COORDINATED SUPPLIER SELECTION AND PROJET SCHEDULING IN RESOURCE-CONSTRAINED CONSTRUCTION SUPPLY CHAINS

By

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ABSTRACT OF THE DISSERTATION

Coordinated Supplier Selection and Project Scheduling in Resource-Constrained Construction Supply Chains

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Dissertation Director: Dr. Lei Lei and Dr. Weiwei Chen

The concept of supply chain management has been evolving in construction industry steadily since mid-1990s as more and more firms experience the power of collaboration for business growth and market expansion. Unlike most manufacturing supply chains, a construction supply chain is more unique and complex due to its characteristics such as one-off project, non-repetition, and highly-customized nature. Although many researchers have devoted their efforts in construction supply chain management and construction project management, there has been a significant gap between what are being studied and what are experienced in practices. The main contribution of this study to the academic literature is its effort toward filling this gap.

This dissertation includes three essays, triggered by common operational challenges encountered in the construction practices. First, we study a resource-dependent project network consisting of multiple concurrent projects that are independent in operations but are subject to the same final quality inspection upon completion. In addition, each independent project consists of a set of activities, the earliest start times of which depend

on the availability of required supplies and the precedence relationships among the activities. Thus, the supplier selection and coordination among these activities need to be considered to guarantee a timely completion of each project. The problem is modeled as a mixed integer linear program (MILP), which contributes the literature as a new mathematical model that describes a common operational problem emerged in coordinating the project resource allocation, the activity schedule, and the final project review operations.

Secondly, we present a formal structural analysis of the problem introduced above, and investigate the effectiveness of a mathematical programming based heuristic. The heuristic decomposes the MILP model into three sub-problems aforementioned, which can be solved independently and consecutively. The overall objective is improved by updating a weight vector in the supplier selection sub-problem, where the shadow prices of some constraints in the project activity scheduling sub-problem and project review sequencing sub-problem are utilized to guide the weight updates. Our empirical studies show that the proposed heuristic is capable of generating near-optimal solutions in a short computational time.

Finally, we conduct a study on project scheduling policies under uncertainty. We focus on the uncertainty that commonly exists in the duration of completing each project activity. Two problems are investigated in this essay. First, we study the impact of a collaboration policy on final project review, under both batch mode slot assignment and sequential mode slot assignment. The benefits of collaboration compared to its non-collaboration counterpart are shown using computer simulation. Then, the resource allocation problem based on time-resource tradeoff problem with uncertain activity durations is introduced. The general problem is discussed and an algorithm for a special case is presented.

Five future extensions from this research are also discussed, such as (1) constrained project scheduling with renewable and nonrenewable resources; (2) project scheduling with inspection requirement and multiple objectives; (3) supplier selection based on 3PL and 4PL in practice; (4) sustainability application; and (5) alternative decomposition schemes of the heuristics.

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Chapter 1

Introduction

The construction industry plays an important role in the competitiveness and prosperity of the overall economy, especially in terms of its significant contributions to shelter, infrastructure, and employment (Anaman & Osei-Amponsah, 2007). A number of researchers have investigated the vital role of the construction sector to general economic growth. Rhodes (2014), for example, states that the construction industry in the UK contributed £83.0 billion in economic output in 2012, which accounted for 6% of the total. In addition, workforce jobs in the construction industry in the UK totaled 2.03 million in 2012 and 2.12 million in 2013, accounting for 6.4% and 6.5% of the workforce, respectively (Rhodes, 2014). Similarly, a study by Oladinrin et al. (2012) indicates the significance of construction linkage with the aggregate economy in Nigeria by studying the time series data from 1990 to 2009 on construction output and Gross Domestic Project (GDP). A recent report of the U.S. Bureau of Economic Analysis shows that the value added to the GDP by construction industry was $652,723 million in 2014, 3.7% of total GDP (http://www.bea.gov/industry/gdpbyind_data.htm). Furthermore, a report by the U.S. Bureau of Labor Statistics shows that employment in the construction industry sector accounted for 4.7% and 3.9% in the years 2002 and 2012 (http://www.bls.gov/emp/ep_table_201.htm). Finally, the construction industry has also played an influential role on the domestic GDP in the People's Republic of China. A report by the National Bureau of Statistics of China shows that the GDP value added by construction was ¥44,790 billion in 2014; this accounted for 7% of the total GDP (http://www.stats.gov.cn/tjsj/zxfb/201509/t20150907_1240657.html) and was responsible for 49,605,000 jobs in China (http://data.stats.gov.cn/easyquery.htm?cn=C01).

The construction industry has been a constant factor in the U.S. national economy, which leads to fierce market competition among building enterprises. A report released in December 2013 by *Statistics of U.S. Businesses* shows that there were 645,240 firms in the construction industry, which accounts for 11.35% of total firms in the nation (https://www.census.gov/econ/susb/). In such a competitive environment, the adoption of supply chain processes is a pressing need for the construction industry. The concept of construction supply chain management (CSCM) has received a considerable amount of attention since mid-1990s, when firms saw the benefits of collaborative relationships in effective competition. Fearne and Fowler (2006) conclude that an efficient supply chain management (SCM) can play a significant role in the effectiveness of a given construction project. In addition, Koctas and Tek (2013) note that "lower costs, shorter execution durations, higher-quality facilities, more reliable work schedules, and faster and more responsive construction processes" are demanded in the construction industry. SCM is vital to those goals.

However, the development of SCM in the construction industry is behind other industries. Love et al. (2004) point out that the construction industry has been slow to employ the concept when many manufacturing organizations are implementing supply chain management to attain the maximum business process efficiently and effectively. Virhoef and Koskela (1999) conclude that the construction industry does not utilize systematic construction project supply chain design. Consequently, there is a need for a supply chain management tool to improve the competitive advantage in the construction industry.

The current research pertaining to the construction industry has primarily focused on project management and the qualitative and conceptual direction of supply chain management. In this paper, we formulate a resource-dependent project network with final project review sequencing, which integrates both construction supply chain management (CSCM) and construction project management. In the rest of this chapter, we provide background and motivation for the study.

