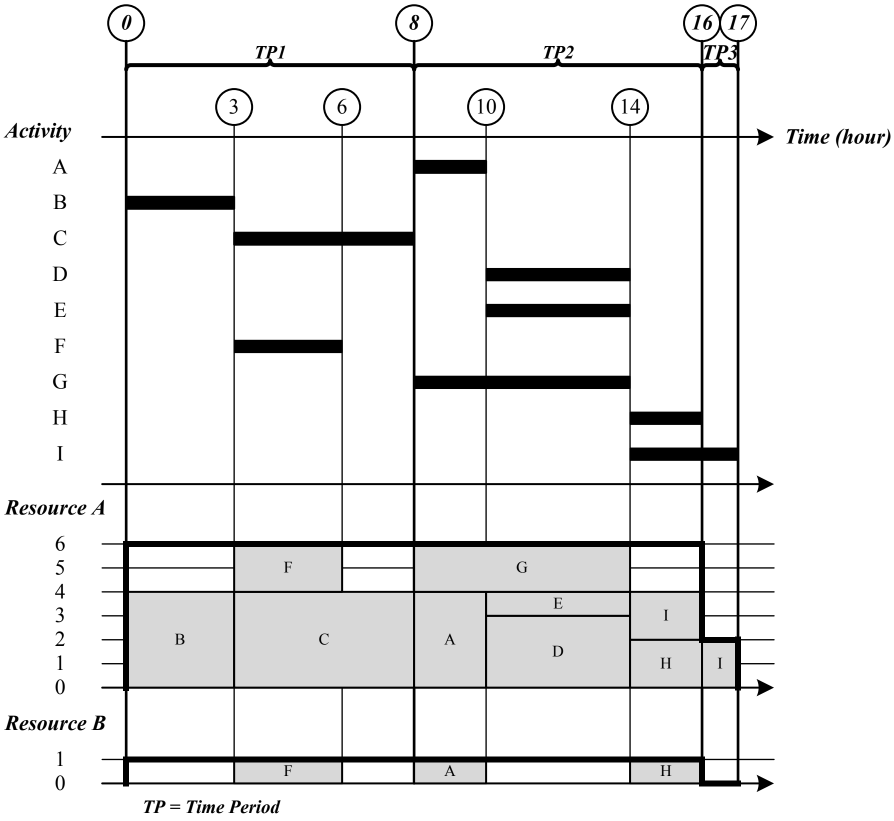


Figure 4.14: RSDMP-P schedule (Scenario 2)—activity bar chart and resource use profile with periodic resource supply limits highlighted

The optimum RSDMP-R schedule is shown in Figure 4.15. The project duration is 22 hours. 4 A resources are only employed during Time period 1; while 6 A resources and 1 B resource are utilized during Time period 2. Only 2 A resources are utilized during Time period 3. The deployed unit is 100 wh [=(4+0)×(8–0)+(6+1)×(16–8)+(2+0)×(22–16)].

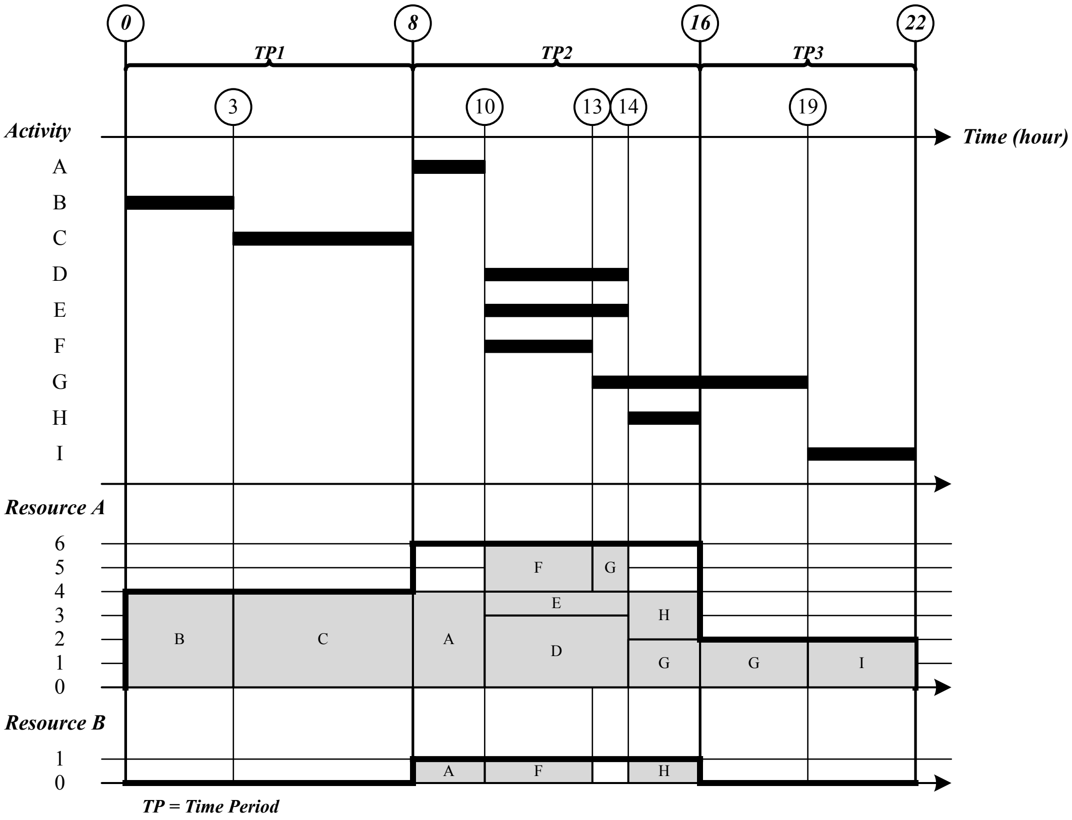


Figure 4.15: RSDMP-R schedule (Scenario 2)—activity bar chart and resource use profile with periodic resource supply limits highlighted

The optimum RSDMP-N project schedule is given in Figure 4.16. The project duration is 19 hours. During Time period 1, 6 A resources and 1 B resource are utilized. 7 A resources and 1 B resource are required during Time period 2. During Time period 3, only 2 A resources are used. The deployed unit is thus 126 wh [=(6+1)×(8–0)+(7+1)×(16–8)+(2+0)×(19–16)].

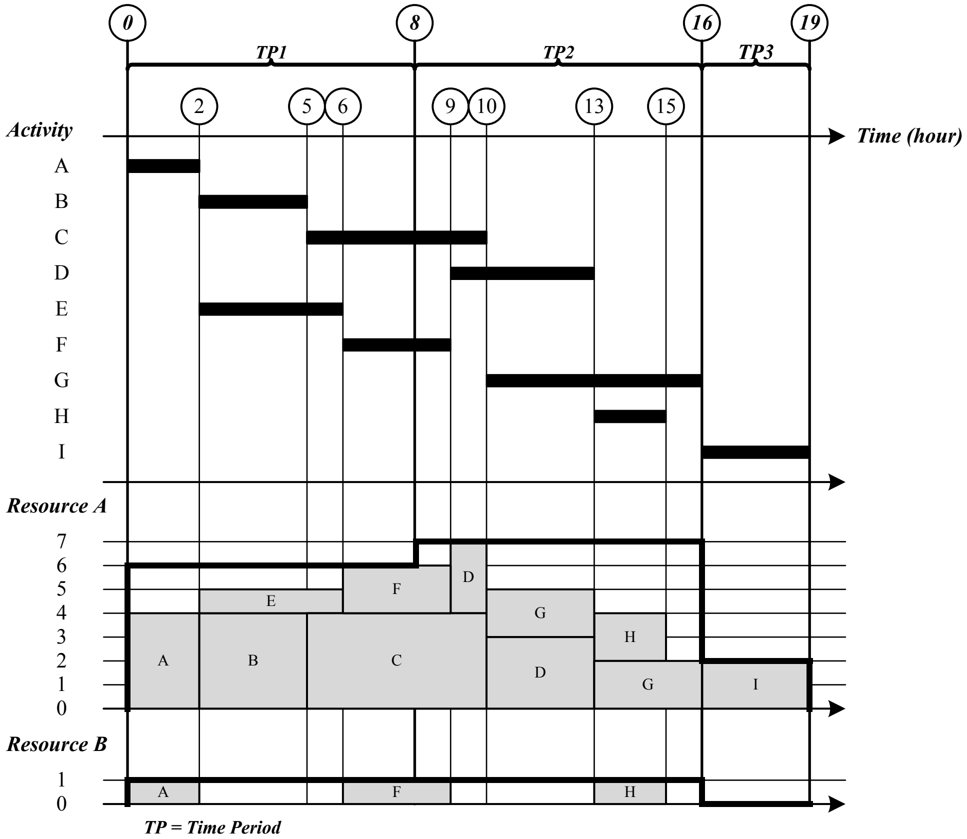


Figure 4.16: RSDMP-N schedule (Scenario 2)—activity bar chart and resource use profile with periodic resource supply limits highlighted

Based upon the budgeted unit, deployed unit, and scheduled unit as derived for resource-constrained schedules resulting from Primavera P6 and RSDMP, the values of BSI, BSV, RUI, and RUV are determined as given in Table 4.5. It can be seen that all the three RSDMP optimized schedules outperform the counterpart schedule generated by Primavera P6 in terms of budget sufficiency and resource utilization. If budget sufficiency and resource utilization are set as the top criteria, the optimum RSDMP-R project schedule should be selected as its BSI (216%) and RUI (91%) are the highest, thought its project duration (22 hours) is longer than the other options but still under the targeted 24-hour project time frame.

Table 4.5: BSI, BSV, RUI and RUV values derived from Primavera P6 versus RSDMP schedules (Scenario 2)

Index	Primavera P6 (19h-687A-222B)	RSDMP-P (17h-662A-110B)	RSDMP-R (22h-462A-010B)	RSDMP-N (19h-672A-110B)
BSI	126.3%	189.5%	216%	171.4%
BSV	45 wh	102 wh	116 wh	90 wh
RUI	53.2%	79.8%	91%	72.2%
RUV	80 wh	23 wh	9 wh	35 wh

In particular, Table 4.6 contrasts budget sufficiency and resource utilization between Primavera P6 and RSDMP-R schedules, showing that RSDMP outperforms Primavera P6 in terms of having higher metrics of budget sufficiency and resource utilization. The differences are significant: BSI increases by 89.7%, BSV increases by 71 wh, RUI increases by 37.8%, and RUV decreases by 71 wh; also note that 71 wh of idled resource time (part of deployed unit) in the Primavera P6 schedule are shifted to contingency in the RSDMP optimized schedule.

Table 4.6: Comparing BSI, BSV, RUI and RUV on Primavera P6 versus RSDMP-R (Scenario 2)

Index	Primavera P6	RSDMP-R	Difference
BSI	126.3%	216.0%	+89.7%
BSV	45 wh	116 wh	+71 wh
RUI	53.2%	91.0%	+37.8%
RUV	80 wh	9 wh	–71 wh

4.4.3 Verification of the proposed analytical approach for assessing budget sufficiency and resource utilization by simulation

In order to verify the proposed approach for the case study example, this subsection provides details on how to assess the budget sufficiency and resource utilization by hand simulation based on the scheduling results derived from the practical approach (Primavera P6) and the optimization approaches (RSDMP), respectively. A resource-activity interaction table is especially developed for showing detailed schedule information (i.e., tracking the utilization of individual resources in the specific resource-constrained project scheduling analysis). Note that given the same schedule scenario on the sample project, the hand simulation approach has produced (i) the identical schedule results (project duration, activity start and finish times) compared with Primavera P6 or RSDMP optimization, and (ii) the same metrics of resource utilization and budget sufficiency as determined by the proposed equations (Equations 4.4–4.7).

The proposed analytical approach is verified for determining budget sufficiency index (BSI), budget sufficiency variance (BSV), resource utilization index (RUI), and resource utilization variance (RUV), based upon the hand simulation approach. The hand simulation approach can be comprehended by use of the resource-activity interaction table. The interaction table provides the data structure for simulating and communicating the individual resource workflows. Detailed resource-activity process interaction can be tracked by allocating the readily available resources to perform activities. As such, the busy time and idle time of individual resources can be statistically collected.

Figures 4.17–4.20 show the modified data structure of the resource-activity interaction table. The table should be read from left-hand side to right-hand side. The activity currently under consideration is denoted in Row (Cur.Act.). Columns (1) and (2) represent resource identifier and resource name, respectively. Column (3) initializes the ready-to-serve (RTS) time of each available resource.

Columns (a), (b), and (c) keep track of resource-activity interactions with respect to the current activity being executed. Column (a) updates the RTS time of each individual resource according to the finish times of previously processed activities. Column (b) flags resource utilization (1 means utilized, or 0 otherwise). Column (c) keeps the idle time of each utilized resource prior to the start time of the current activity. The early start time and early finish time of the current activity are entered in Row (EST) and Row (EFT), respectively.

Column (4) represents the end-of-service (EOS) time of each individual resource. It is the resource release time after delivering the last activity (i.e., project end activity) with respect to each individual resource.

Columns (5), (6) and (7) collect the statistics of each individual resource. Column (5) denotes the total-service-time (TST) of individual resources. It is the accumulated service time between the resource arrival time and resource release time for particular available time periods. Column (6) tracks the total-idle-time (TIT) of particular resource. The TIT is determined by accumulating the resource idle times as denoted in Column (c) with respect to all activities. Column (7) calculates the total-busy-time (TBT) [i.e., TBT = TST (Column 5) – TIT (Column 6)] of each individual resource.

From the simulation perspective, the deployed unit is calculated by aggregating the TST for all resources [i.e., $\sum_{\text{Res}} \text{TST}_{\text{Res}}$ = summation of Column (5)]. The scheduled unit is calculated by combining the TBT for all resources [i.e., $\sum_{\text{Res}} \text{TBT}_{\text{Res}}$ = summation of Column (7)]. Built upon the TST and TBT of resources, the budget sufficiency index (BSI), budget sufficiency variance

(BSV), resource utilization index (RUI), and resource utilization variance (RUV) are alternatively expressed as per Equations (4.17), (4.18), (4.19), and (4.20), respectively.

$$\text{Budget sufficiency index (BSI)} = \frac{\text{Budgeted unit}}{\sum_{\text{Res}} \text{TST}_{\text{Res}}} \tag{4.17}$$

$$\text{Budget sufficiency variance (BSV)} = \text{Budgeted unit} - \sum_{\text{Res}} \text{TST}_{\text{Res}} \tag{4.18}$$

$$\text{Resource utilization index (RUI)} = \frac{\sum_{\text{Res}} \text{TBT}_{\text{Res}}}{\sum_{\text{Res}} \text{TST}_{\text{Res}}} \tag{4.19}$$

$$\text{Resource utilization variance (RUV)} = \sum_{\text{Res}} \text{TST}_{\text{Res}} - \sum_{\text{Res}} \text{TBT}_{\text{Res}} \tag{4.20}$$

The resource schedule formulated by Primavera P6 in Scenario 1 (Figure 4.9) is used to illustrate the resource-activity interaction table as presented in Figure 4.17. In total, 7 units of Resource A and 2 units of Resource B are initialized with the identifiers A1–A7 and B1–B2, respectively (Columns 1 and 2). They are available at Time 0 (Column 3). All resources take part in executing the project start activity at Time 0.

Cur.Act			Start			A			B			D			C			F			E			H			G			I			End				Stat.		
(1)	(2)	(3)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(4)	(5)	(6)	(7)
1	A1	0	0	1	0	0	1	0	2	1	0	5			5	1	0	10			10			10			10			10	1	6	19	1	0	19	19	6	13
2	A2	0	0	1	0	0	1	0	2			2	1	0	6			6	1	0	9			9	1	0	11			11			11	1	8	19	19	8	11
3	A3	0	0	1	0	0	1	0	2			2	1	0	6			6	1	0	9			9	1	0	11			11			11	1	8	19	19	8	11
4	A4	0	0	1	0	0	1	0	2			2	1	0	6			6			6	1	0	10			10			10			10	1	9	19	19	9	10
5	A5	0	0	1	0	0			0	1	2	5			5	1	0	10			10			10			10	1	0	16			16	1	3	19	19	5	14
6	A6	0	0	1	0	0			0	1	2	5			5	1	0	10			10			10			10	1	0	16			16	1	3	19	19	5	14
7	A7	0	0	1	0	0			0	1	2	5			5	1	0	10			10			10			10			10	1	6	19	1	0	19	19	8	11
8	B1	0	0	1	0	0	1	0	2			2			2			2			2			2	1	7	11			11			11	1	8	19	19	15	4
9	B2	0	0	1	0	0			0			0			0			0	1	6	9			9			9			9			9	1	10	19	19	16	3
EST			0			0			2			2			5			6			6			9			10			16			19						
EFT			0			2			5			6			10			9			10			11			16			19			19						

Direction to read →

Figure 4.17: Resource-activity interaction table formulated based upon Primavera P6 schedule for validation (Scenario 1)

Activity A is the first activity being executed (Cur.Act.) in accordance with Primavera P6 schedule. The RTS time of all resources are Time 0 (Column a). Resources A1–A4 and B1 are selected and allocated to perform the activity (Column b). The allocated resources have 0 idle time prior to the start time of Activity A (Column c). As the resource requirement of Activity A is satisfied, Activity A starts at Time 0 (Row EST) and completes at Time 2 (Row EFT).