1.1. Background

The application of supply chain management has been widely implemented in many manufacturing industries since the mid-1980s. The benefits of implementing supply chain management are multitudinous: reducing cost, increasing return, better information sharing among partners, and greater uncertainties control, etc. Fundamentally, construction supply chain is similar to manufacturing supply chain in funding, sourcing, transaction, and communication. However, construction supply chain is unique in nature – e.g., it involves greater complexity and more uncertainty in the production system, temporary supply chain configuration, a higher rate of customer influence on the product (Koctas & Tek, 2013), long production duration, and complications due to the larger number of people involved. Hence, compared to manufacturing supply chain management (MSCM), which emphasizes the modeling of production volume, “CSCM is primarily concerned with the coordination of discrete quantities of materials that must be delivered to specific construction projects” (Tran & Tookey, 2012).

The construction supply chain network from a contractor's point of view is presented in Figure 1.1. The contractor wins the bid based on their project planning report, which primarily includes elements such as the specific work requirements, quality and quantity of the work, required resources, estimated price, scheduled activities, and a risks evaluation. The project then can be executed, based on the project planning report. In the execution process, the contractor needs to negotiate and work with all the team members (e.g., suppliers, subcontractors, clients, government, and the surrounding community), schedule and allocate resources (i.e., materials, equipment, and labor force), control risks through process tracking, and make appropriate adjustments as external (e.g., weather and policy) or internal factors (e.g., financing) change. The finished project should be inspected by a capable inspection team, and only a qualified project should be submitted to the client.

The major stakeholders of a construction supply chain are the clients, contractor (and sub-contractors), and suppliers (and sub-suppliers); other participants, such as financial organizations, governmental agencies, engineers, architects, insurance companies, material manufacturers, and the inspection team could also be involved. Cost optimization, time reduction, and quality standardization are the main foci and goals of all the major stakeholders. Resource scheduling and allocation is the most important, but also the most challenging part for stakeholders to achieve their objectives. The reasons are: (1) resources are the major expenditure of a construction project; they usually take up approximately 90% of the total cost; and (2) project duration invariably changes, depending on fluctuations in the resources. Most of the project activities are in precedent relations. An activity can only start when all of its precedent activities are completed, and the start time of each activity cannot be later than its latest start time because of concerns about the target due time (Zhou et al., 2013). Thus, the project duration could be delayed or postponed in accordance with the unavailability of resources. In addition, project costs also change due to the availability of resources. Indeed, unavailable resources can lead to an increase in the project duration. Specifically, project crashing may be implemented for expediting the process before deadline, resulting in additional resources and cost input in a short-term time frame. From a long-term perspective, when the whole project is delayed, there would be a heavy financial penalty to the contractor and significant monetary loss to client.

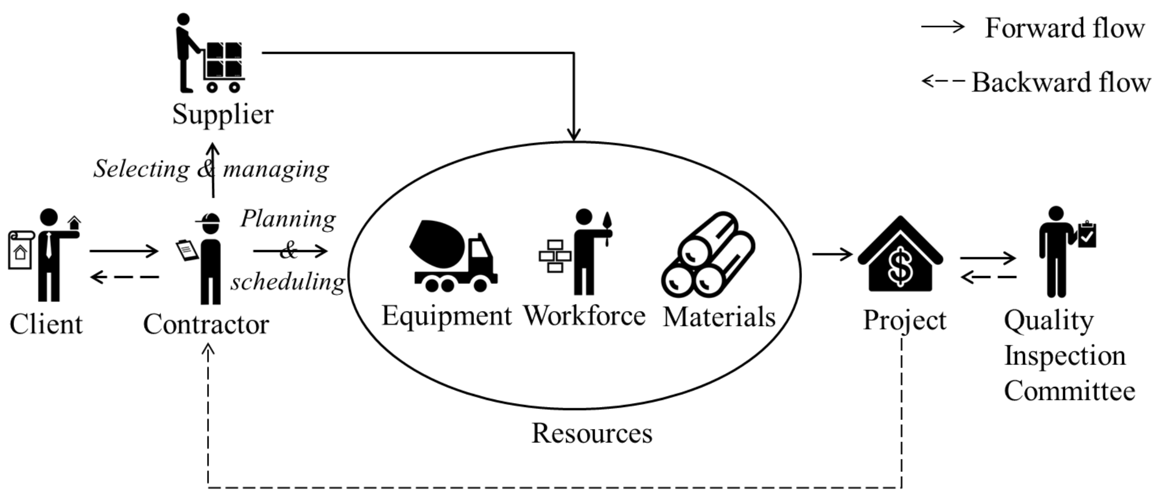

Figure 1.1 Generic configuration of construction supply chain.

In typical construction projects, the cost of materials takes up a major part of all three types of resources: materials, equipment, and workforce. Strong evidence shows that materials can constitute 50% to 60% of the total cost of a project, and the management of materials affects 80% of the project schedule (Safa et al., 2014).

Therefore, the selection of an effective and efficient material supplier can optimize the project's duration, cost, and quality. In practice, projects are often assigned to different project managers. Thus, the supplier selection is managed on a one-for-one basis, as shown in Figure 1.2. In addition, according to the project-based temporary practices, supply chain players come together for a project and go their separate ways when the project is completed so that supply chain players put forth their own benefits but may disregard coordination with other stakeholders. When that happens, it fails to take full advantage of supplier sharing in a supply chain, which might result in reducing duplication in operations (e.g., setup), fewer people involved, price discounts from suppliers, and enhanced cooperation and communication between buyer and seller (Patil & Adavi, 2012). Patil and Adavi (2012) also point out that supplier selection is critical in reducing delays and cost and time overrun; that selection is the prerequisite for downstream integration in the construction supply chain; otherwise, it is difficult to complete the project with minimum time and cost variance. Unfortunately, very limited research has been done on the supplier selection problem in construction supply chain management, not to mention for a coordinated supplier selection problem in a resource-dependent project network in construction supply chain management (See Figure 1.3).

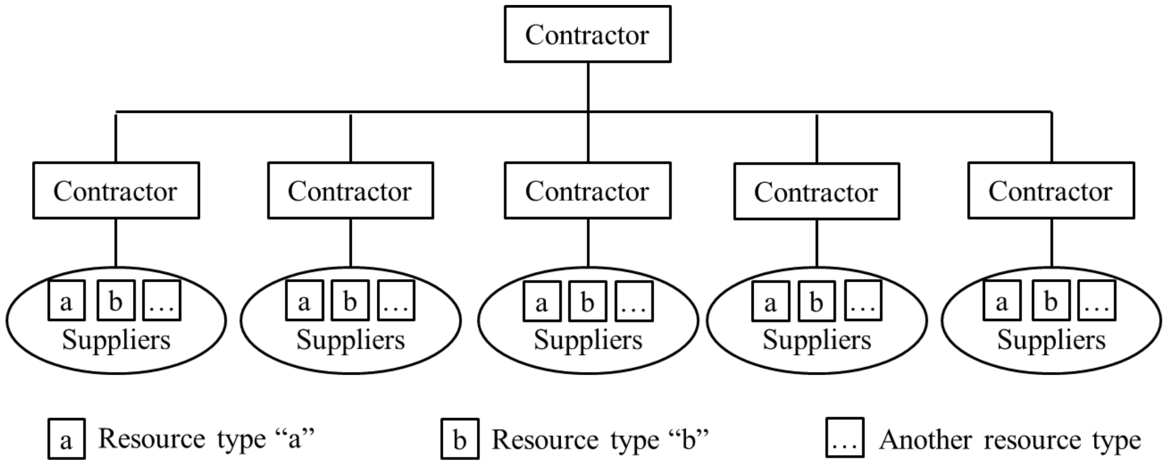

Figure 1.2 Supplier selection based on a one-for-one basis.

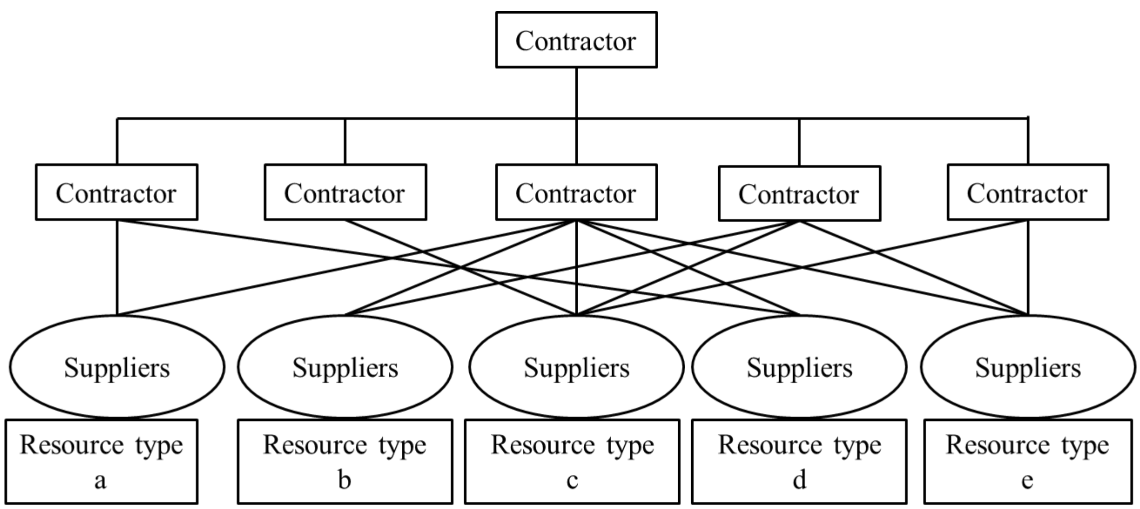

Figure 1.3 Coordinated supplier selection in a resource-dependent project network.

1.2. Motivation

The case that motivated this study was based on YLF Construction Co. Ltd., one of the companies that worked on harnessing the Dagu (DG) River for the local government. Specifically, there were four independent projects located in four separate cities. The main construction on each project consisted of dredging and building dikes, culverts, and sluices, which were organized into six procedures in precedence: (1) preparation and measurement, (2) earthworks, (3) building dikes and engineering work, (4) revetment engineering work, (5) planting engineering work, and (6) electrical and metal structure installation engineering work. Moreover, each procedure included hundreds of additional activities in concurrence with the work and/or in prior to it, and the earliest start times depended on the availability of required supplies and the mutual dependencies among these many activities. For most types of resources – rebar, cement, sand, rock, and other materials – were commonly used in the four projects. All of the construction durations of the projects were approximately one year: from the end of 2012 to the end of 2013. The major challenge for YLF Construction Co. Ltd. was to complete all the projects within the shortened projection duration in order to ensure local residents' safety as a public infrastructure. In detail, the DG River is located at the intersection of east longitude 119° 40'-120° 39' and north latitude 35° 54'-37°22'. Due to the oceanic climate, the rainfall concentrates in June and July every year so that all the projects have to be interrupted at that time because of the deep mud that made the work site impassable and the heavy machinery incapacitated. Consequently, procedures (1) to (3) had to be completed before June. Otherwise, the annual floods would destroy the unstable dikes and spell disaster for adjoining areas. Furthermore, new dikes might need to be built, which would lead to extra costs – e.g., crashing fees, penalties, and/or time delays. Meanwhile, all the projects must meet every single quality standard. An unqualified project needed to be reworked until it met the standard. The successful completion of all the projects then marked the completion of the entire construction project.

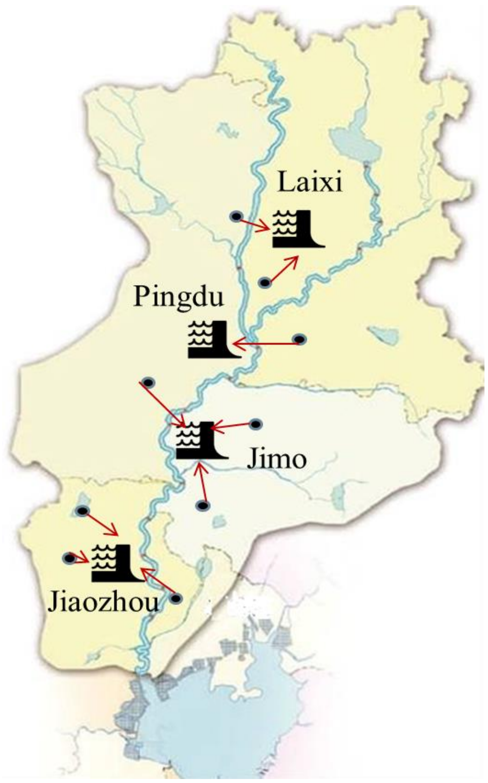

Figure 1.4 Geographic of the motivated case.