Then, the resources for executing Activity B (Cur.Act.) as depicted in Primavera P6 schedule are selected and allocated. The RTS time of all individual resources according to the finish times of previously processed activity is updated (Column a). For example, the previous processed activity of Resource A1 is Activity A, while the previously processed activity of Resource A5 is null. The RTS time of Resources A1–A4 and B1 is updated as Time 2, because these resources are available from Time 2 (after the completion time of Activity A). The RTS time of Resources A5–A7 and B2 is Time 0. To execute Activity B, Resources A1, A5, A6 and A7 are allocated (Column b). The resource idle time, which is the time duration between the finish time of Activity A and the start time of Activity B, is tracked (Column c). In this case, the idle time of Resource A1 is 0 because the finish time of Activity A and the start time of Activity B are at Time 2. The idle time of Resources A5, A6 and A7 is 2 time units because the resources are not utilized between Time 0 and Time 2. Activity B starts at Time 2 (Row EST) and completes at Time 5 (Row EFT). Similarly, data on the detailed resource workflows for performing Activities D, C, F, E, H, G, I, End, are entered and presented.

The EOS time of individual resources is given (Column 4). The TST of all resources is 19 time units (Column 5) because all resources are available throughout the project duration (i.e., from Time 0 to Time 19). The TIT of each individual resource is calculated by combining all idle times as indicated in Column (c) with respect to all activities (Column 6). For example, the TIT of Resource A5 is calculated as 5 time units (=0+0+2+0+0+0+0+0+0+0+3=5). The resource TBT is then determined (Column 7). For example, the TBT of Resource A5 is 14 time units (=19–5).

As such, the BSI, BSV, RUI and RUV can be determined as per Equations (4.17–4.20):

- BSI is 126.3%

  [=216/(19+19+19+19+19+19+19+19+19)];
- BSV is 45 wh

  [=216–(19+19+19+19+19+19+19+19+19)];
- RUI is 53.2%

  [=(13+11+11+10+14+14+11+4+3)/(19+19+19+19+19+19+19+19+19)];
- RUV is 80 wh

  [=(19+19+19+19+19+19+19+19+19)–(13+11+11+10+14+14+11+4+3)].

Given the formulated optimum RSDMP-N schedule for Scenario 1 (Figure 4.12), the resource-activity interaction table is presented as Figure 4.18.

Cur.Act			Start			A			B			E			C			G			F			D			I			H			End				Stat.		
(1)	(2)	(3)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(4)	(5)	(6)	(7)
1	A1	0	0	1	0	0	1	0	2	1	0	5			5	1	0	10			10	1	0	13	1	0	17			17			17	1	2	19	19	2	17
2	A2	0	0	1	0	0	1	0	2	1	0	5			5	1	0	10			10	1	0	13	1	0	17			17	1	0	19	1	0	19	19	0	19
3	A3	0	0	1	0	0	1	0	2	1	0	5			5	1	0	10			10			10	1	3	17			17	1	0	19	1	0	19	19	3	16
4	A4	0	0	1	0	0	1	0	2			2	1	0	6			6	1	4	16			16			16	1	0	19			19	1	0	19	19	4	15
5	A5	0	0	1	0	0			0	1	2	5			5	1	0	10	1	0	16			16			16	1	0	19			19	1	0	19	19	2	17
6	B1	0	0	1	0	0	1	0	2			2			2			2			2	1	8	13			13			13	1	4	19	1	0	19	19	12	7
EST			0			0			2			2			5			10			10			13			16			17			19						
EFT			0			2			5			6			10			16			13			17			19			19			19						

Direction to read →

Figure 4.18: Resource-activity interaction table formulated based upon RSDMP-N schedule for validation (Scenario 1)

The BSI, BSV, RUI and RUV can be calculated:

- BSI is 189.5%

  [=216/(19+19+19+19+19+19)];
- BSV is 102 wh

  [=216–(19+19+19+19+19+19)];
- RUI is 79.8%

  [=(17+19+16+15+17+7)/(19+19+19+19+19+19)];
- RUV is 23 wh

  [=(19+19+19+19+19+19)–(17+19+16+15+17+7)].

As a result, it is found that the calculated BSI, BSV, RUI, and RUV values based on the hand simulation approach (Equations 4.17–4.20) are identical to the BSI, BSV, RUI, and RUV values derived based on Equations (4.4–4.7) as discussed in example case study section.

In Scenario 2, the resource-activity interaction tables corresponding to the Primavera P6 (Figure 4.13) and the RSDMP-R schedules (Figure 4.15) are shown in Figures 4.19 and 4.20, respectively. In this scenario, the quantities of resource supply are varied with respect to three time periods over the project duration. The shaded cell in the resource-activity interaction table shows that the involved resources are not available for performing current activities.

Cur.Act			Start			A			B			E			C			D			G			F			H			I			End				Stat.		
(1)	(2)	(3)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(4)	(5)	(6)	(7)
1	A1	0	0	1	0	0	1	0	2	1	0	5			5	1	0	10			10			10			10			10	1	6	19	1	0	19	19	6	13
2	A2	0	0	1	0	0	1	0	2	1	0	5			5			5	1	3	12			12			12			12	1	4	19	1	0	19	19	7	12
3	A3	0	0	1	0	0	1	0	2			2	1	0	6			6			6	1	4	16			16			16			16	1	0	16	16	4	12
4	A4	0	0	1	0	0	1	0	2			2			2	1	3	10			10	1	0	16			16			16			16	1	3	19	19	6	13
5	A5	0	0	1	0	0			0	1	2	5			5	1	0	10			10			10	1	0	13			13			13	1	6	19	19	8	11
6	A6	0	0	1	0	0			0	1	2	5			5	1	0	10			10			10	1	0	13			13			13	1	6	19	19	8	11
7	A7	8																8	1	0	12			12			12	1	0	14			14	1	5	19	11	5	6
8	A8	8																8	1	0	12			12			12	1	0	14			14	1	5	19	11	5	6
9	B1	0	0	1	0	0	1	0	2			2			2			2			2			2			2	1	10	14			14	1	5	19	19	15	4
10	B2	0	0	1	0	0			0			0			0			0			0			0	1	10	13			13			13	1	6	19	19	16	3
EST			0			0			2			2			5			8			10			10			12			16			19						
EFT			0			2			5			6			10			12			16			13			14			19			19						

Direction to read →

Figure 4.19: Resource-activity interaction table formulated based upon Primavera P6 schedule for validation (Scenario 2)

For example, the Primavera P6 schedule shows that 6 units of Resource A and 2 units of Resource B are available for performing Activities A, B, E, and C. As such, Resources A1–A6 and Resources B1–B2 are available during Time period 1. However, the shaded cells have specified that Resources A7–A8 are not available. They become available for executing Activities D, G, F, and H. As such, Resource A3 is not presented when selecting resources to execute Activity I. Note that the guideline for selecting available resources to perform activities with varied resource supply can be found in Siu et al. (2015a). The resource-activity interaction table is utilized (Figure 4.19) for assessing BSI, BSV, RUI, and RUV:

- BSI is 126.3%

  [=216/(19+19+16+19+19+19+11+11+19+19)];
- BSV is 45 wh

  [=216–(19+19+16+19+19+19+11+11+19+19)];
- RUI is 53.2%

  [=(13+12+12+13+11+11+6+6+4+3)/(19+19+16+19+19+19+11+11+19+19)];
- RUV is 80 wh

[=(19+19+16+19+19+19+11+11+19+19)–(13+12+12+13+11+11+6+6+4+3)].

Meanwhile, the BSI, BSV, RUI and RUV of the formulated optimum RSDMP-R schedule (Figure 4.15) can be evaluated based on the corresponding resource-activity interaction table (Figure 4.20):

Cur.Act			Start			B			C			A			D			F			E			G			H			I			End				Stat.		
(1)	(2)	(3)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(4)	(5)	(6)	(7)
1	A1	0	0	1	0	0	1	0	3	1	0	8	1	0	10			10	1	0	13			13	1	0	19			19	1	0	22	1	0	22	22	0	22
2	A2	0	0	1	0	0	1	0	3	1	0	8	1	0	10			10			10	1	0	14			14			14			14	1	2	16	16	2	14
3	A3	0	0	1	0	0	1	0	3	1	0	8			8	1	2	14			14			14			14	1	0	16			16	1	0	16	16	2	14
4	A4	0	0	1	0	0	1	0	3	1	0	8			8	1	2	14			14			14			14	1	0	16			16	1	0	16	16	2	14
5	A5	8										8	1	0	10	1	0	14			14			14			14			14			14	1	2	16	8	2	6
6	A6	8										8	1	0	10			10	1	0	13			13	1	0	19			19	1	0	22	1	0	22	14	0	14
7	B1	8										8	1	0	10			10	1	0	13			13			13	1	1	16			8	1	8	16	8	1	7
EST			0			0			3			8			10			10			10			13			14			19			22						
EFT			0			3			8			10			14			13			14			19			16			22			22						

Direction to read →

Figure 4.20: Resource-activity interaction table formulated based upon RSDMP-R schedule for validation (Scenario 2)

- BSI is 216.0%

  [=216/(22+16+16+16+8+14+8)];

- BSV is 116 wh

  [=216–(22+16+16+16+8+14+8)];

- RUI is 91.0%

  [=(22+14+14+14+6+14+7)/(22+16+16+16+8+14+8)];

- RUV is 9 wh

  [=(22+16+16+16+8+14+8)–(22+14+14+14+6+14+7)].

In brief, the calculated BSI, BSV, RUI and RUV values based on the hand simulation approach by use of the refined resource-activity interaction table are identical to those derived based on

Equations (4.4–4.7). In such a way, the proposed approach can be verified based on the case problem.

4.5 Refinery plant turnaround project

As denoted in previous chapters, the industrial plant turnaround project aims at preserving, maintaining, and improving the production capacity of the plant. Preventive, predictive, and corrective maintenance activities are scheduled to be performed (Stephens 2010). The shutdown of major industrial plants has marked impact upon regional or even national gross domestic output (Pokharel and Jiao 2008). Substantial economic loss would be incurred if the project is delayed. Meanwhile, found work which might not be anticipated during project planning stage can be commonplace for a turnaround project (O'Connor and Tucker 1986; Georgy et al. 2000; Lenahan 2006; Siddiqui and Rafiuddin 2012; Siu et al. 2013). A turnaround project generally requires stringent control on budget sufficiency and resource utilization to ensure successful project delivery. In practice, resource-constrained project scheduling is mandatory for managing resource workflows in industrial turnaround projects, which is generally stipulated in the contract conditions (KBR 2010).

The three-month turnaround project located in Alberta Canada consists of (i) replacing four elbows in the reactor; (ii) removing existing head and cyclone assemblies; (iii) installing new head and cyclone assemblies; and (iv) completing refractory and tie in electrical instrumentation, piping and platforming. The scope for the present case study was narrowed down to the reactor portion, consisting of 107 activities. Activities along with their resource requirements are summarized in Appendix A. The project involves 19 types of resources. The project time frame is targeted at 200 hours. The control budget (budgeted unit) is 20,800 wh.

The schedule assessment approach is applied for two scenarios: Scenario 1, where the resources are constantly supplied throughout the project duration (Table 4.7), and Scenario 2, where the resource provision limits are re-accessed after first 100 hours (Table 4.8).

Table 4.7: Constant resource supply limits for turnaround project (Scenario 1)

Resource identifier	Resource supply limits
A	16
B	11
C	2
D	7
E	10
F	10
G	5
H	5
I	2
J	2
K	15
L	1
M	1
N	1
O	4
P	5
Q	3
R	2
S	2

Table 4.8: Periodic resource supply limits for turnaround project (Scenario 2)

Resource identifier	Resource supply limits over Time period 1	Resource supply limits over Time period 2
A	12	20
B	12	10
C	1	2
D	7	7
E	10	10
F	10	10
G	5	6
H	5	5
I	2	2
J	2	2
K	15	15
L	1	1
M	1	1
N	1	1
O	4	4
P	5	5
Q	3	3
R	2	2
S	2	2

Primavera P6 and RSDMP methods were applied, each capable of formulating resource-constrained project schedules for the two scenarios. The quantities of resource supply over the project duration can be significantly reduced by use of RSDMP-R approach, compared with the RSDMP-P and RSDMP-N schedules. The corresponding optimum quantities of resource supply for Scenario 1 and Scenario 2 are given in Tables 4.9 and 4.10, respectively. As such, the deployed unit derived from the Primavera P6 and RSDMP-R schedules in two different scenarios is summarized in Table 4.11.

Table 4.9: Optimum constant resource supply limits determined by RSDMP-R approach (Scenario 1)

Resource identifier	Resource supply limits
A	10
B	6
C	1
D	6
E	6
F	3
G	5
H	1
I	1
J	1
K	6
L	1
M	1
N	1
O	2
P	2
Q	1
R	1
S	1

Table 4.10: Optimum periodic resource supply limits determined by RSDMP-R approach (Scenario 2)

Resource identifier	Resource supply limits over Time period 1	Resource supply limits over Time period 2
A	12	7
B	8	5
C	1	0
D	6	0
E	6	0
F	3	0
G	5	1
H	1	1
I	1	1
J	1	0
K	4	7
L	0	1
M	0	1
N	0	1
O	0	2
P	0	2
Q	0	1
R	0	1
S	0	1

Table 4.11: Contrasting deployed unit between Primavera P6 and RSDMP-R in two scenarios

Scenario	Primavera P6	RSDMP-R
1	17,992 wh	11,200 wh
2	19,396 wh	7,840 wh

4.5.1 Comparison of BSI, BSV, RUI, and RUV

Based upon the budgeted unit (i.e., 20,800 wh), the deployed unit (Table 4.11), and the scheduled unit (=3,836 wh), the budget sufficiency metrics (BSI and BSV), and the resource utilization metrics (RUI and RUV) are calculated. Tables 4.12 and 4.13 compare the values of BSI, BSV, RUI, and RUV on the Primavera P6 and RSDMP-R project schedules from Scenario 1 and Scenario 2, respectively.

The results show that RSDMP outperforms Primavera P6 by significantly increasing BSI by 70.1% and 158.1% in Scenarios 1 and 2, respectively. Accordingly, BSV increases by 6,792 wh and 11,556 wh for Scenarios 1 and 2. RUI also increases by 12.9% and 29.2% for Scenarios 1 and 2. RUV decreases by 6,792 wh and 11,556 wh for Scenarios 1 and 2. It is noteworthy that 6,792 wh and 11,556 wh of idled resource time (part of the deployed unit) are actually shifted from idled time in the Primavera P6 schedule into contingency in the RSDMP-R optimized schedule in Scenarios 1 and 2, respectively.

Table 4.12: Contrasting Primavera P6 and RSDMP-R schedules (Scenario 1 of turnaround project)

Index	Primavera P6	RSDMP-R	Difference
BSI	115.6%	185.7%	+70.1%
BSV	2,808 wh	9,600 wh	+6,792 wh
RUI	21.3%	34.3%	+12.9%
RUV	14,156 wh	7,364 wh	–6,792 wh

Table 4.13: Contrasting Primavera P6 and RSDMP-R schedules (Scenario 2 of turnaround project)

Index	Primavera P6	RSDMP-R	Difference
BSI	107.2%	265.3%	+158.1%
BSV	1,404 wh	12,970 wh	+11,556 wh
RUI	19.8%	48.9%	+29.2%
RUV	15,560 wh	4,004 wh	–11,556 wh

4.5.2 Cross-validation by practitioners

In the current case, the actual data collected from a turnaround project during field execution can be loosely related to the as-planned project schedules established in project stages of bidding and workface planning. In addition, the industry benchmark on resource utilization [e.g., work percentage based on systematic work sampling studies (Thomas 1991) and oil and gas industrial sectors (CII 2010)] provides the yardstick to check the model outputs. They are not expected to equate but should fall on the similar range. For instance, the tool time of skilled trades working on industrial-construction projects is reported to be around 30% (Burleson et. al 1998; Gouett et. al 2011; COAA 2014), while 60% is expected reasonable to reach through better workface planning (Suncor Energy 2014). If the project is executed with the same work scope as per the planned resource schedule, the realistic upper boundary of resource utilization is equal to the relevant value of RUI (generally not exceeding 85%). Any delay factors which materialize in the field but are not explicitly considered in scheduling will prevent resource utilization from reaching the upper boundary. The resource-loaded workface plan by use of Primavera P6 produces a resource utilization index similar to the comparable industry benchmark, while the optimization method has shown the feasibility to increase resource utilization simply by optimizing the resource schedule, without making any fundamental changes to existing methods in current practice.