This study constructs a resource-dependent project network with final project review sequencing. The inspection is typically performed by a single inspection team, and the successful completion of all these projects marks the end of the entire construction project. As such, the sequencing of the final quality inspection process is critical to the completion time of the entire project. Meanwhile, each independent project consists of a set of activities, the earliest start time of which depends on the availability of required supplies and the mutual dependencies among these many activities. Thus, proper supplier selection and coordination among these activities are considered to guarantee a timely completion of each project. In this study, we coordinate the supplier selection, activities scheduling and project review sequencing based on the case in practice.

In the remainder of this paper, particularly in Chapter 2, we provide a literature review on construction project management, construction supply chain management, and interface between these two. In Chapter 3, a mixed integer linear program (MILP) model is defined, in accordance with the coordinated supplier selection and resource-dependent project management with final project review sequencing. Moreover, a structural analysis of the problem – including the computational complexity and the sub-problem analysis – is presented. In Chapter 4, a heuristic approach based on mathematical programming is proposed; also, a number of numerical tests are conducted to show the effectiveness of it in solving the aforementioned MILP model. In Chapter 5, we study two strategic-level problems in project management under uncertainty: (1) a collaboration policy on final project review, both under batch mode slot assignment and sequential mode slot assignment, and (2) a resource allocation strategy based on time-resource tradeoff subjects to uncertainty of activity durations. Finally, conclusions and future research possibilities are discussed in Chapter 6.

Chapter 2

Literature Review

In this chapter, we present a literature review on construction project management, construction supply chain management (which includes supplier selection problem), and interface between construction project management and supply chain management.

2.1. Construction Project Management

Construction project management has been studied more thoroughly and more seriously in the past two decades. Fundamentally, construction project management is a subdivision of project management (Zhou et al., 2013), which involves the activities, resources, precedence relations, and performance measures. A detailed review of the project scheduling problem can be found in Icmeli et al. (1993), Kolisch & Padman (2001), Herroelen (2005), Ozdamar & Ulusoy (1995), and Hartmann & Briskorn (2010). Resource selection is one of the most important and challenging part in project scheduling, so the extant literature is quite rich in resource-constrained project scheduling problem studies. Such reviews can be found in Ozdamar and Ulusoy (1995), Herroelen et al. (1998), Brucker et al. (1999), and Hartmann & Briskorn (2010).

Construction project management has its own characteristics due to the unique features in nature, such as the "one of a kind" nature of some projects, site projection, temporary multi-organization, and regulatory intervention (Dave & Koskela, 2009). A number of other studies have addressed project management in construction that can be categorized in a number of ways; for example, these methodologies have been categorized as mathematical, heuristic, and meta-heuristic, with regard to the existing methods and algorithms (Zhou et al., 2013). In this paper, a variety of methodologies, objectives, and constraints that differ from that of Zhou et al. is categorized in Table 3.1 and Table 3.2. In Table 3.1, we present 29 researches in construction project management not only regarding to their methodologies (such as mathematical, heuristic, meta-heuristic, and simulation), but also with respect to the objectives (such as time, cost, resource, and quality). Similarly, in Table 3.2, we categorize the 29 researches in accordance with their constraints (such as precedence, time, cost, and resource).

Moreover, some literature has focused on studying specific project types such as (1) repetitive projects (Zhang et al., 2006; El-Rayes & Moselhi, 2001), (2) multi-projects (Elazouni, 2009), and concurrent projects (Lim et al., 2014; Silva et al., 2012; Maheswari et al., 2006; Lee et al., 2005; Kamara & Anumba, 2000; Nkasu & Leung, 1997; Eldin, 1997; and Kusiak & Park, 1990), and (3) the specifics of inspection and monitoring (Wang, 2008; Hanne & Nickel, 2005; Pradhan & Akici 2012; Gordon et al., 2007; Gordon et al., 2008; Gordon et al., 2009; and Boukamp & Akinci, 2007). Although resource-constrained project scheduling problem is the main stream in construction project management studies, there is a lack of consideration for both non-renewable resources and renewable resources constrained in construction project management, especially in concurrent project management. Furthermore, although some literature has studied the topic of inspection and monitoring, few of them have integrated inspection process into project management as a decisive factor in project duration.

Table 2.1

Summary of construction project management research with respect to the objectives.

Methodologies		References	Objective			
			Time	**Cost**	**Resource**	**Quality**
Mathematical Methods	CPM	Lu et al. (2008)	Y			
		Hegazy and Menesi (2010)	Y			
	IP	Talbot (1982)	Y	Y		
	LP	Johnson and Liberatore (2006)	Y	Y		Y
	LP/IP hybrid	Burns et al. (1996)		Y		
	LP/CPM	Adeli and Karim (1997)		Y		
	Dynamic programming	El-Rayes and Moselhi (2001)	Y			
Heuristic Methods	Current float model	Shanmuganayagam (1989)	Y			
	LINRES	Abeyasinghe et al. (2001)	Y			
	Branch and cut	Kis (2005)	Y			
	Augmented heuristic algorithm	Wongwai and Malaikrisanachalee (2011)	Y			
	TCT/CRS	Hegazy and Menesi (2012)	Y			
		Tsubakitani and Deckro (1990)	Y			
		Hegazy et al. (2000)	Y			
		Zhang et al. (2006)	Y			
		Elazouni (2009)	Y			
		Peng et al. (2011)		Y		
Meta-heuristic Methods	GA	Chan et al. (1996)			Y	
	GA	Feng et al. (1997)	Y	Y		

	GA	Leu and Yang (1999)	Y	
	GA	Leu et al. (2001)	Y	Y
	GA	Toklu (2002)	Y	
	GA	Senouci and Eldin (2004)		Y
	GA	Marzouk and Moselhi (2004)	Y	Y
	GA	Chen and Weng (2009)		Y
	GA	Jaskowski and Sobotka (2012)	Y	
	GA	Ghoddousi et al. (2013)	Y	Y
	ACO	Ng and Zhang (2008)	Y	Y
	Computational algorithm	Wang and Huang (1998)	Y	Y
	Constraint programming	Menesi et al. (2013)		Y
Simulation	Hierarchical simulation modeling method	Sawhney and AbouRizk (1995)		
		Marzouk and Moselhi (2004)		
		Blaszczyk and Nowak (2009)		
		Lim et al. (2014)		

Table 2.2

Summary of construction project management research with respect of constraints.

Methodologies		**References**	**Constraints**			
			Precedence	**Time**	**Cost**	**Resource**
Mathematical Methods	CPM	Lu et al. (2008)	Y			Y
		Hegazy and Menesi (2010)	Y			

	IP	Talbot (1982)	Y			Y
	LP	Johnson and Liberatore (2006)	Y			
	LP/IP hybrid	Burns et al. (1996)	Y			
	LP/CPM	Adeli and Karim (1997)	Y			
	Dynamic programming	El-Rayes and Moselhi (2001)	Y			Y
Heuristic Methods	Current float model	Shanmuganayagam (1989)	Y			Y
	LINRES	Abeyasinghe et al. (2001)	Y			Y
	Branch and cut	Kis (2005)	Y			Y
	Augmented heuristic algorithm	Wongwai and Malaikrisanachalee (2011)	Y			Y
	TCT/CRS	Hegazy and Menesi (2012)	Y	Y		Y
		Tsubakitani and Deckro (1990)	Y			Y
		Hegazy et al. (2000)	Y			Y
		Zhang et al. (2006)	Y			Y
		Elazouni (2009)	Y		Y	
		Peng et al. (2011)	Y	Y		
Meta-heuristic Methods	GA	Chan et al. (1996)	Y			
	GA	Feng et al. (1997)	Y			

	GA	Leu and Yang (2000)	Y		Y
	GA	Leu et al. (2001)	Y		
	GA	Toklu (2002)	Y		Y
	GA	Senouci and Eldin (2004)	Y	Y	Y
	GA	Marzouk and Moselhi (2004)	Y		
	GA	Chena and Weng (2009)	Y		Y
	GA	Jaskowski and Soborka (2012)	Y		
	GA	Ghoddousi et al. (2013)	Y		Y
	ACO	Ng and Zhang (2008)	Y		
	Computational algorithm	Wang and Huang (1998)	Y		
	Constraint programming	Menesi et al. (2013)	Y	Y	Y
Simulation	Hierarchical simulation modeling method	Sawhney and AbouRizk (1995)			
		Marzouk and Moselhi (2004)			
		Blaszczyk and Nowak (2009)			
		Lim et al. (2014)			

2.2. Construction Supply Chain Management

Construction supply chain management (CSCM) has been studied since the mid-1990s, and most existing studies focus on qualitative and conceptual frameworks. The major

CSCM topics investigated are about (1) logistical problems (Vijhoef & Koskea, 2000; Sobotka, 2000; Bygballe & Jahre, 2009; and Vidalakis et al., 2011), (2) CSC relationships (Palaneeswaran et al., 2003; Meng, 2010), such as clients, contractors (Agapiou et al., 1998; Holt, 2000), subcontractors (Dainty et al., 2001), (3) source selection (Palaneeswaran et al., 2001), and source of uncertainty (Gosling et al., 2013), (4) risk management (Tah & Carr, 2001; Liu & Guo, 2009), and (5) decision-making (O' Brien, 1998; Cox & Ireland, 2002; Kaare & Koppel, 2010). Last but not least, research reviews on the construction supply chain by London and Kenley (2001) and O'Brien et al. (2002) are recommended for further details.

The issues related to supplier selection in CSCM have been discussed by Lam et al. (2010), which solve a material supplier selection problem using the selection model on the fuzzy Principal Component Analysis (PCA) from the perspective of property developers. Safa et al. (2014) develop an integrated construction materials management (ICMM) model involved in supplier selection process. The purpose is to optimize and validate purchasing at each stage of fabrication for each construction package.

2.3. Construction Project Management and Supply Chain Management

Very limited research has been done on the interface of construction project management and supply chain management. Ayers (2009) proposes a concept of "supply chain project management," in which both operations are integrated, thereby managing the supply chain and project management so that industry personnel involved in either job function can consider their operations from the same perspective. Pan et al. (2011) introduce a construction project supply chain model that aims to explore the behavior of the construction supply chain process and develop a performance evaluation method to improve the supply chain management of the construction project. Elima and Dodin (2013) develop an integrated supply chain (ISC) that is modeled as a project network (PN). The project captures all the activities involved in the ISC for a multi-component family of projects regardless of the number of tiers in the ISC. The PN is formulated as a mixed integer program in which the optimal solution provides the duration for all processing and shipping/distribution activities, as well as scheduling of orders. To sum up, developing supply chain models for multiple projects is difficult because of the complexities involved (Koctas & Tek, 2013). To the best of our knowledge, the current literature has largely focused on analyzing an individual supply chain on a single independent construction project that is managed by one general contractor.

Moreover, the existing researches of construction project management software or project management software has not investigated a coordinated problem of supply chain management and project management, although professionals in the construction industry have a strong interest in developing better methods for project planning and control. Most of the current researches focus on scheduling and resource management (Karim & Adeli, 1998; Kolisch, 1999), information modeling (Arnold & Javernick-Will, 2013; Gokce et al., 2013; and Vaughan et al., 2013), and risk management (Neves et al., 2014). Furthermore, a number of surveys identifying software use and project performance can be found in Higgs (1995), King (1995), Cabanis (1996), and Hegazy & El-Zamzamy (1998). Liberatore et al. (2001) focus on future research and the use of project management software in the construction industry. Based on a random survey (240 responded) of professionals at the Project Management Institute (PMI), the study concludes that (1) there has been a significant increase in the usage of PM software over past five years; (2) project complexity is the most influential factor to determine the time to use PM software, and other influential factors are software capabilities, size of projects and client requests; (3) construction professionals prefer to work on fewer projects with larger numbers of activities; (4) the most frequently using software package is Primavera, while the Microsoft Project is also a heavy-use one; (5) critical path analysis is in extensive usage by the construction respondents for “planning and control, resource scheduling for planning, and earned value analysis for control”; and (6) the key determinants of the usage of specific analytical techniques depend on the number of activities. To sum up, construction professionals express a clear interest in future research on resource scheduling/leveling in general (e.g., integration of PM software, and making the use easier) and a net present value option in particular.