The detailed schedule results alongside the aforementioned metrics were then examined by domain experts to further corroborate the validity and effectiveness of the proposed methodologies (Sargent et al. 2007). Those domain experts are experienced industry professionals who are responsible for project scheduling and resource planning and who will directly benefit from the research study. The assessment results (BSI, BSV, RUI, and RUV) in the case study, based upon the Primavera P6 and RSDMP schedules, were presented to the project management including the senior corporate managers, project managers, project schedulers, and site superintendents. The experts have at least 10 years of experience each in turnaround project management. They interpreted the analytical results independently and confirmed their feasibility and validity by cross-checking against experiences.

In the end, domain experts concurred that relevant metrics were logical and reasonable based upon the executable project plan being presented. Specifically, such expert validation would impart confidence in the proposed metrics derived from the scheduling optimization approaches. Instead of conservatively deploying the maximum available resource limits as in the current practice, the contractor can deploy the optimum resource limits and execute the optimized resource schedule. Meanwhile, the research deliverables will provide the project management team of a contractor with effective decision support in regard to (i) identifying unrealistically low baseline budget based on detailed workface planning; (ii) avoiding underutilization of resources and productivity loss due to crowding on workface, (iii) having sufficient budget as contingency against any unplanned work, and (iv) delivering the project on time and under budget. For instance, if the baseline budget is not sufficient, the proposed budget sufficiency metrics would be instrumental in building an analytical case to identify unrealistically low baseline budget based on detailed workface planning, i.e., the BSI is lower than 1 for a Primavera P6 resource-loaded schedule. This provides a quantitative basis to justify (i) increasing the budget or (ii) performing resource scheduling optimization so as to increase the budget sufficiency.

4.5.3 Limitation of proposed metrics

It should be emphasized that the interpretation and use of the derived metrics of resource utilization and budget sufficiency must be based on the scope of work being planned. During project execution, changes to the work scope and the workface plan may take place, including work package definition, activity execution sequence, resource supply, and resource demand. Hence, relevant metrics may no longer be applicable unless they are reassessed based on the updated or reoptimized resource schedule that closely mirrors the changed work scope.

In short, the proposed metrics will be more applicable to project planning stages instead of project execution control stages. Those metrics are specific to a particular project schedule, which is subject to changes throughout project development phases. During the project execution, the change of work scope is commonplace in reality. The project schedule needs to be updated in accordance with the changed work scope. The proposed metrics need to be reevaluated based upon the updated project schedule. Given a considerable change of work scope, those updated metrics would become incomparable with the respective values derived from the original schedule. Thus, those particular values of metrics may have a relatively short life span. On the other hand, the project schedule updating process itself can be a challenging task. For example, the contractor often finds himself in a situation where the baseline schedule is not allowed to change without owner's approval.

In addition, the proposed resource utilization metrics are not intended for assessing each individual resource but the collection of resources employed on the project. The resource utilization can be slightly different between individual craft persons (within trades). The optimization in regard to uniformly distributing the work load among the individual resources can be a worthwhile endeavor in the future research.

4.6 Conclusions

This chapter formalizes a novel schedule assessment approach for quantifying and visualizing budget sufficiency and resource utilization from resource scheduling perspectives. Graphical representations are adopted to facilitate definitions of terminology and metrics relevant to budget sufficiency and resource utilization in an integrative fashion. The budgeted unit, deployed unit, and scheduled unit are first defined, which can be readily derived based upon the formulated resource-constrained project schedule. Then, two budget sufficiency metrics [budget sufficiency index (BSI) and budget sufficiency variance (BSV)] plus two resource utilization metrics [resource utilization index (RUI) and resource utilization variance (RUV)] are defined based on the budgeted unit, deployed unit and scheduled unit. BSI and BSV measure the sufficiency of control budget for deploying resources in executing a project schedule with resource constraints, while RUI and RUV measure the utilization efficiency of deployed resources. This chapter also contrasts the application of a practical scheduling approach (Primavera P6) and the resource supply-demand matching problem (RSDMP) optimization approaches to generate multiple alternative resource-constrained project schedules under time-dependent resource constraints in terms of budget sufficiency and resource utilization for case study projects. The results of the case studies show that budget sufficiency and resource utilization for resource-constrained project schedules can be quantified, verified, analyzed and compared using the proposed schedule assessment metrics in a straightforward yet objective manner. The results also proved that the RSDMP approaches outperform Primavera P6 with regard to higher budget sufficiency and higher resource utilization, such that more contingency can be reserved in the control budget against unexpected works. Nevertheless, the developed metrics are evaluated by use of an analytical approach instead of tapping into experts’ experience, lending decision support to senior management, project schedulers, and site superintendents.

CHAPTER 5: CONCLUSIONS[5]

This chapter draws the research conclusions, and recapitulates the contributions.

5.1 Research conclusions

This research study advances the existing knowledge of resource-based project scheduling, while improving the existing practice of planning industrial-construction projects under resource constraints. Quantitative scheduling methods have been developed in an attempt to formulate resource-constrained project schedules by minimizing the total project duration subject to resource supply limits. The limits of resource provisions over different time periods can vary during the project duration. The sufficiency of the control budget for executing the formulated project schedule and the efficiency of the deployed resources can be objectively assessed based on newly devised metrics. With the quantitative scheduling methods for industrial-construction project scheduling and workface planning under time-dependent resource constraints being developed, the set objectives of this research study given in Chapter 1 have been achieved.

As given in Chapter 2, the resource supply-demand matching problem (RSDMP) is established based upon the literature of resource-based scheduling problems as reported in the construction engineering and management domain, and the operations research and management science domains, including resource allocation, resource leveling, and time-cost/time-resource tradeoff.

---

[5] Portions of this chapter have been published in the journal of computing in civil engineering, ASCE. 10.1061/(ASCE)CP.1943-5487.0000498, 04015028; journal of construction engineering and management, ASCE. 10.1061/(ASCE)CO.1943-7862.0001027, 04015048; journal of construction engineering and management, ASCE, in ASCE. 10.1061/(ASCE)CO.1943-7862.0001106, 04016003.

A RSDMP approach, which consists of a mathematical model along with a two-stage optimization approach, is developed to determine the theoretical optimum resource supply for formulating resource-constrained project schedules. The mathematical model is developed based on integer programming. It is composed of an objective function to minimize activity completion time, project completion time and resource supply, technology constraints to maintain the activity precedence relationships, and resource constraints to guarantee the resource demand aggregated from activities at a particular time point is less than the maximum resource supply over the project time period, while expressing the resource supply as a range of lower and upper boundaries in consideration of site safety and spatial requirements. The two-stage optimization approach is associated with the practical context of making the optimum cost budgeting decision and maximizing the cushion against potential delays during project execution. The innovative use of a resource-activity interaction table verifies the validity of the RSDMP approach while facilitating workface planning of allocating work to individual craft persons. Based upon the example case study and practical case study, it is found that the RSDMP analytical solution outperforms the solutions resulting from the simulation based and evolutionary-algorithm based approaches, on formulating the workface executable schedules with the shortest project duration and the leanest resource supply. The proposed method provides the analytical basis to reassess the target duration and resource supply limits.

As denoted in Chapter 3, the resource supply-demand matching problem (RSDMP) with time-dependent resource constraints is identified based upon the literature reviews of resource-constrained project scheduling methodologies in the construction engineering and management domain, and the operations research and management science domains. To address the determination of optimum resource supply quantities for different project periods, an enhanced RSDMP approach, which consists of a RSDMP mathematical model along with a two-stage optimization framework, is developed. The RSDMP mathematical model optimizes the resource supply for particular time periods, while minimizing activity completion times, and project completion time. For each specific time period, resource availability is given as a range (a lower bound and an upper bound). The time-dependent resource constraints are imposed to maintain the balance between resource demand and supply in particular time periods. Furthermore, the two-stage solution framework is devised to align with critical decision making processes in current practices of project scheduling and workface planning. As a result of the RSDMP approach, the optimum resource supply for particular time periods can be theoretically determined. The matrix and vector formulations of the RSDMP mathematical model are suggested for enumerating the RSDMP solutions. Based on the small example and practical case studies, it is found that the proposed approach overcomes the drawbacks (e.g., lengthen project duration, undersupply or oversupply resources) of breaking down the project into subprojects according to the time periods associated with corresponding resource availability constraints, while being computationally effective to determine the optimum time-dependent resource availability limits for scheduling the project in practical settings.

As discussed in Chapter 4, the quantitative metrics for assessing budget sufficiency and resource utilization are established in the context of resource-constrained project schedules. The literature on measuring budget sufficiency and resource utilization in the construction engineering and management domain are reviewed. The analytical metrics of budgeted unit, deployed unit, scheduled unit, budget sufficiency index, budget sufficiency variance, resource utilization index, and resource utilization variance are defined, visualized, and verified. Based upon the example case study and the practical case study, the resource-constrained scheduling methods by Primavera P6 practical approach and the RSDMP approaches are demonstrated; the definitions of the metrics and calculation procedures are illustrated; the applicability and effectiveness of the proposed methodology when dealing with a project of practical size and complexity are discussed. It is worth noting that Primavera P6 relies on heuristic rules in resource leveling, while RSDMP applies analytical optimization algorithms to shorten project duration and streamline resource supply limits. As such, RSDMP approaches outperform Primavera P6 with regard to higher budget sufficiency and higher resource utilization, while reserving more contingency in the control budget against unexpected works. A significant portion of the idle resource time in the Primavera P6 schedule is shifted to add to the contingency in the optimum RSDMP schedule.

As a result of this research study, construction researchers and construction practitioners can formulate an integral view of resource-based scheduling development. The developed research deliverables (both methodologies, solution algorithms, findings and insights gained) contribute to the knowledge of planning the industrial-construction projects under time-dependent resource constraints with both academic and practical significances, as summarized in the next sections.

5.2 Academic contributions

The academic contributions of this research study to existing knowledge include the following.

- Generalization of resource supply-demand matching problem (RSDMP): The RSDMP is defined in contrast with established resource-based scheduling problems as reported in the literature, including resource allocation, resource leveling, and time-cost/time-resource tradeoff.

- Development of RSDMP approach: The method for solving RSDMP is formalized in the context of integer programming mathematical model and two-stage optimization approach. The result is an optimum resource-constrained project schedule providing the shortest project duration with the leanest resource supply. The optimum resource requirement is identified between the lower and upper boundaries of the resource supply limit.

- Visualization of resource workflow: The resource-activity interaction table is designed and applied to present the workflows of individual craft persons for facilitating workface planning, while verifying the RSDMP results.

- Development of modified RSDMP approach: The method for solving RSDMP is enhanced by modifying the RSDMP mathematical model in consideration of time-dependent resource constraints. The result is the optimum project schedule, providing the shortest project duration with the leanest resource supply for particular time periods. The optimum resource requirement is identified for each period.

- Development of RSDMP matrix and vector formulation: The RSDMP formulations are elaborated in matrix and vector formats, which provide standardized inputs for computers to generate feasible solutions. The computing times of RSDMP analysis for case studies are benchmarked in association with the author's computer specifications. The readers could replicate and verify the RSDMP results by use of the mathematical optimization software systems (e.g., MATLAB, and CPLEX).

- Development of budget sufficiency and resource utilization metrics: The sufficiency of control budget for deploying resources to execute the project schedule can be measured by budget sufficiency index/variance; while the utilization efficiency of deployed resources based on the project schedule can be assessed by resource utilization index/variance. It proves that the substantial and tangible improvements on Primavera P6 schedules are achievable by applying RSDMP optimization approaches (i.e., higher budget sufficiency, and higher resource utilization).

- Refining the design of resource-activity interaction table: The table is modified for tracking the total service time, total busy time, and total idle time, of individual resources. The metrics of resource utilization and budget sufficiency can be hand simulated, while cross-validating with the analytical approach.

5.3 Industrial contributions

The industrial contributions are recapitulated based on the collaborative research efforts with the partner company and a real-world turnaround project case study, as below.

- Formulation of resource-constrained project schedules: The RSDMP approach provides optimum yet reliable project schedules with resource constraints, by use of the input data and relevant information prepared for planning industrial-construction projects (i.e., activity definitions, activity durations, resource demand for performing activities, activity precedence relationships, and resource supply for delivering the project). The optimum plan obtained is resource-loaded, practically feasible, and workface executable.

- Determination of resource supply: The RSDMP approach analytically quantifies the optimum amount of resource supply (e.g., skilled labor resources) factoring in the site spatial and safety requirements to match the project demand.

- Determination of optimum resource supply limits for particular time periods: The enhanced RSDMP approach analytically quantifies the optimum amount of resource supply for each particular time period of project duration. As such, oversupply and undersupply of resources could be avoided while alleviating the resource shortage challenge in the real world.

- Presentation of resource workflows: The RSDMP approach advances current scheduling practice of workface planning by visualizing the resource workflow of individual craft persons.

- Assessments of resource-constrained project schedules: Instead of the commonly applied metrics of total project duration and total project cost, the budget sufficiency index/variance and resource utilization index/variance are effective for appraising multiple alternative project schedules. This provides a quantitative basis to justify increasing the control budget or performing resource scheduling optimization so as to deliver the project with unexpected work on time and within budget.

5.4 Limitations of the proposed quantitative approaches

The applications of the proposed quantitative methods (the developed RSDMP approaches and the derived metrics of resource utilization and budget sufficiency) are based on the inputs of work scope, including the work package definitions, activity definitions, activity precedence relationships, and crew productivity for delivering the activities with particular durations. During project execution, changes in scheduling inputs that inform the project schedules and workface plans may take place. For example, the extra work items (that are generated from executing the planned activities) and additional work items (that are not part of the original plan but inserted when delivering the formulated plans) may be found. As a result, the planned RSDMP schedules and its associated metrics of resource utilization and budget sufficiency are no longer valid. The proposed quantitative methods must be reapplied in order to update and reformulate the resource schedule in accordance with the changed scheduling inputs—ideally all done by the superintendent or foreman who makes decisions at the workface level. Yet, there are still many barriers in terms of training, culture, software interfaces, and system integration to overcome before turning this vision into a reality.

5.5 Envisioned future research

This subsection envisions possible future research directions on the basis of the developed quantitative methods. From a theoretical perspective, the developed RSDMP mathematical models can be modified and extended for formulating workface schedules under time-dependent resource constraints in consideration of activity splitting and resource interruptions. Activity interruptions are commonly seen when the resources are preempted and reallocated for executing other more critical activities or work packages. The continuity of the resource flow by use of the RSDMP techniques based on both serial and parallel scheduling paradigms can be further explored and compared (Ahuja et al. 1994). A possible solution is to divide one interrupted activity into subactivities. Resources are allocated for performing sub-activities in a parallel fashion, as opposed to the current serial approach. The RSDMP approach can be used for determining the optimum resource supply on the interrupted workflows on an hour-by-hour basis.

On the other hand, the RSDMP mathematical model can be potentially integrated with the auction protocol based simulation methodology proposed for stochastically solving the resource constrained multi-project scheduling problems (RCMPSP) (Taghaddos et al. 2014). The objective of RCMPSP is to minimize the total duration of multiple projects while sharing the same resource pool. In addition, the sensitivity analysis of relative importance parameters associated with the proposed RSDMP objective function can be further conducted in order to examine the tradeoff between resource direct cost and project indirect cost. Alternative optimum resource schedules can be formulated in connection with particular combinations of relative importance parameters. Moreover, the uncertainty of resource supply could be quantified in association with the uncertainties in activity duration and work scope as of critical work packages defined in workface planning. The RSDMP mathematical model can be further extended to formulate the resource-constrained project schedule with uncertainties. As a result, the proposed metrics in terms of budget sufficiency and resource utilization can be evaluated with respect to particular confidence levels.

Placed in a wider perspective, applications of the developed quantitative approaches can be explored in other knowledge areas. For instance, research has examined the possibilities of implementing developed RSDMP approaches to provide production and logistics schedules, so as to quantify the optimum resource supply at particular time periods and visualize the optimum workflows of individual resources (Siu et al. 2016). In the near future, the developed RSDMP approaches can be also integrated with real time data collected by sensors in order to enable reactive, predictive, and proactive resource scheduling and workface planning. With automatic identification and data capture technologies, the real time information, such as work progress and working location of allocated workers, materials, and equipment can be collected with time stamps. The crew productivity for past hours can be scientifically determined. Based upon the updated crew productivity, the activity duration with its resource requirement can be modified for executing the remaining activities, through a similar strategy proposed in Siu et al. (2015a). As a result, the RSDMP resource-constrained project schedule, along with corresponding metrics of budget sufficiency and resource utilization, can be dynamically updated to materialize more effective project planning and control.