This study builds an interface between construction project management and construction supply chain management, and therefore has practical significance. The research that investigates both supplier selection and activities scheduling based on a network consisting of multiple concurrent projects that are independent in operation, and each independent project consists of a set of activities. In addition, project review sequencing considered in this study, an inclusion that is essential both for reducing projection duration and project quality. With the objective of minimizing the completion time of the entire construction project, the research problem is modeled as a mixed integer linear program (MILP). A heuristic method, combined with mathematical programming (MP), is proposed to solve the MILP model. Heuristic has been used widely in practice, and study broadly in research (Moselhi, 1993; Zhang et al., 2006a; Elazouni, 2009; and Hegazy et al., 2000). First, the heuristic methods are very inexpensive to use in computer programs (Hegazy, 1999). Moreover, “the heuristic methods have the advantage of being simple to understand, easy to apply, and are able to rationalize the scheduling process and make it manageable for practical-size projects” (Zhang et al., 2006).

Chapter 3

Coordinated Supplier Selection and Project Scheduling in Resource-Constrained Construction Supply Chains

In this Chapter, we first describe the problem under study, and model the problems as a MILP.

3.1. Problem Description

The problem is based on a coordinated supplier selection and resource-dependent project network with final project review sequencing encountered in a real-life case of construction industry practice as presented in Chapter 1. The network consists of multiple concurrent projects that are independent in operation, and that share some similar types of non-renewable resources. Each independent project consists of a set of activities, the earlier start times of which depend on the availability of required supplies (non-renewable resources such as rebar, cement, and stone, etc.) and the mutual dependencies among these activities (due to procedural requirements, some activities need to be completed before other activities can start). In addition to the dependency on non-renewable resources, each activity also relies on so-called renewable resources (such as manpower and machine). Renewable resources can be re-used in different activities, but one such resource can only be occupied by one single activity at a time. For each project, after all activities are completed, this project is marked initial completion, but is subject to final quality inspection. The inspection is typically performed by a single inspection team, and the successful completion of all these projects marks the completion of the entire construction project. Given that each project has a due date, the objective is to minimize the total weighted tardiness for all projects. The problem is depicted in Figure 3.1.

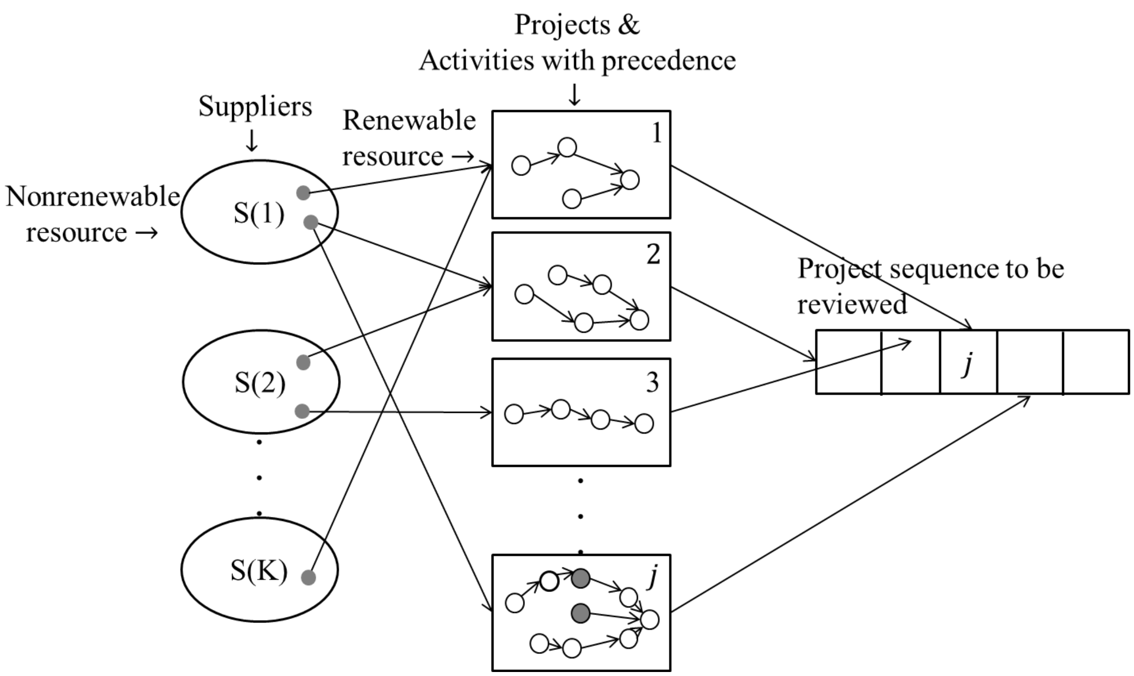

Figure 3.1 A supply chain network with both renewable and non-renewable resources.

3.2. Mathematical Model

A set of projects, J. Each independent project $j \in J$ consists of a set of activities $A(j), j \in J$. For all activities $A = \cup_{j \in J} A(j)$, it is assumed that the activities to be completed in different projects are different, i.e., $A(j_1) \cap A(j_2) = \emptyset, \forall j_1, j_2 \in J, j_1 \neq j_2$. It is also assumed that each project needs both non-renewable resources $K(j) = \cup_{a \in A(j)} K(a), j \in J$ where $\cup_{a \in A(j)} K(a) = K$ and renewable resources $L(j), j \in J$, such as crews and machines. Different projects do not share renewable resources. We further assume that a single unit is available for each resource in each project. Moreover, a set of activities $AL(l) \subset A(j), l \in L(j)$ in project j may require renewable resource l and non-renewable resource $K(a), a \in A$. In addition, there are a set of precedence constraints $E(j), j \in J$ for activities in project j. Specifically, $(a, b) \in E(j)$ for $a, b \in A(j)$ means that activity a needs to be completed before activity b starts.