5.6 Final remarks

A reliable resource-constrained project schedule provides a baseline plan that is instrumental in guiding activity execution, and controlling resource supply and resources' workflow, ensuring manpower, material, tools, and equipment as required for executing particular activities will be ready at the right time. With regard to the limitations of existing resource-based scheduling approaches for formulating and evaluating schedules, the planners heavily relied on rule-of-thumb or experience for delivering practical projects constrained by limited resources.

To advance the state-of-the-art and add to the knowledge, this research study develops quantitative scheduling methods for providing analytical decision support to project stakeholders, and improves the efficiency, predictability, and controllability of the projects with resource constraints. With the mathematical, simulation, and evolutionary-algorithm optimization approaches, empowered by commonly available computing means, the theoretical results can be achievable for projects of practical size and complexity, potentially enabling both field superintendents and project management to make informed, sound decisions in terms of project scheduling, resource allocation, and project budgeting.

REFERENCES

AACE (Association for the Advancement of Cost Engineering International). (2006). AACE International recommended practice no. 14R-90, responsibility and required skills for a project planning and scheduling professional, TCM framework: 7.2—schedule planning and development. Morgantown, WV, United States.

AACE (Association for the Advancement of Cost Engineering International). (2010). Schedule levels of detail—as applied in engineering, procurement and construction. International Recommended Practice, Morgantown, WV, United States.

AACE (Association for the Advancement of Cost Engineering International). (2011). AACE International recommended practice no. 18R-97, cost estimate classification system—as applied in engineering, procurement, and construction for the process industries, TCM Framework: 7.3—Cost estimating and budgeting. Morgantown, WV, United States.

AbouRizk, S., and Shi, J. (1994). "Automated construction simulation optimization." Journal of construction engineering and management. 120(2), 374–385.

Ahuja, H. N., Dozzi, S. P., and AbouRizk, S. (1994). Project management: techniques in planning and controlling construction projects. 2nd edition, Wiley, NY, United States.

Al-Bataineh, M., AbouRizk, S., and Parkis, H. (2013). "Using simulation to plan tunnel construction." Journal of construction engineering and management. 139(5), 564–571.

Alcaraz, J., Maroto, C., and Ruiz, R. (2003). "Solving the multimode resource constrained project scheduling problem with genetic algorithms." The journal of the operational research society. 54(6), 614–626.

Anbari, F. T. (2003). “EV project management and extensions.” Project management journal, 34(4), 12–23.

Ashuri, B., and Tavakolan, M. (2013). “Shuffled frog-leaping model for solving time-cost-resource optimization problems in construction project planning.” Journal of computing in civil engineering. 10.1061/(ASCE)CP.19431246-5487.0000315, 04014026.

Barraza, G., and Bueno, R. (2007). “Cost contingency management.” Journal of construction engineering and management, 23(3), 140–146.

Bernold, L., and AbouRizk, S. (2010). Managing performance in construction. Wiley, Hoboken, NJ, United States.

Blum, C., and Roli, A. (2003). “Metaheuristics in combinatorial optimization: overview and conceptual comparison.” ACM computing surveys. 35(3), 268–308.

Boctor, F. F. (1990). “Some efficient multi-heuristic procedures for resource-constrained project scheduling.” European journal of operational research. 49, 3–13.

Brucker, P., Drexl, A., Mohring, R., Neumann, K., and Pesch, E. (1999). “Resource-constrained project scheduling: Notation, classification, models and methods.” European journal of operational research. 112(1), 3–41.

Burleson, R., Haas, C., Tucker, R., and Stanley, A. (1998). “Multiskilled labor utilization strategies in construction.” Journal of construction engineering and management, 124(6), 480–489.

Chen, S., Griffis, F., Chen, P., and Chang, L. (2012). “Simulation and analytical techniques for construction resource planning and scheduling.” Automation in construction. 21, 99–113.

Christodoulou, S. (2005). “Ant colony optimization in construction scheduling.” Computing in civil engineering 2005. 1–11.

Christodoulou, S., Ellinas, G., and Michaelidou-Kamenou, A. (2010). “Minimum moment method for resource leveling using entropy maximization.” Journal of construction engineering and management. 136(5), 518–527.

CII (Construction Industry Institute). (2010). Guide to activity analysis, University of Texas at Austin, Austin, TX, United States.

CII (Construction Industry Institute). (2013). Advanced work packaging: design through workface execution. Implementation resource 272-2, Version 3.0, University of Texas at Austin, Austin, TX, United States.

Cioffi, D. F., and Khamooshi, H. (2009). “A practical method of determining project risk contingency budgets.” Journal of the operational research society. 60(4), 565–571.

COAA (Construction Owners Association of Alberta). (2014). COAA workface planning rules. Edmonton, AB, Canada.

Construction Specifications Institute (2011). The CSI project delivery practice guide. Wiley, Hoboken, NJ, United States.

CPLEX, version 12.6 [Computer software]. Armonk, NY, United States, IBM Corporation.

De la Garza, J. M., and Kim, K. (2005). “Evaluation of the resource-constrained critical path method algorithms.” Journal of construction engineering and management. 131(5), 522–532.

Demeulemeester, E, De Reyck, B, and Herroelen, W (2000) “The discrete time/resource tradeoff problem in project networks: a branch-and-bound approach.” IIE TRANS. 32(11), 1059–1069.

Doersch, R. H., and Patterson, J. H. (1977). “Scheduling a project to maximize its present value: a zero-one programming approach.” Management science. 23(8), 882–889.

Dorndorf, U., Pesch, E., and Phan-Huy, T. (2000). “A time-oriented branch-and-bound algorithm for resource-constrained project scheduling with generalized precedence constraints.” Management science. 46(10), 1365–1384.

Easa, S. (1989). “Resource leveling in construction by optimization.” Journal of construction engineering and management. 115(2), 302–316.

Elbeltagi, E., Hegazy, T., and Grierson, D. (2005) “Comparison among five evolutionary-based optimization algorithms.” Journal of advanced engineering informatics. 19(1), 43–53.

Fayek, A. R., and Peng, J. (2013). “Adaptation of workface planning for construction contexts.” Canadian journal of civil engineering. 40(10), 980–987.

Finke, G. (2008). Operational research and networks. Wiley, Etobicoke, ON, Canada.

Fondahl, J. W. (1991). ‘‘The development of the construction engineer: past progress and future problems.’’ Journal of construction engineering and management. 117(3), 380–392.

Georgy, M., Chang, L., and Walsh, K. (2000). “Engineering performance in industrial construction.” ASCE Construction research congress. Orlando, Florida, United States, 917–927.

Ghoddousi, P., Eshtehardian, E., Jooybanpour, S., and Javanmardi, A. (2013). “Multimode resource-constrained discrete time-cost-resource optimization in project scheduling using non-dominated sorting genetic algorithm.” Automation in construction. 30, 216–227.

Gouett, M., Haas, C., Goodrum, P., and Caldas, C. (2011). “Activity analysis for direct-work rate improvement in construction.” Journal of construction engineering and management. 137(12), 1117–1124.

Gould, F., and Joyce, N. (2013). Construction project management. Prentice Hall, Upper Saddle River, NJ, United States.

Griffith, A. (2005). "Scheduling practices and project success." AACE International transactions.

Hall, J. R. (1980). "Multiproject scheduling through zero-one programming." Management science. 26(2), 228.

Hariga, M., and El-Sayegh, S. (2011). "Cost optimization model for the multiresource leveling problem with allowed activity splitting." Journal of construction engineering and management. 137(1), 56–64.

Harris, P. E. (2008). Project planning and scheduling using Primavera P6 for all industries including versions 4 to 6: planning and progressing project schedules with and without roles and resources in an established enterprise environment. Eastwood Harris Pty, Victoria, Australia.

Harris, P. E. (2012). Project planning and control using oracle Primavera P6: version 8.2 EPPM web. Eastwood Harris Pty, Victoria, Australia.

Harris, P. E. (2013). Project planning and control using oracle Primavera P6 versions 8.1, 8.2 and 8.3 professional client & optional client. Eastwood Harris Pty, Victoria, Australia.

Harris, R. (1990). "Packing method for resource leveling." Journal of construction engineering and management, 116(2), 331–350.

Harris, R. I. (1978). Precedence and arrow networking techniques for construction. Wiley, NY, United States.

Hartmann, S. (2001) "Project scheduling with multiple modes: a genetic algorithm." Annals of operations research. 102(1–4), 111–135.

Hegazy, T. (1999). "Optimization of resource allocation and leveling using genetic algorithms." Journal of construction engineering and management. 125(3), 167–175.

Hegazy, T. (2002). Computer-based construction project management. Prentice Hall, Upper Saddle River, NJ, United States.

Hegazy, T., and Kassab, M. (2003). “Resource optimization using combined simulation and genetic algorithms.” Journal of construction engineering and management. 129(6), 698–705.

Heon Jun, D., and El-Rayes, K. (2011). “Multiobjective optimization of resource leveling and allocation during construction scheduling.” Journal of construction engineering and management. 137(12), 1080–1088.

Hinze, J. (2008). Construction planning and scheduling. 3rd edition, Prentice Hall, Upper Saddle River, NJ, United States.

Hiyassat, M. (2001). “Applying modified minimum moment method to multiple resource leveling.” Journal of construction engineering and management. 127(3), 192–198.

Hossein Hashemi Doulabi, S., Seifi, A., and Shariat, S. (2011). “Efficient hybrid genetic algorithm for resource leveling via activity splitting.” Journal of construction engineering and management. 137(2), 137–146.

Hu, J., and Flood, I. (2012) “A multi-objective scheduling model for solving the resource-constrained project scheduling and resource leveling problems.” Computing in civil engineering 2012, 49–56.

IBM. (2014). IBM ILOG CPLEX Optimization Studio V12.6.1 documentation, Armonk, NY, United States.

Jiang, G., and Shi, J. (2005). “Exact algorithm for solving project scheduling problems under multiple resource constraints.” Journal of construction engineering and management. 131(9), 986–992.

Kandil, A., El-Rayes, K., and El-Anwar, O. (2010). “Optimization research: enhancing the robustness of large-scale multiobjective optimization in construction.” Journal of construction engineering and management. 136, 17–25.

Karaa, F., and Nasr, A. Y. (1986). “Resource management in construction.” Journal of construction engineering and management. 112(3), 346–357.

KBR. (2010). KBR industrial services. Houston, TX, United States.

Kelley, J. E., and Walker, M. R. (1959). “Critical-path planning and scheduling.” Proceedings of the eastern joint computer conference. 160–173.

Khamooshi, H., and Cioffi, D. (2013). “Uncertainty in task duration and cost estimates: fusion of probabilistic forecasts and deterministic scheduling.” Journal of construction engineering and management. 139(5), 488–497.

Kim, D., Menches, C., and O’Connor, J. (2013). “Stringing construction planning and execution tasks together for effective project management.” Journal of management in engineering. 10.1061/(ASCE)ME.1943-5479.0000267, 04014042.

Kim, J., and Ellis, R. (2008). “Permutation-based elitist genetic algorithm for optimization of large-sized resource-constrained project scheduling.” Journal of construction engineering and management. 134(11), 904–913.

Kim, J. L. (2009). “Improved genetic algorithm for resource-constrained scheduling of large projects.” Canadian journal of civil engineering. 36(6), 1016–1027.

Kim, K., and De la Garza, J. M. (2003). “Phantom float.” Journal of construction engineering and management. 129(5), 507–517.

Koulinas, G., and Anagnostopoulos, K. (2012). "Construction resource allocation and leveling using a threshold accepting–based hyperheuristic algorithm." Journal of construction engineering and management. 138(7), 854–863.

Koulinas, G., and Anagnostopoulos, K. (2013). "A new tabu search-based hyper-heuristic algorithm for solving construction leveling problems with limited resource availabilities." Automation in construction. 31, 169–175.

Koulinas, G., Kotsikas, L., and Anagnostopoulos, K. (2014). "A particle swarm optimization based hyper-heuristic algorithm for the classic resource constrained project scheduling problem." Information sciences. 277(1), 680–693.

Law, A. M., and Kelton, W. D. (2000). Simulation modeling and analysis. McGraw-Hill, NY, United States.

Lee, D., Yi, C., Lim, T., and Arditi, D. (2010). "Integrated simulation system for construction operation and project scheduling." Journal of computing in civil engineering. 24(6), 557–569.

Lenahan, T. (2006). Turnaround, shutdown and outage management: effective planning and step-by-step execution of planned maintenance operations. Elsevier/Butterworth-Heinemann, Oxford, United Kingdom.

Leu, S. S., and Hung, T. H. (2002). "An optimal construction resource leveling scheduling simulation model." Canadian journal of civil engineering. 29(2), 267–275.

Leu, S. S., Yang, C. H., and Huang, J. C. (2000). "Resource leveling in construction by genetic algorithm-based optimization and its decision support system application." Automation in construction. 10(1), 27–41.

Li, H., and Zhang, H. (2013). "Ant colony optimization-based multimode scheduling under renewable and nonrenewable resource constraints." Automation in construction. 35, 431–438.

Li, S. (1996). "New approach for optimization of overall construction schedule." Journal of construction engineering and management. 122(1), 7–13.

Liao, T. W., Egbelu, P. J., Sarker, B. R., and Leu, S. S. (2011). "Metaheuristics for project and construction management—a state-of-the-art review." Automation in construction. 20(5), 491–505.

Lova, A., Tormos, P., Cervantes, M., and Barber, F. (2009). "An efficient hybrid genetic algorithm for scheduling projects with resource constraints and multiple execution modes." International journal of production economics. 117(2), 302–316.

Lu, M., Lam, H. C., and Dai, F. (2008). "Resource-constrained critical path analysis based on discrete event simulation and particle swarm optimization." Automation in construction. 17(6), 670–681.

Lu, M., and Li, H. (2003). "Resource-activity critical-path method for construction planning." Journal of construction engineering and management. 129(4), 412–420.

Martínez, J. C., and Ioannou, P. G. (1993). "Resource leveling based on the modified minimum moment heuristic." Proceedings of the 1993 5th international conference on computing in civil and building engineering, June 7–9, 1993, Reston, Virginia, United States, 287–294.

MathWorks (2014). Optimization toolbox user's guide. Natick, MA, United States.

MATLAB, version R2014a [Computer software]. Natick, MA, MathWorks.

McCahill, D., and Bernold, L. (1993). "Resource-oriented modeling and simulation in construction." Journal of construction engineering and management. 119(3), 590–606.

Megow, N., Möhring, R. H. and Schulz, J. (2011). "Decision support and optimization in shutdown and turnaround scheduling." Journal on computing. 23(2), 189–204.

Menesi, W., and Hegazy, T. (2014). "Multimode resource-constrained scheduling and leveling for practical-size projects." Journal of management in engineering. 04014092.

Mingozzi, A., Maniezzo, V., Ricciardelli, S. and Bianco, L. (1998). "An exact algorithm for the resource-constrained project scheduling problem based on a new mathematical formulation." Management science. 44(5), 714–729.

Möhring, R. H, Schulz, A. S., Stork, F., and Uetz, M. (2003). "Solving project scheduling problems by minimum cut computations." Management science. 49(3), 330–350.

Nemhauser, G. L., and Wolsey, L. A. (1999). Integer and combinatorial optimization. Wiley-Interscience, NY, United States.

Ng, S., and Zhang, Y. (2008). "Optimizing construction time and cost using ant colony optimization approach." Journal of construction engineering and management. 134(9), 721–728.

O'Connor, J., and Tucker, R. (1986). "Industrial project constructability improvement." Journal of construction engineering and management. 112(1), 69–82.

OSSA (Oil Sands Safety Association). (2013). Confined space entry and monitor standard. Oil Sands Safety Association, Alberta, Canada.

Padilla, E., and Carr, R. (1991). "Resource strategies for dynamic project management." Journal of construction engineering and management. 117(2), 279–293.

Park, M., Lee, H., Son B., and Ryu, H. (2005). "Dynamic resource management." Computing in civil engineering 2005. 1–12.

Patterson, J., Slowinski, R., Talbot, F., and Weglarz, J. (1989). “An algorithm for a general class of precedence and resource constrained scheduling problem.” Advances in project scheduling. 3–28.

Patterson, J. H. (1984). “A comparison of exact approaches for solving the multiple constrained resource project scheduling problem.” Management science. 30(7), 854–867.

Patterson, J. H., and Huber, W. D. (1974). “A horizon-varying, zero-one approach to project scheduling.” Management science. 20(6), 990–998.

Peng, W., and Wang C. (2009). “A multimode resource-constrained discrete time–cost tradeoff problem and its genetic algorithm based solution.” International journal of project management. 27, 600–609.

Peurifoy, R. L., and Oberlender, G. (2013). Estimating construction costs. 6th edition, McGraw-Hill Higher Education, NY, United States.

Pidd, M. (2009). Tools for thinking: modelling in management science. Wiley, NY, United States.

Pinker, E. J., and Larson, R. C. (2003) “Optimizing the use of contingent labor when demand is uncertain.” European journal of operational research. 144, 39–55.

Pokharel, S., and Jiao, J. (2008). “Turnaround maintenance management in a processing industry.” Journal of quality in maintenance engineering, 14(2), 109–122.

Primavera P3, version 3.1 [Computer software]. Redwood Shores, CA, Oracle Corporation, Redwood Shores, CA, United States.

Primavera P6, version 8.0 [Computer software]. Redwood Shores, CA, Oracle Corporation, Redwood Shores, CA, United States.

Pritsker, A. B., Waiters, L. J., and Wolfe, P. M. (1969). “Multiproject scheduling with limited resources: a zero-one programming approach.” Management science. 16(1), 93–108.

Project Management Institute (2013). A guide to the project management body of knowledge (PMBOK guide). 5th edition. Project Management Institute, PA, United States.

Rardin, R. L. (1998). Optimization in operations research. Prentice Hall, Upper Saddle River, NJ, United States.

Rieck, J., Zimmermann, J., and Gather, T. (2012). “Mixed-integer linear programming for resource leveling problems.” European journal of operational research. 221, 27–37.

Rothwell, G. (2005). “Cost contingency as the standard deviation of the cost estimate.” Cost engineering. 47(7), 22–25.

Sadeghbeigi, R. (2012). Fluid catalytic cracking handbook—an expert guide to the practical operation, design, and optimization of FCC units. Elsevier/Butterworth-Heinemann, Oxford, United Kingdom.

Sargent, R. G., Tew, J. D., Manivannan, M. S., Sadowski, D. A., and Seila, A. F. (2007). “Verification and validation of simulation models.” Winter simulation conference 2007. Dec. 9–12 2007, Washington, DC, United States, 77–87.

Savelsbergh, M. W. P. (1994). “Preprocessing and probing techniques for mixed integer programming problems.” Journal of computing. 6(4), 445–454.

SDESA version 1.0 [Computer software]. Canada, Univ. of Alberta.

Seibert, J., and Evans, G. (1991). “Time-constrained resource leveling.” Journal of construction engineering and management. 117(3), 503–520.

Siddiqui, M., and Rafiuddin, M. (2012). "Identifying scheduling inefficiencies for industrial projects using the flowline view: a case study." Computing in civil engineering 2012. 81–88.

Siu, M. F. (2011). Study of time extensions and the cost implications in construction project scheduling, M.Phil. thesis. The Hong Kong Polytechnic University, Hung Hom, Hong Kong.

Siu, M. F., Lu, M., and AbouRizk, S. (2015a). "Methodology for crew-job allocation optimization in project and workface scheduling." ASCE Computing in civil engineering 2015. 652–659.

Siu, M. F., Lu, M., and AbouRizk, S. (2015b). "Resource supply and demand matching scheduling approach for construction workface planning." Journal of construction engineering and management, 10.1061/(ASCE)CO.1943-7862.0001027, 04015048.

Siu, M. F., Lu, M., and AbouRizk, S. (2015c). "Zero-one programming approach to determine optimum resource supply under time-dependent resource constraints." Journal of computing in civil engineering, 10.1061/(ASCE)CP.1943-5487.0000498, 04015028.

Siu, M. F., Lu, M., and AbouRizk, S. (2016). "Optimizing job sequence and resource use in structural steel fabrication scheduling." 16th International conference on computing in civil and building engineering. Jul. 6–8, 2016, Osaka, Japan.

Siu, M. F., Lu, M. and AbouRizk, S., and Tidder, V. (2013) "Improving sophistication and representation of skilled labor schedules on plant shutdown and maintenance projects." 13th International conference on construction applications of virtual reality. Oct. 30–31, 2013, London, United Kingdom, 160–171.

Son, J., and Mattila, K. (2004). “Binary resource leveling model: activity splitting allowed.” Journal of construction engineering and management. 130(6), 887–894.

Son, J., and Skibniewski, M. (1999). “Multiheuristic approach for resource leveling problem in construction engineering: hybrid approach.” Journal of construction engineering and management. 125(1), 23–31.

Song, J., Fagerlund, W., Haas, C., Tatum, C., and Vanegas, J. (2005). “Considering prework on industrial projects.” Journal of construction engineering and management. 131(6), 723–733.

Sprecher, A. (2000). “Scheduling resource-constrained projects competitively at modest memory requirements.” Management science. 46(5), 710–723.

Sprecher, A., and Drexl, A. (1998). “Multimode resource-constrained project scheduling by a simple, general and powerful sequencing algorithm.” European journal of operational research. 107(2), 431–450.

Stephens, M. P. (2010). Productivity and reliability-based maintenance management. Purdue University Press. West Lafayette, IN, United States.

Suncor Energy. (2014). Annual report 2014. Suncor Energy, Calgary, Alberta, Canada.

Taghaddos, H., Hermann, U., AbouRizk, S., and Mohamed, Y. (2014). “Simulation-based multiagent approach for scheduling modular construction.” Journal of computing in civil engineering. 28(2), 263–274.

Talbot, F. B. (1982). “Resource-constrained project scheduling with time-resource tradeoffs: the non-preemptive case.” Management science. 28(10), 1197–1210.

Tam, K., and Dissanayake, W. (1998). “Constrained project scheduling by ranked positional weight method.” Canadian journal of civil engineering. 25, 424–436.

Tang S. L. (1999). Linear optimization in applications. Hong Kong University Press, Aberdeen, Hong Kong.

Thomas, H. R. (1991). “Labor productivity and work sampling: the bottom line.” Journal of construction engineering and management. 117(3), 423–444.

Thompson, P., and Perry, J. G. (1992). Engineering construction risks: a guide to project risk analysis and assessment implications for project clients and project managers. Thomas Telford, London, United Kingdom.

Touran, A. (2010). “Probabilistic approach for budgeting in portfolio of projects.” Journal of construction engineering and management. 136(3), 361–366.

Vanhoucke, M, and Debels, D; (2007). “The discrete time/cost tradeoff problem: extensions and heuristic procedures.” Journal of scheduling. 10 (4–5) 311–326.

Winston, W. L. (2003). Operations research: applications and algorithms. Thomson Brooks/Cole, Pacific Grove, CA, United States.

Wongwai, N., and Malaikrisanachalee, S. (2011). “Augmented heuristic algorithm for multi-skilled resource scheduling.” Automation in construction. 20(4), 429–445.

Xie, H., AbouRizk, S., and Zou, J. (2012). “Quantitative method for updating cost contingency throughout project execution.” Journal of construction engineering and management. 138(6), 759–766.

Zhang, H., and Li, H. (2004). “Simulation-based optimization for dynamic resource allocation.” Automation in construction. 13(3), 409–420.

Zhang, H., Li, H., and Tam, C. (2006a). “Particle swarm optimization for preemptive scheduling under break and resource-constraints.” Journal of construction engineering and management. 132(3), 259–267.

Zhang, H., Li, X., Li, H., and Huang, F. (2005). “Particle swarm optimization-based schemes for resource-constrained project scheduling.” Automation in construction. 14(3), 393–404.

Zhang, H., Tam, C., Li, H., and Shi, J. (2006b). “Particle swarm optimization-supported simulation for construction operations.” Journal of construction engineering and management. 132(12), 1267–1274.

Zhu, G., Bard, J. F., and Yu, G. (2006). “A branch-and-cut procedure for the multimode resource-constrained project-scheduling problem.” Journal on computing. 18(3), 377–390.

APPENDIX A: ACTIVITY AND RESOURCE DEFINITIONS OF TURNAROUND PROJECT

Identifier	Activity names	Dur. (h)	Suc. (s)	Resources
1	Install hex on external riser at cut line, approximately 30 sq ft	50	-	A[2]; B[2]
2	Pre job meeting to install new reactor head	1	3	C[1]; D[6]
3	Position crane and install rigging on new head	8	4	C[1]; D[6]
4	Lift new head and swing amine unit	4	6	C[1]; D[6]
5	Remove rigging and boom clear of work area	4	7;8;10	C[1]; D[6]
6	Continue swing and lower new reactor head onto shell	5	5	C[1]; D[6]
7	Hoard in decking on lower dipleg bracing back to shell	10	15	E[6]
8	Fit and tack new head to existing reactor shell	20	23	A[4]; B[4]
9	Install landing from stairway to RX Platform 0	10	16	F[3]; G[5]
10	Install braces & structural section at Platform 0, section 090 from RX to reg	30	63	A[3]; B[1]; G[1]
11	Sign off to close regen manway MX-5 (plenum)	1	12	H[1]; I[1]; J[1]
12	Sign off to close regen manway MX-3 (plenum)	1	13	H[1]; I[1]; J[1]
13	Sign off to close regen OHL manway MX-4 (top OHL)	1	14	H[1]; I[1]; J[1]
14	Sign off to close regen OHL manway MX-6 (vertical section)	1	17	H[1]; I[1]; J[1]
15	Install bulkhead #2 in reactor at lower elevation, also access into riser	10	24	E[6]
16	Install landing from stairway to RX 0 1	10	25	F[3]; G[5]
17	Sign off to close regen OHL manway MX-7 (bottom section)	1	18	H[1]; I[1]; J[1]
18	Sign off to close regen OHL manway (west of stack valve)	1	19, 20	H[1]; I[1]; J[1]
19	Install refractory plug—regen manway MX-5 (plenum)	4	22	A[1]; B[1]
20	Install manway cover—regen manway MX-3 (plenum)	3	21	A[2]
21	Install manway cover—regen OHL manway (west of stack valve)	3	-	A[2]
22	Install refractory plug—regen OHL manway MX-4 (top OHL)	4	26	A[1]; B[1]
23	Weld out new reactor head to existing reactor shell (25%)	20	31,32	A[3]; B[3]
24	Lower riser into position, fit and tack	20	33	A[4]; B[1]

Identifier	Activity names	Dur. (h)	Suc. (s)	Resources
25	Install landing from stairway to RX Platform 2	10	29	F[3]; G[5]
26	Install refractory plug—regen OHL manway MX-6 (vertical section)	4	27	A[1]; B[1]
27	Install refractory plug—regen OHL manway MX-7 (bottom section)	4	28	A[1]; B[1]
28	Install refractory—regen manway MX-5 (plenum)	6	30	K[3]
29	Install landing from stairway to RX Platform 3	10	57	F[3]; G[5]
30	Install refractory—regen OHL manway MX-4 (top OHL)	6	34	K[3]
31	Weld connect pressure tap piping from riser to shell, located just below riser outlet horn	10	36	P[2]; Q[1]
32	Weld out new reactor head to existing reactor shell (50%)	20	40,41	A[3]; B[3]
33	Weld out new riser duct to existing lower riser section	40	51	A[2]; B[2]
34	Install refractory—regen OHL manway MX-6 (vertical section)	6	35	K[3]
35	Install refractory—regen OHL manway MX-7 (bottom section)	6	37	K[3]
36	LPI weld connection pressure tap piping from riser to shell, located just below riser outlet horn	4	38	L[1]; R[1]
37	Refractory cure time—regen OHL manway MX-4,5,6,7	12	42	
38	Sign off install of pressure tap piping from riser to shell, located just below riser outlet horn	1	39	H[1]; I[1]; R[1]; S[1];
39	Weld connect pressure tap piping from riser to shell, located above level “A” riser bracing	10	43	P[2]; Q[1]
40	Weld out new reactor head to existing reactor shell (75%)	20	52	A[3]; B[3]
41	Backgouge reactor weld of new shell to existing shel	10	48	A[4]; B[2]
42	Install cover plate—regen manway MX-5 (plenum)	2	44	A[2]
43	LPI weld connection pressure tap piping from riser to shell, located above level “A” riser bracing	4	46	L[1]; R[1]
44	Install cover plate—regen OHL manway MX-4 (top OHL)	2	45	A[2]
45	Install cover plate—regen OHL manway MX-6 (vertical section)	2	49	A[2]
46	Sign off install of pressure tap piping from riser to shell, located above level “A” riser bracing	1	47	H[1]; I[1]; R[1]; S[1]
47	Weld connect TI piping from riser to shell, located above level “A” riser bracing	10	50	P[2]; Q[1]
48	Weld inside of new shell to existing shell	20	55	A[4]; B[2]
49	Install cover plate—regen OHL manway MX-7 (bottom section)	2	-	A[2]
50	LPI weld connection TI piping from riser to shell,	4	53	L[1]; R[1]

Identifier	Activity names	Dur. (h)	Suc. (s)	Resources
	located above level “A” riser bracing			
51	Final NDE on riser weld	4	54	M[1]
52	Weld out new reactor head to existing reactor shell (100%)	20	55	A[3]; B[3]
53	Sign off installation of TI piping from riser to shell, located above level “A” riser bracing	1	-	H[1]; I[1]; R[1]; S[1]
54	Install OD riser hex mesh at cut line. approximately 15 sq ft	25	56	A[2]; B[2]
55	Phase array weld of new reactor head to existing reactor shell	10	58,59	N[1]
56	Install refractory in hex on external riser weld location. Approximately 47 sq ft (3 packing)	40	74	K[6]
57	Ball test primary cyclones and sign off to install riser manway	2	61	H[1]; I[1]; J[1]
58	Layout and install refractory anchors on reactor head weldout area—288 anchors	20	67	A[2]; B[2]
59	Buff shell weld for painting	10	62	O[2]
60	Install bridge steel from new stairway to reactor head	30	-	F[3]
61	Install riser manway and seal weld	8	64	A[2]; B[1]
62	Paint shell weld for painting	5	-	O[2]
63	Install Platform 1, section 0–90 from RX to reg	30	86	A[3]; B[1]; G[1]
64	NDE on riser manway cover	1	65	A[2];B[1]; I[1]
65	Remove scaffold from ACB	6	66	E[5]
66	Final cleaning of ACB	4	68	A[2]
67	Install refractory on new reactor head to existing shell weld area	20	-	K[1]
68	Sign off to close Reactor MW-MX-4,5,6,7,8,9 (ACB)	4	69	H[1]; I[1]; J[1]
69	Close reactor MW-MX-4 (ACB)—install refractory plug	6	70,71	A[1]; B[1]
70	Close reactor MW-MX-5 (ACB)—install refractory plug	6	72	A[1]; B[1]
71	Close reactor MW-MX-4 (ACB)—install refractory in manway neck	6	73	K[4]
72	Close reactor MW-MX-6 (ACB)—install refractory plug	6	75	A[1]; B[1]
73	Close reactor MW-MX-5 (ACB)—install refractory in manway neck	6	76	K[4]
74	Sign off refractory installation on riser OD	2	-	H[1]; I[1]; S[1]
75	Close reactor MW-MX-7 (ACB)—install refractory	6	79	A[1]; B[1]

Identifier	Activity names	Dur. (h)	Suc. (s)	Resources
	plug			
76	Close reactor MW-MX-6 (ACB)—install refractory in manway neck	6	80	K[4]
77	Riser—remove all internal scaffolding in riser	5	78	E[4]
78	Riser—weld on riser manway	12	83	A[1]; B[1]
79	Close reactor MW-MX-8 (ACB)—install refractory plug	6	81	A[1]; B[1]
80	Close reactor MW-MX-7 (ACB)—install refractory in manway neck	6	82	K[4]
81	Close reactor MW-MX-9 (ACB)—install refractory plug	6	85	A[1]; B[1]
82	Close reactor MW-MX-8 (ACB)—install refractory in manway neck	6	84	K[4]
83	Riser—NDE on riser manway weld	1	-	A[1]; B[1]; L[1]
84	Close reactor MW-MX-9 (ACB)—install refractory in manway neck	6	85	K[4]
85	Close reactor MW-MW-MX-4,5,6,7,8,9 (ACB)—cure time	12	87	
86	Install Platform 2, Section 090 from RX to reg	30	107	A[3]; B[1]; G[1]
87	Close reactor MW-MX-4 (ACB)—close manway cover plate	3	88	A[2]
88	Close reactor MW-MX-5 (ACB)—close manway cover plate	3	89	A[2]
89	Close reactor MW-MX-6 (ACB)—close manway cover plate	3	90	A[2]
90	Close reactor MW-MX-7 (ACB)—close manway cover plate	3	91	A[2]
91	Close reactor MW-MX-8 (ACB)—close manway cover plate	3	92	A[2]
92	Close reactor MW-MX-9 (ACB)—close manway cover plate	3	-	A[2]
93	Sign off to close reactor MW-MX-1 (shell)	1	96	H[1]; I[1]; J[1]
94	Sign off to close reactor MW-Big MW	1	97	H[1]; I[1]; J[1]
95	Sign off to close reactor MW-Stripper cone	1	98	H[1]; I[1]; J[1]
96	Close reactor MW-MX-1 (Shell)	5	-	A[2]
97	Close reactor MW-MX-Big MW	6	-	A[4]
98	Install refractory plug—stripper cone manway	4	99	A[1]; B[1]
99	Install refractory—stripper cone manway	6	100	K[3]

Identifier	Activity names	Dur. (h)	Suc. (s)	Resources
100	Install cover plate—stripper cone manway	2	-	A[2]
101	Sign off to close reactor MW-MX-10 (plenum)	1	103	H[1]; I[1]; J[1]
102	Sign off to close reactor MW-MX-11 (plenum)	1	104	H[1]; I[1]; J[1]
103	Close reactor MW-MX-10 (plenum)—close manway cover plate	3	-	A[2]
104	Close reactor MW-MX-11 (plenum)—install refractory plug	6	105	A[1]; B[1]
105	Close reactor MW-MX-11 (plenum)—install refractory in manway neck	5	106	K[4]
106	Close reactor MW-MX-11 (plenum)—close manway cover plate	3	-	A[2]
107	Install Platform 3, section 090 from RX to reg	30	-	A[3]; B[1]; G[1]

Note: A = boilermaker; B = boilermaker welder; C = msg 80 3,600 ton; D = rigger; E = scaffolder; F = iron worker; G = sterling-130 ton crane; H = technical; I = inspection; J = complex process operator; K = refractory; L = liquid penetrant inspection; M = x-ray; N = paut inspection; O = painter; P = pipefitter; Q = pipefitter welder; R = inspector; S = supervisor; Dur. = duration; Suc. = successor(s).