A set of suppliers, $S(k), k \in K$, provides non-renewable resource k to the project that has corresponding requirements, where $\cup_{k \in K} S(k) = S$. We assume each supplier only supplies one type of resource – i.e., $S(k_1) \cap S(k_2) = \emptyset, \forall k_1, k_2 \in K, k_1 \neq k_2$. In reality, if one supplier is responsible for more than one resource, it can be modeled as multiple suppliers, each of which supplies one resource with its own respective capacity and release time.

Project review sequencing depends on the project completion time and the subsequent review time. There is only one project reviewed at one time by a single inspection team. The successful completion of all these projects marks the completion of the entire construction project.

The following notations are used for formulating the model.

<u>Sets</u>

- J: set of projects;
- $A(j), j \in J$: set of activities to be completed in project j;

- $A = \cup_{j \in J} A(j)$: set of all activities. We assume that activities to be completed in different projects are different, i.e., $A(j_1) \cap A(j_2) = \emptyset, \forall j_1, j_2 \in J, j_1 \neq j_2$;
- $K(a), a \in A$: set of non-renewable resources needed by activity a, e.g., raw materials;
- $K(j) = \cup_{a \in A(j)} K(a), j \in J$: set of non-renewable resources needed by project j;
- $K = \cup_{a \in A} K(a)$: set of all non-renewable resources;
- $S(k), k \in K$: set of suppliers for non-renewable resource k. We assume each supplier only supplies one type of resource, i.e.,$S(k_1) \cap S(k_2) = \emptyset, \forall k_1, k_2 \in K, k_1 \neq k_2$. In reality, if one supplier has more than one resource, it can be modeled as multiple suppliers, each of which supplies one resource with respective capacity and release time.
- $S = \cup_{k \in K} S(k)$: set of all suppliers for non-renewable resources;
- $L(j), j \in J$: set of renewable resources used in project j, such as labors and machines. Different projects do not share renewable resources. We further assume that a single unit is available for each resource in each project.
- $AL(l) \subset A(j), l \in L(j)$: set of activities in project j that require renewable resource l;
- $E(j), j \in J$: set of precedence constraints for activities in project j. $(a, b) \in E(j)$ for $(a, b) \in A(j)$ means that activity a needs to be completed before activity b starts;

Parameters

- $Q_{jk}, j \in J, k \in K(a), a \in A$: desired quantity of non-renewable resource k for project j to complete all activities in this project. Here we assume that each supplier delivers the required quantity of resource to each project in a single delivery.
- $DD_j,\ j \in J$: due date of project j;
- $C_s, s \in S$: capacity of supplier s;
- $r_s, s \in S$: release time of supplier s;
- $\tau_{sj}, s \in S, j \in J$: shipping time from supplier s to project j;
- $c_{sj}, s \in S, j \in J$: unit cost of supplying project *j* from supplier s, including both purchasing and shipping cost;
- $P_a, a \in A$: construction duration for activity a;
- R_j, j $\in$ J: review duration for project j;
- B: total budget for non-renewable resources;
- $\omega_j, j \in J$: weight of project j, indicating the relative importance of meeting the due date for this project.

Variables

- $x_{sj}, s \in S(k), k \in K(j), j \in J$: binary variable, equal 1 if supplier s serves project j, and 0 otherwise;
- $y_{ab}, a, b \in AL(l), a = b, l \in L(j), j \in J$: binary variable, equal 1 if activity a is scheduled before activity b, and 0 otherwise, where a and *b* share the same renewable resource *l* in project j;

- $z_{ij}, i \in \{0\} \cup J, j \in J, i \neq j$: binary variable, equal 1 if project i is reviewed immediately before project j where project 0 is a dummy project, and 0 otherwise;
- $q_{sj}, s \in S, j \in J$: shipping quantity from supplier s to project j;
- $ST_a, a \in A$: start time of activity a;
- $CT_j, j \in J$: construction completion time of project j;
- $DT_j, j \in \{0\} \cup J$: review completion time of project j, where DT_0 represents the review starting time;
- $TD_j, j \in J$: tardiness of project j;

Formulation

The objective of the problem is to minimize the weighted total tardiness of the projects.

$$\min \sum_{j \in J} \omega_j \cdot TD_j \qquad (1)$$

The tardiness of each project is the difference between its review completion time and the due date.

$$TD_j \geq DT_j - DD_j \qquad \forall j \in J \qquad (2)$$

The shipping quantity from each supplier is subject to the capacity constraint.

$$\sum_{j \in J} q_{sj} \leq C_s \qquad \forall s \in S \qquad (3)$$

The total amount of each non-renewable resource received by each project has to satisfy the demand. Typically, one single supplier is selected for each resource for each project. Different projects may select different suppliers due to varied costs (e.g., shipping costs). M is a big positive number.

$$\sum_{s \in S(k)} q_{sj} \geq Q_{jk} \qquad \forall j \in J, k \in K(j) \qquad (4)$$

$$q_{sj} \leq M \cdot x_{sj} \qquad \forall s \in S(k), k \in k(j), j \in J \qquad (5)$$

$$\sum_{s \in S(k)} x_{sj} = 1 \qquad \forall j \in J, k \in K(j) \qquad (6)$$

The total procurement cost for non-renewable resources should fall within the budget.

$$\sum_{j \in J} \sum_{s \in S} c_{sj} \cdot q_{sj} \leq B \qquad (7)$$

An activity can only start after all required non-renewable resources are available.

$$ST_a \geq \sum_{s \in S(k)} (r_s + \tau_{sj}) \cdot x_{sj} \qquad \forall k \in K(a), a \in A(j), j \in J \qquad (8)$$

Activities of each project should follow the precedence constraints.

$$ST_a + P_a \leq ST_b \qquad \forall (a,b) \in E(j), j \in J \qquad (9)$$

Activities that share the same renewable resource cannot start simultaneously.

$$ST_a + P_a - M \cdot (1 - y_{ab}) \leq ST_b \qquad \forall a, b \in AL(l), a \neq b, l \in L(j), j \in J \text{ (10)}$$

$$ST_b + P_b - M \cdot y_{ab} \leq ST_a \qquad \forall a, b \in AL(l), a \neq b, l \in L(j), j \in J \text{ (11)}$$