APPENDIX B: SOLUTION ITERATIONS FOR MATHEMATICAL PROGRAMMING

This section demonstrates the input-to-output processing of iterating solutions devised to solve the mathematical programming model, which is based on the RSDMP mathematical model built for the case study example (Subsection 3.4.1—Scenario 1, Stage 1 optimization). The standard matrix and vector formulations are first introduced for model input. Screen captures are then provided for automatically generating the analytical solution using MATLAB version 2014.

The elements in Vector ***x*** are the decision variables $x^{\mathrm{t}}_{\mathrm{Act}}$, $x^{\mathrm{t}}_{\mathrm{Proj}}$ and $R^{\mathrm{tp}}_{\mathrm{Res}}$. The vector is divided into three partitions (Figure B.1). Partitions P1, P2 and P3 correspond to activity completion times, project completion time and resource supply, respectively.

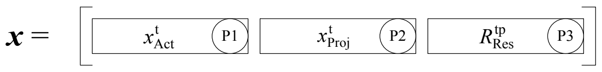


Figure B.1: Vector ***x***

Vector ***f*** corresponds to the decision variables $x^{\mathrm{t}}_{\mathrm{Act}}$, $x^{\mathrm{t}}_{\mathrm{Proj}}$ and $R^{\mathrm{tp}}_{\mathrm{Res}}$ (Figure B.2). P4 indicates the coefficients of $x^{\mathrm{t}}_{\mathrm{Act}}$. P5 contains the coefficients of $x^{\mathrm{t}}_{\mathrm{Proj}}$. P6 are the coefficients of $R^{\mathrm{tp}}_{\mathrm{Res}}$.

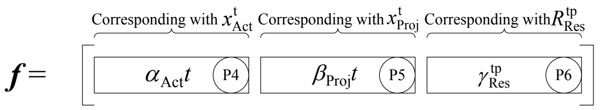


Figure B.2: Vector ***f***

Partition P1 declares the decision variables $x_{\mathrm{Act}}^{\mathrm{t}}$ for Activities Start, A, B, C, D from time t = 0 to 100, i.e., $\{x_{\mathrm{Start}}^{0},...,x_{\mathrm{Start}}^{100},x_{\mathrm{A}}^{0},...,x_{\mathrm{A}}^{100},x_{\mathrm{B}}^{0},...,x_{\mathrm{B}}^{100},x_{\mathrm{C}}^{0},...,x_{\mathrm{C}}^{100},x_{\mathrm{D}}^{0},...,x_{\mathrm{D}}^{100}\}$. P2 contains $x_{\mathrm{Proj}}^{\mathrm{t}}$ from time t = 0–100, i.e., $\{x_{\mathrm{Proj}}^{0},...,x_{\mathrm{Proj}}^{100}\}$. P3 identifies R_{BM}^{0-100} and R_{PF}^{0-100}. Referring to Equation (3.14), P4 categorizes $\{0,...,100,0,...,100,0,...,100,0,...,100,0,...,100\}$ with respect to $\{x_{\mathrm{Start}}^{0},...,x_{\mathrm{Start}}^{100},x_{\mathrm{A}}^{0},...,x_{\mathrm{A}}^{100},x_{\mathrm{B}}^{0},...,x_{\mathrm{B}}^{100},x_{\mathrm{C}}^{0},...,x_{\mathrm{C}}^{100},x_{\mathrm{D}}^{0},...,x_{\mathrm{D}}^{100}\}$; P5 sets $\{0,...,100\}$ for $\{x_{\mathrm{Proj}}^{0},...,x_{\mathrm{Proj}}^{100}\}$, and P6 includes the coefficients $\{1,1\}$ of $\{R_{\mathrm{BM}}^{0-100},R_{\mathrm{PF}}^{0-100}\}$.

Matrix **A** and Vector ***b*** define the inequalities (Figure B.3). Matrix **A** contains both the technological and time-dependent resource constraints. P7, P8 and P9 are the coefficients of $x_{\mathrm{Act}}^{\mathrm{t}}$, $x_{\mathrm{Proj}}^{\mathrm{t}}$ and $R_{\mathrm{Res}}^{\mathrm{tp}}$, respectively. For example, Equation (3.15) expresses a row (*n*th row) of Matrix **A** and Vector ***b***. P7, P8, and P9 define $\{0,...,100;20,...,-80\}$, $\{0,...,0\}$ and $\{0,...,0\}$ corresponding to $\{x_{\mathrm{A}}^{0},...,x_{\mathrm{A}}^{100};x_{\mathrm{B}}^{0},...,x_{\mathrm{B}}^{100}\}$, $\{x_{\mathrm{Proj}}^{0},...,x_{\mathrm{Proj}}^{100}\}$ and $\{R_{\mathrm{BM}}^{0-100},R_{\mathrm{PF}}^{0-100}\}$. Other elements at the *n*th row are 0. The *n*th element of Vector ***b*** is 0. Equation (3.18) articulates at the *m*th row of Matrix **A** and Vector ***b***. The elements $\{x_{\mathrm{A}}^{1},...,x_{\mathrm{A}}^{25}\}$, $\{x_{\mathrm{B}}^{1},...,x_{\mathrm{B}}^{20}\}$, $\{x_{\mathrm{C}}^{1},...,x_{\mathrm{C}}^{10}\}$, $\{x_{\mathrm{D}}^{1},...,x_{\mathrm{D}}^{25}\}$ and R_{BM}^{0-100}, with respect to P10 and P12, are $\{2,...,2\}$, $\{2,...,2\}$, $\{3,...,3\}$, $\{3,...,3\}$ and -1. The *m*th element of Vector ***b*** is 0. Partition P11 is 0.

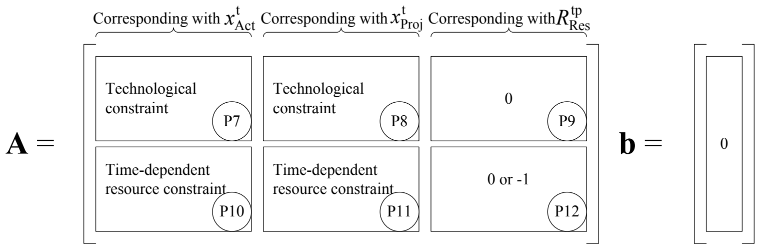


Figure B.3: Matrix **A** and Vector ***b***

Matrix $\mathbf{A}_{\mathbf{eq}}$ and Vector $\boldsymbol{b}_{\mathbf{eq}}$ define equalities (Figure B.4). This matrix constrains that only one completion time is allowed for the activity and project. Note, the elements in Partition P15 are 0. For example, the *o*th row of $\mathbf{A}_{\mathbf{eq}}$ identifies Equation (3.16). P13 denotes the elements $\{1,...,1\}$, which correspond to $\{x_{\mathrm{A}}^{0},...,x_{\mathrm{A}}^{100}\}$. The *o*th element in Vector $\boldsymbol{b}_{\mathbf{eq}}$ is 1.

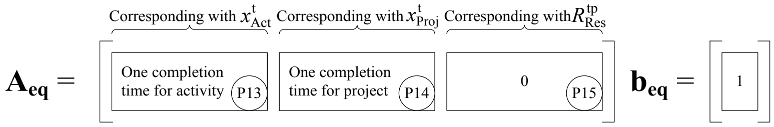


Figure B.4: Matrix $\mathbf{A}_{\mathbf{eq}}$ and Vector $\boldsymbol{b}_{\mathbf{eq}}$

Vectors ***lb*** and ***ub*** define the ranges of decisions variables. The structures of Vectors ***lb*** and ***ub*** are shown in Figures B.5 and B.6. The lower bound of decision (binary) variables $x_{\mathrm{Act}}^{\mathrm{t}}$ and $x_{\mathrm{Proj}}^{\mathrm{t}}$ is 0. They are defined in P16 and P17. The lower bound of resource limit $lb_{\mathrm{Res}}^{\mathrm{tp}}$ is defined in P18 in connection with $R_{\mathrm{Res}}^{\mathrm{tp}}$. Similarly, the upper bound of binary variables associated with $x_{\mathrm{Act}}^{\mathrm{t}}$ and $x_{\mathrm{Proj}}^{\mathrm{t}}$ is 1 (P19 and P20). The upper bound of resource limit $ub_{\mathrm{Res}}^{\mathrm{tp}}$ is specified in P21 in connection with $R_{\mathrm{Res}}^{\mathrm{tp}}$. Therefore, Equation (3.17) is transformed to Vectors ***lb*** and ***ub***, which define the lower (the elements are 0) and upper (the elements are 1) bounds with respect to $\{x_{\mathrm{Start}}^{0}, x_{\mathrm{Start}}^{1},..., x_{\mathrm{Start}}^{100}, x_{\mathrm{A}}^{0}, x_{\mathrm{A}}^{1},..., x_{\mathrm{Proj}}^{100}\}$. As defined by Equations (3.22) and (3.23), the parameters lb_{BM}^{0-100} and lb_{PF}^{0-100}, which are included in P18, are 0 and 0, respectively; and the parameters ub_{BM}^{0-100} and ub_{PF}^{0-100}, which are included in P21, are 10 and 5, respectively.

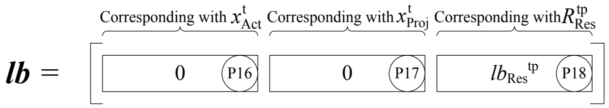


Figure B.5: Vector ***lb***

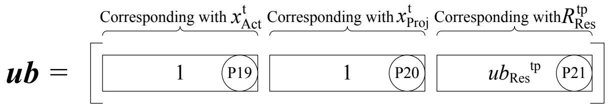
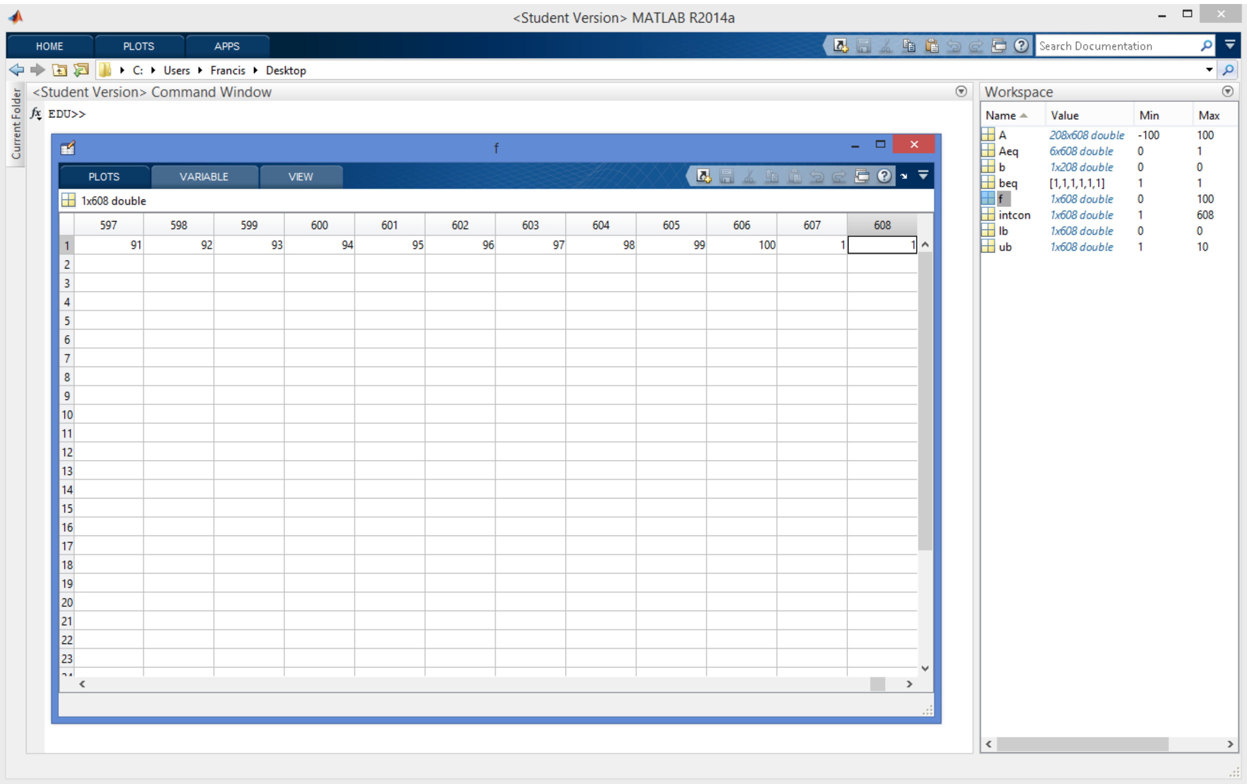


Figure B.6: Vector ***ub***

To iterate the analytical optimum solution using MATLAB version 2014, Vectors ***f***, Matrix **A**, Vector ***b***, Matrix $\mathbf{A}_{\mathbf{eq}}$, Vector $\boldsymbol{b}_{\mathbf{eq}}$, Vector ***lb***, and Vector ***ub*** are defined in its workspace (Figures B.7 to B.13), in accordance with the matrix and vector formulations (Figures B.1 to B.6).

Figure B.7 defines Vector ***f*** (Partitions P4, P5, and P6). Its dimension is 1 row × 608 columns [i.e., (5 x_{Act}^{t} +1 x_{Proj}^{t} decision variables) × 101 time units + 2 $R_{\text{Res}}^{\text{tp}}$ decision variables].

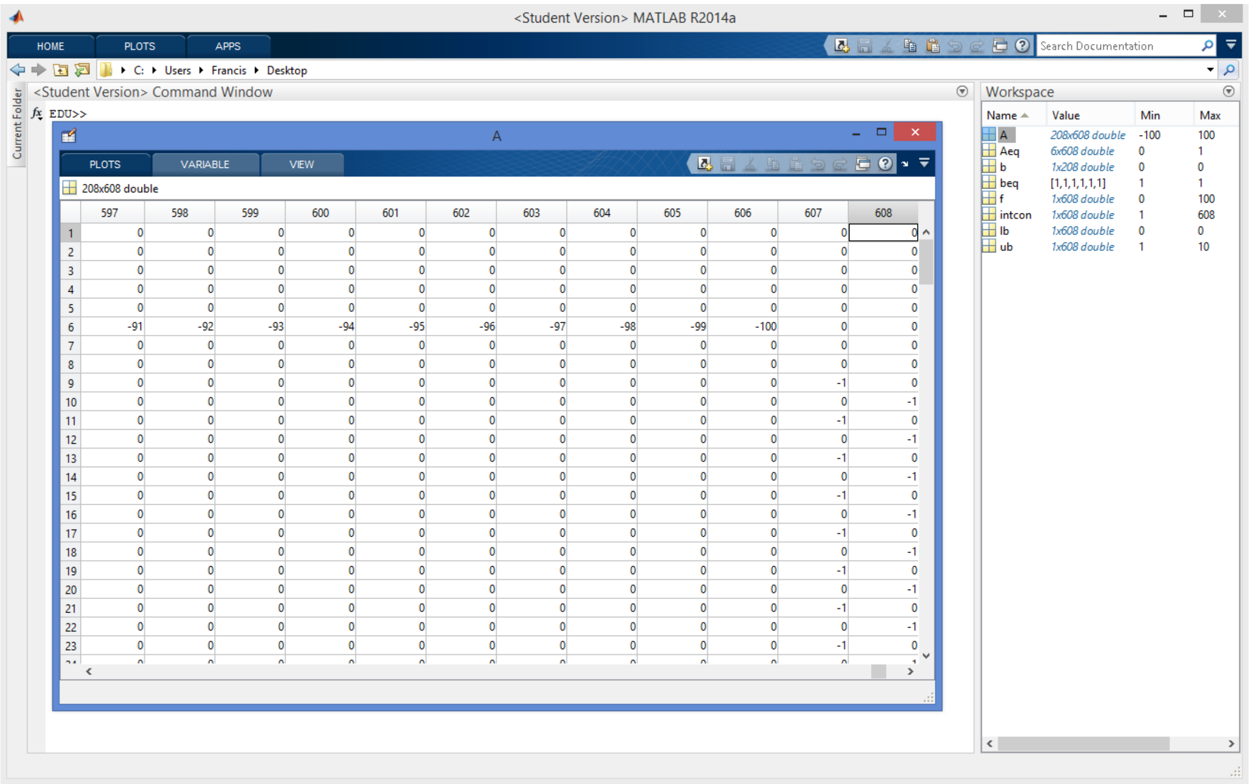


	597	598	599	600	601	602	603	604	605	606	607	608
1	91	92	93	94	95	96	97	98	99	100	1	1

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10

Figure B.7: Vector ***f*** defined in MATLAB workspace

Figure B.8 defines Matrix **A** (Partitions P7, P8, P9, P10, P11, and P12). Its dimension is 208 rows [i.e., 6 technological constraints + (101 time units × 2 $R_{\text{Res}}^{\text{tp}}$ time-dependent resource constraints)] × 608 columns [i.e., (5 $x_{\text{Act}}^{\text{t}}$ +1 $x_{\text{Proj}}^{\text{t}}$ decision variables) × 101 time units + 2 $R_{\text{Res}}^{\text{tp}}$ decision variables].



```
EDU>>
```

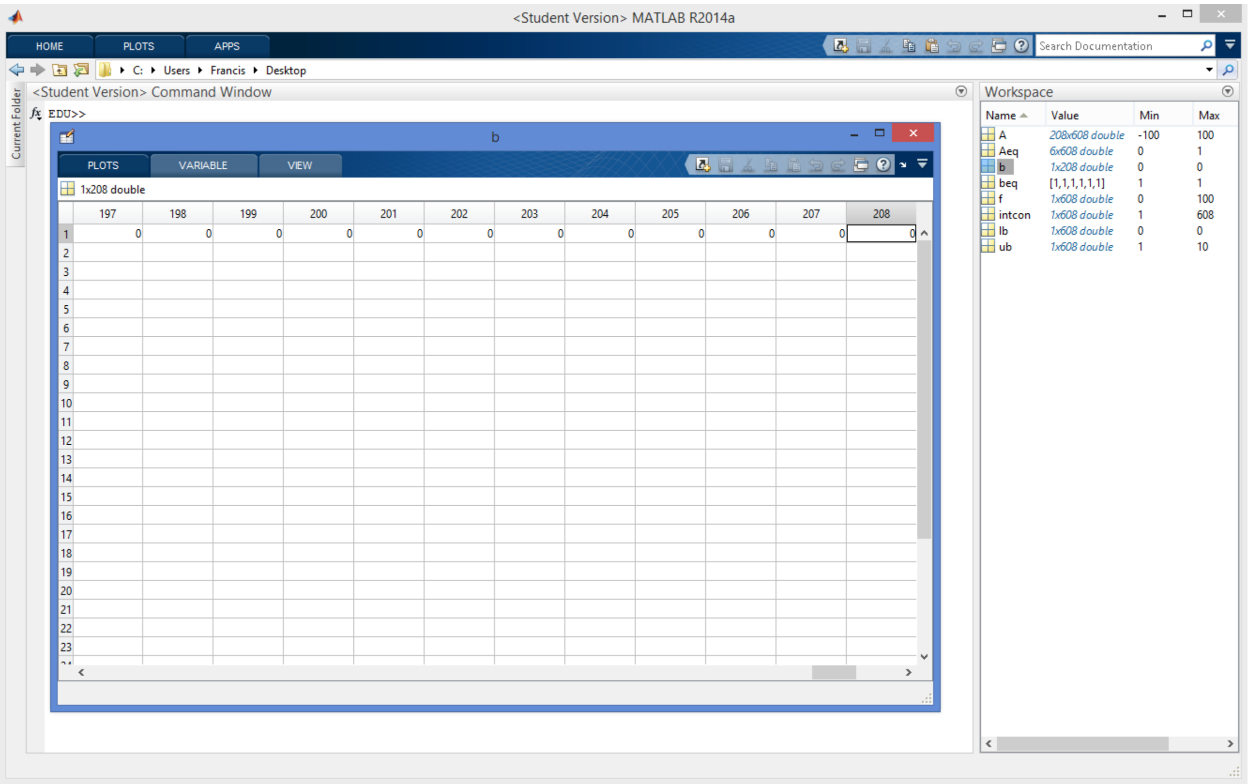
208x608 double

	597	598	599	600	601	602	603	604	605	606	607	608
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	-91	-92	-93	-94	-95	-96	-97	-98	-99	-100	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	-1	0
10	0	0	0	0	0	0	0	0	0	0	0	-1
11	0	0	0	0	0	0	0	0	0	0	-1	0
12	0	0	0	0	0	0	0	0	0	0	0	-1
13	0	0	0	0	0	0	0	0	0	0	-1	0
14	0	0	0	0	0	0	0	0	0	0	0	-1
15	0	0	0	0	0	0	0	0	0	0	-1	0
16	0	0	0	0	0	0	0	0	0	0	0	-1
17	0	0	0	0	0	0	0	0	0	0	-1	0
18	0	0	0	0	0	0	0	0	0	0	0	-1
19	0	0	0	0	0	0	0	0	0	0	-1	0
20	0	0	0	0	0	0	0	0	0	0	0	-1
21	0	0	0	0	0	0	0	0	0	0	-1	0
22	0	0	0	0	0	0	0	0	0	0	0	-1
23	0	0	0	0	0	0	0	0	0	0	-1	0

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10

Figure B.8: Matrix **A** defined in MATLAB workspace

Figure B.9 defines Vector ***b***. Its dimension is 1 row × 208 columns [i.e., 6 technological constraints + (101 time units × 2 $R_{\text{Res}}^{\text{tp}}$ time-dependent resource constraints)].

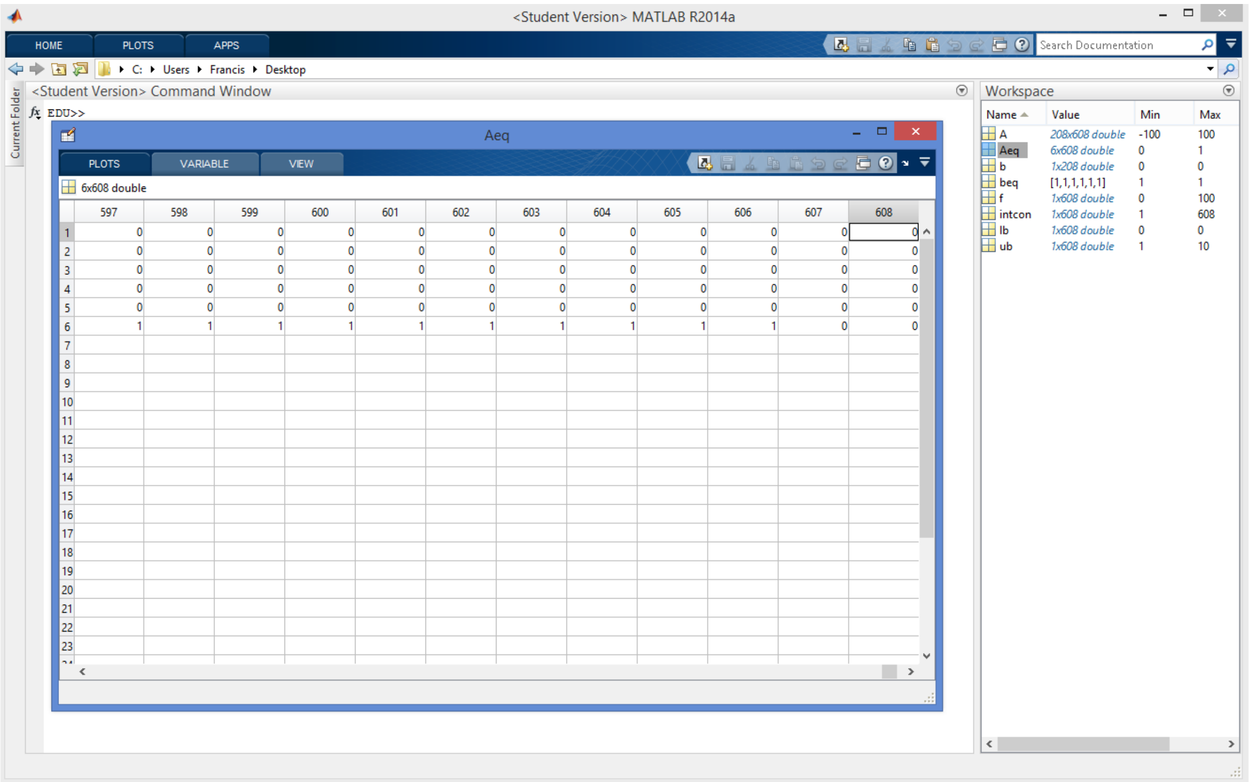


	197	198	199	200	201	202	203	204	205	206	207	208
1	0	0	0	0	0	0	0	0	0	0	0	0

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10

Figure B.9: Vector ***b*** defined in MATLAB workspace

Figure B.10 defines Matrix $\mathbf{A}_{\mathbf{eq}}$ (Partitions P13, P14, and P15). Its dimension is 6 rows [i.e., (5 $x_{\text{Act}}^{t}+1\, x_{\text{Proj}}^{t}$ decision variables)] × 608 columns [i.e., ($5\, x_{\text{Act}}^{t}+1\, x_{\text{Proj}}^{t}$ decision variables) × 101 time units + 2 $R_{\text{Res}}^{\text{tp}}$ decision variables].



```
EDU>>
```

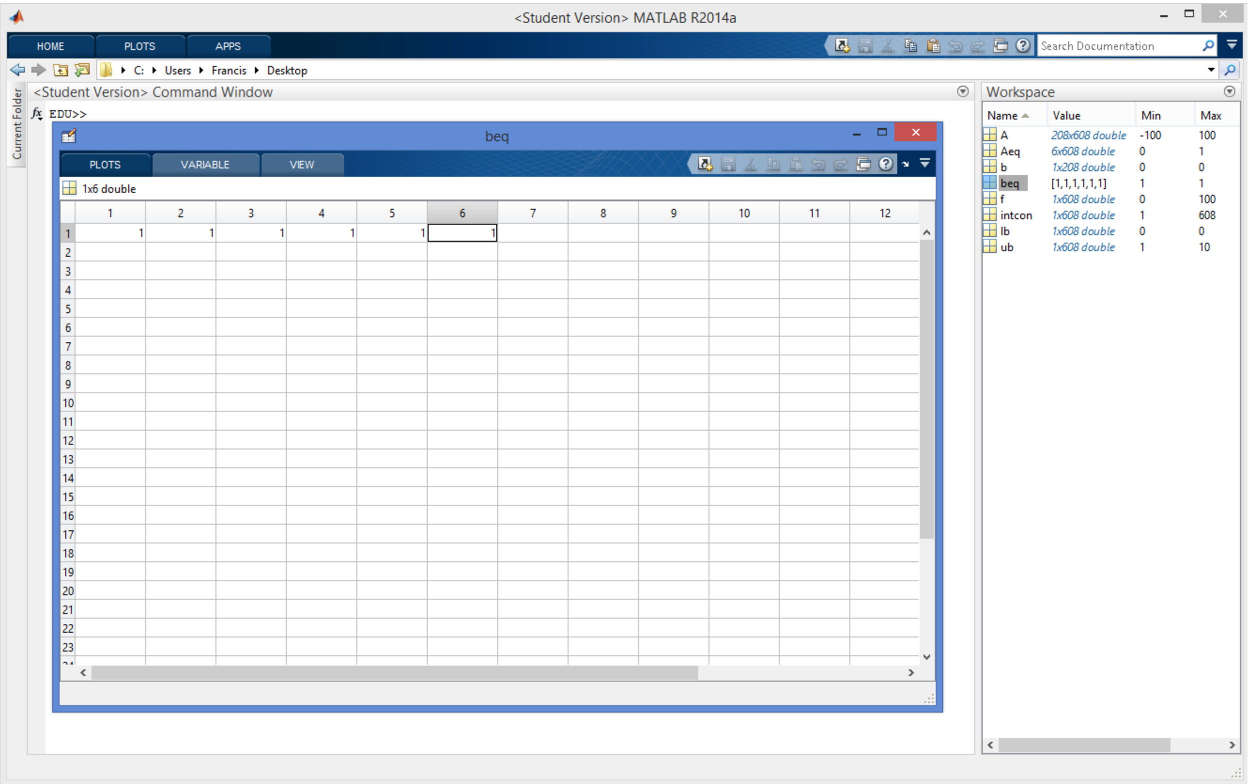
6x608 double

	597	598	599	600	601	602	603	604	605	606	607	608
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	1	1	1	1	1	1	1	1	1	1	0	0
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10

Figure B.10: Matrix $\mathbf{A}_{\mathbf{eq}}$ defined in MATLAB workspace

Figure B.11 defines Vector $\boldsymbol{b}_{\mathbf{eq}}$. Its dimension is 1 row × 6 columns [i.e., ($5\,x_{\mathrm{Act}}^{t}$+$1\,x_{\mathrm{Proj}}^{t}$ decision variables)].



```
EDU>>
```

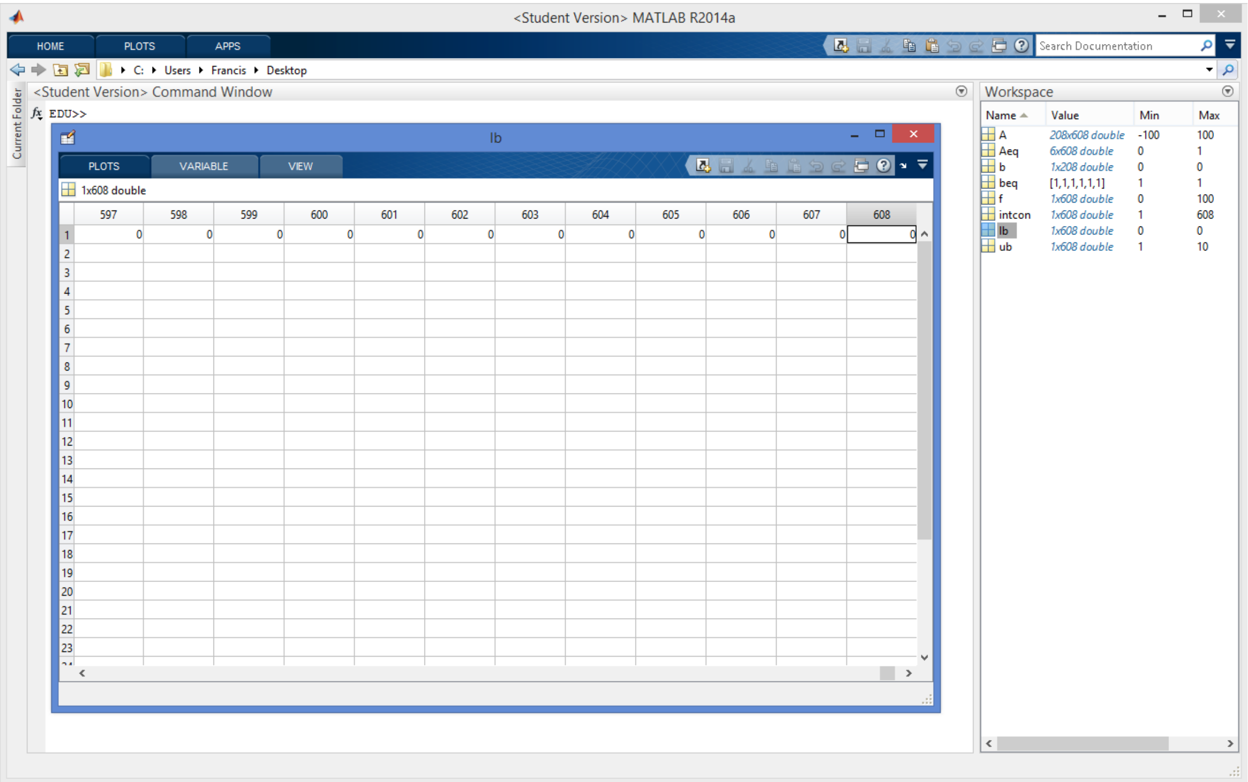
1x6 double

	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	1	1	1						
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10

Figure B.11: Vector $\boldsymbol{b}_{\mathbf{eq}}$ defined in MATLAB workspace

Figure B.12 defines Vector ***lb*** (Partitions P16, P17, and P18). Its dimension is 1 row × 608 columns [i.e., (5 $x_{\text{Act}}^{\text{t}}$+1 $x_{\text{Proj}}^{\text{t}}$ decision variables) × 101 time units + 2 $R_{\text{Res}}^{\text{tp}}$ decision variables].

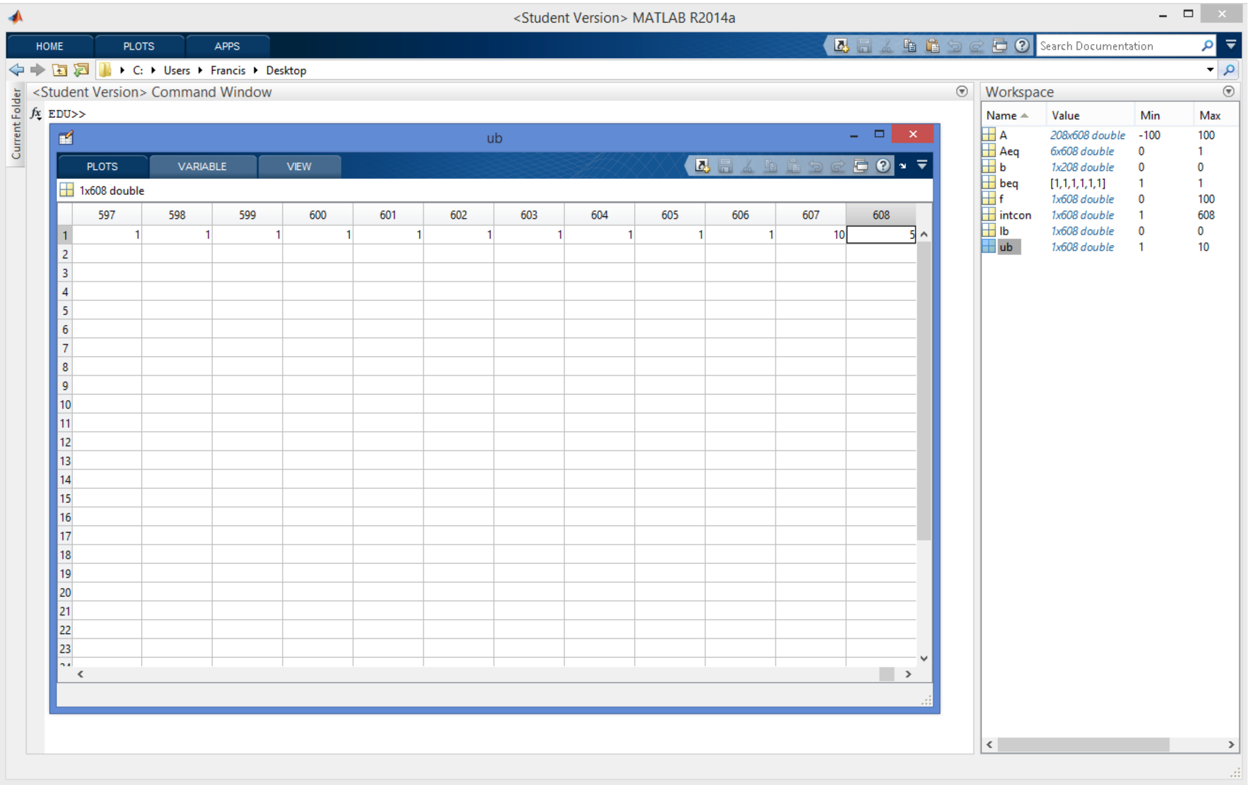


	597	598	599	600	601	602	603	604	605	606	607	608
1	0	0	0	0	0	0	0	0	0	0	0	0

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10

Figure B.12: Vector ***lb*** defined in MATLAB workspace

Figure B.13 defines Vector ***ub*** (Partitions P19, P20, and P21). Its dimension is 1 row × 608 columns [i.e., (5 $x^{\mathrm{t}}_{\mathrm{Act}}$+1 $x^{\mathrm{t}}_{\mathrm{Proj}}$ decision variables) × 101 time units + 2 $R^{\mathrm{tp}}_{\mathrm{Res}}$ decision variables].



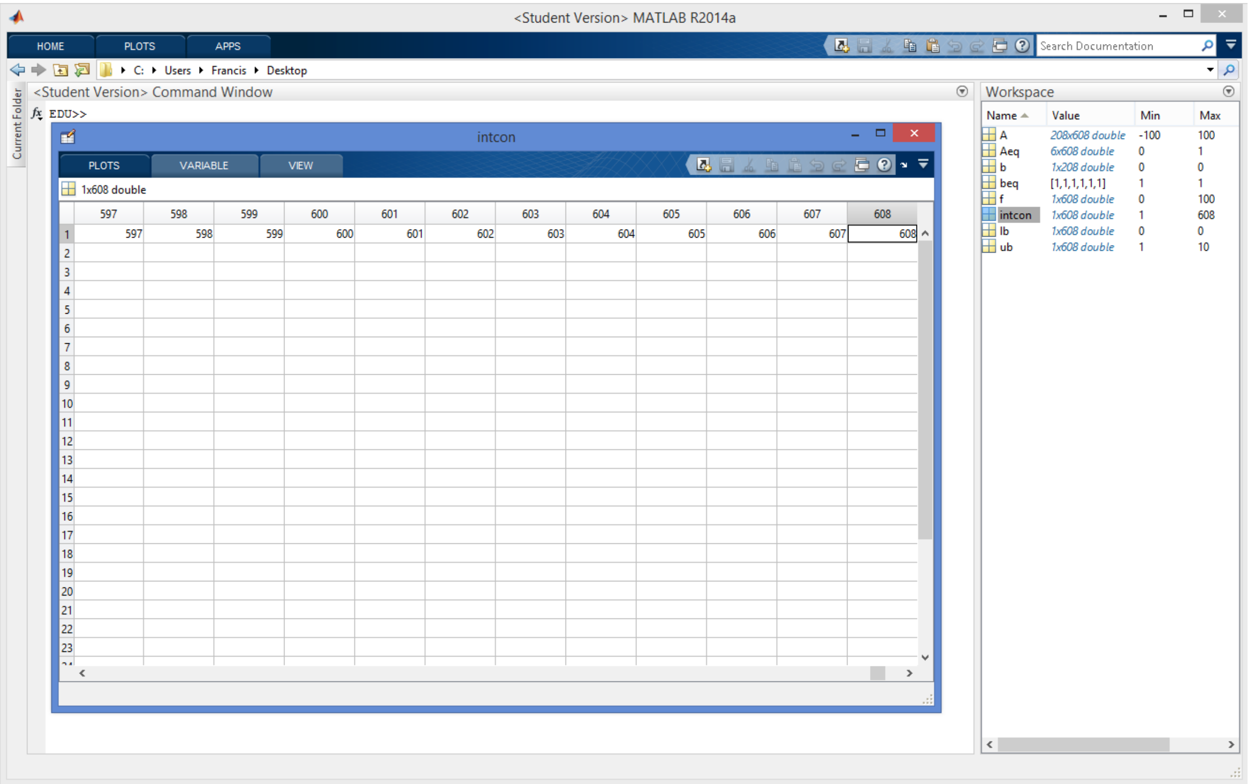
```
EDU>>
```

	597	598	599	600	601	602	603	604	605	606	607	608
1	1	1	1	1	1	1	1	1	1	1	10	5

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10

Figure B.13: Vector ***ub*** defined in MATLAB workspace

Figure B.14 defines Vector ***intcon***. The vector declares that all decision variables have integer values. Its dimension is 1 row × 608 columns [i.e., (5 x^{t}_{Act} +1 x^{t}_{Proj} decision variables) × 101 time units + 2 $R^{\text{tp}}_{\text{Res}}$ decision variables].

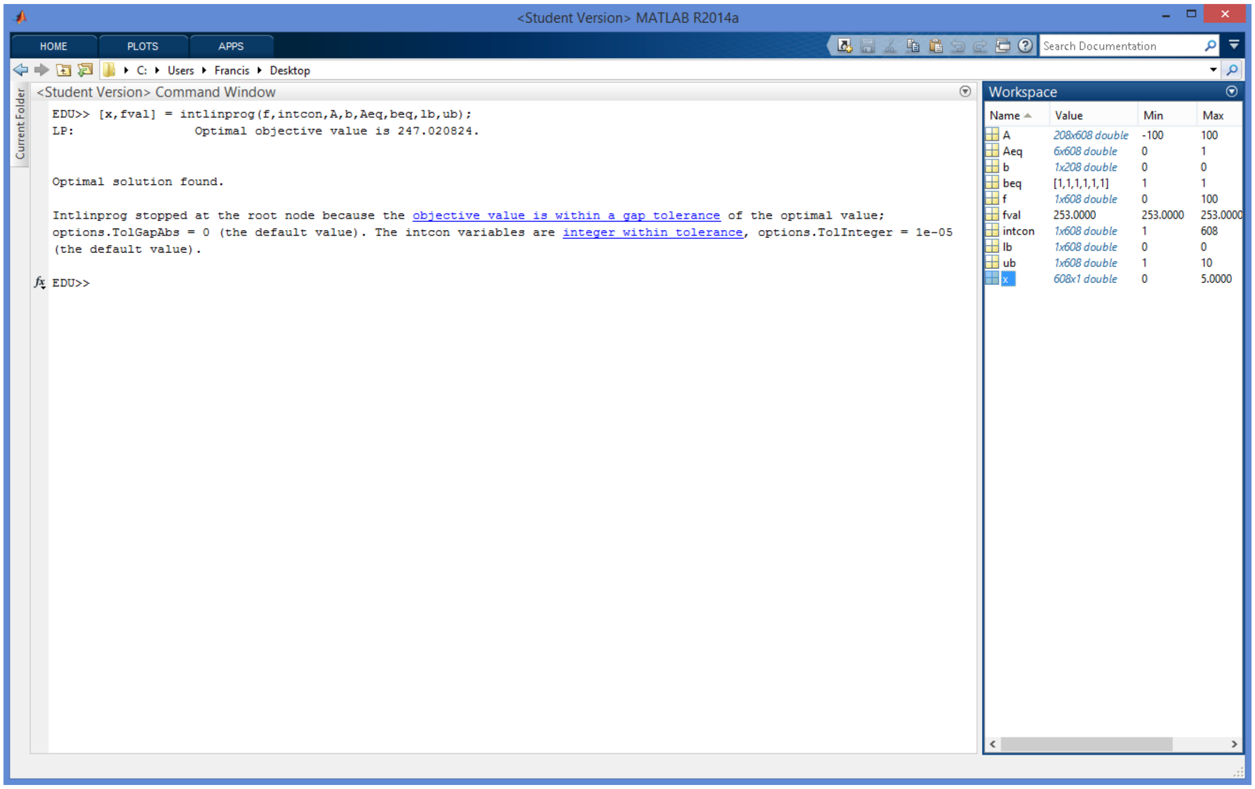


	597	598	599	600	601	602	603	604	605	606	607	608
1	597	598	599	600	601	602	603	604	605	606	607	608

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10

Figure B.14: Vector ***intcon*** defined in MATLAB workspace

To generate the RSDMP solution, Syntax "x = intlinprog (***f***, ***intcon***, **A**, ***b***, $\mathbf{A}_{\mathbf{eq}}$, $\boldsymbol{b}_{\mathbf{eq}}$, ***lb***, ***ub***)" is entered in MATLAB command window, as presented in Figure B.15.

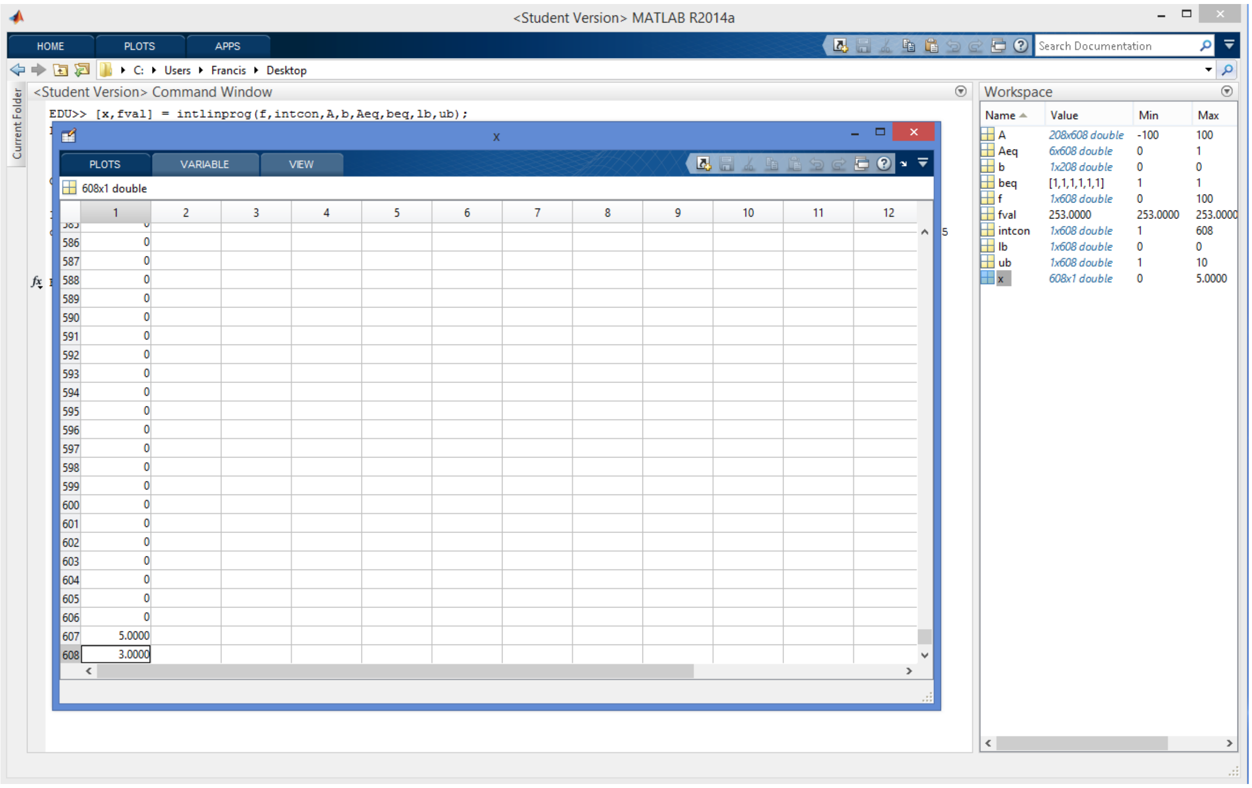


```
EDU>> [x,fval] = intlinprog(f,intcon,A,b,Aeq,beq,lb,ub);
LP:                Optimal objective value is 247.020824.


Optimal solution found.

Intlinprog stopped at the root node because the objective value is within a gap tolerance of the optimal value;
options.TolGapAbs = 0 (the default value). The intcon variables are integer within tolerance, options.TolInteger = 1e-05
(the default value).

fx EDU>>
```

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
fval	253.0000	253.0000	253.0000
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10
x	608x1 double	0	5.0000

Figure B.15: MATLAB syntax for solving integer linear programming model

If the theoretical optimum solution is found, Vector ***x*** will be generated in MATLAB workspace (Figure B.16). The optimum values of the decision variables $x_{\text{Act}}^{t}, x_{\text{Proj}}^{t}, R_{\text{Res}}^{tp}$ are stored in Partitions P1, P2, and P3 of Vector ***x***, respectively. Based on the derived activity completion times, project completion time, and resource supply for particular time periods, the optimum RSDMP schedule and resource usage histogram can be formulated.



```
EDU>> [x,fval] = intlinprog(f,intcon,A,b,Aeq,beq,lb,ub);
```

	1	2	3	4	5	6	7	8	9	10	11	12
586	0											
587	0											
588	0											
589	0											
590	0											
591	0											
592	0											
593	0											
594	0											
595	0											
596	0											
597	0											
598	0											
599	0											
600	0											
601	0											
602	0											
603	0											
604	0											
605	0											
606	0											
607	5.0000											
608	3.0000											

Name	Value	Min	Max
A	208x608 double	-100	100
Aeq	6x608 double	0	1
b	1x208 double	0	0
beq	[1,1,1,1,1,1]	1	1
f	1x608 double	0	100
fval	253.0000	253.0000	253.0000
intcon	1x608 double	1	608
lb	1x608 double	0	0
ub	1x608 double	1	10
x	608x1 double	0	5.0000

Figure B.16: Vector ***x*** generated in MATLAB workspace