A project is considered completed once all its activities are completed.

$$CT_j \geq ST_a + P_a \qquad \forall j \in J, a \in A(j) \qquad (12)$$

The project review completion time is determined by the construction completion time and the sequence of review. There is only one project reviewed immediately before or after another project.

$$DT_j \geq CT_j + R_j \qquad \forall j \in J \qquad (13)$$

$$DT_j \geq DT_i - M \cdot (1 - z_{ij}) + R_j \qquad \forall i \in \{0\} \cup J, j \in J, i \neq j \qquad (14)$$

$$\sum_{i \in \{0\} \cup J, i \neq j} z_{ij} = 1 \qquad \forall j \in J \qquad (15)$$

$$\sum_{j \in J} z_{0j} = 1 \qquad (16)$$

$$\sum_{j \in J, j \neq i} z_{ij} \leq 1 \qquad \forall i \in j \qquad (17)$$

3.3. Computational Complexity

Before trying to solve the proposed MILP model, we first provide some analysis on the computational complexity of the above-defined problem, called problem **P**.

Theorem 1. *Problem **P** is strongly NP hard.*

Proof. We prove strongly NP-hardness of our problem by restriction. We consider the following restricted instance of problem **P**:

1. For all $j \in J, |A(j)| = 1,$ and, $E(j) = \emptyset$, that is, for each project, there is only one activity and therefore no precedence constraints exist. This restriction can be understood as if the internal activities of each project have been "streamlined", and thus no sequencing is needed for these activities. Consequently, Eqs. (8) – (10) can be dropped.
2. For all $k \in K, |S(k)| = 1$. That is for each non-renewable resource, there is only one supplier available. With this restriction, the supplier selection variables and constraints, Eqs. (4) and (5), can be dropped.

3. $C_s \geq \sum_{\{(j,k)|j\in J,k\in K(j),s\in S(k)\}} Q_{jk}$ for all $s \in S$. This restriction indicates that the single supplier available for each no-renewable resource has sufficiently large capacity to satisfy the demand from al projects. Therefore, the capacity constraints for demand and supply, Eqs. (2) and (3), are always satisfied and thus can be dropped.

4. $B \geq \sum_{s\in S} \sum_{\{(j,k)|j\in J,k\in K(j),s\in S(k)\}} c_{sj} \cdot Q_{jk}$. This restriction indicates that the budget for purchasing all required non-renewable resources can always be satisfied. Hence, the budget constraint, Eq. (6), can be dropped.

5. $\max_{\{s|k\in K(j_1),s\in S(k)\}} r_s + \tau_{sj1} + P_{a1} = \max_{\{s|k\in K(j_2),s\in S(k)}\left(r_s + \tau_{sj2}\right) + P_{a2}$ for all $j_1, j_2 \in J, j_1 \neq j_2, a_1 \in A(j_1), a_2 \in A(j_2)$. This condition restricts the completion time of each project. Under this condition, the earliest completion time of all projects is the same, meaning that all projects can be ready for quality inspection at the same time, denoted by ET. Therefore, Eq. (7) can be dropped, and Eq. (13) can be rewritten as

$$DT_j \geq ET + R_j \qquad \forall j \in j \tag{18}$$

With the aforementioned restriction, the problem now becomes the problem of “sequencing to minimize weighted tardiness”. Its decision problem can be described as follows Garey and Johnson (1979):

Given a set T of tasks, for each task $t \in T$ a length $l(t) \in \mathbb{Z}^+$, a weight $\omega(t) \in \mathbb{Z}^+$, and a deadline $d(t) \in \mathbb{Z}^+$, and a positive integer N, is there a one-processor schedule σ for T such that the sum, taken over all $t \in T$ satisfying $\sigma(t) + l(t) > d(t), of\ (\sigma(t) + l(t) - d(t) \cdot\ \omega(t) is\ N\ or\ less$?

Here, T maps to J in problem **P**, *l(t)* to R_j, $\omega(t)$ to ω_j, and *d(t)* to $DD_j - ET$. According to Garey and Johnson (1979), the decision problem of "sequencing to minimize weighted tardiness" is NP-complete in the strong sense. Therefore, the corresponding optimization problem is strongly NP hard. Such optimization problem is a special case, i.e., a restricted version, of our original problem **P**. We thus conclude that problem **P** is also strongly NP hard.

As Theorem 1 shows, the proposed MILP problem is NP-hard, which shows the worst case scenarios. To show the computational complexity of the problem in real cases, we generated random test cases, and solve them using Gurobi MILP solver in a computer with Intel Core i5-3317U CPU @ 1.70 GHz, 4.00 GB memory installed, and 64-bit operating system. In this test, we focus on three networks of project size $|J|$ (Test 1), activity number $|A|$ (Test 2), and non-renewable resource number $|L|$ (Test 3); the value of each test is shown in Table 3.1, and other parameters are shown in Table 3.2 (which generated in accordance with the real-world case).

Table 3.1

Parameters of Test 1 – 3 for computational time.

Test 1	**Test 2**	**Test 3**
$\boldsymbol{|J| \in \{3, 4, 5, 6, 7\}}$	$|A| \in \{5, 6, 7, 8, 9\}$	$|L| \in \{5, 10, 15, 25\}$
$\boldsymbol{a = 5}$	$j = 3$	$j = 3$
$\boldsymbol{l = 5}$	$l = 5$	$a = 5$

In Test 1, we set both the activity number and the non-renewable resource number equal to 5, while project size changes from 3 to 7. The same as Test 1, we test the activity number from 5 to 9, while make the project size equals to 3 and the non-renewable resource number equals to 5 in Test 2. In Test 3, we also keep the project size equals to 3 and the activity number equals to 5, testing the non-renewable resource number from 5 to 25. For the three tests, we observe the results within a CPU time limit of 5 hours for the Test 1 and 2 hours for the Test 2 and 3. Figure 3.2 – 3.4 below illustrate the computational time in accordance with Test 1 – 3.

Table 3.2

Other parameters for computational time.

Parameters	**Data Range of Parameters**
Types of renewable resources	$k \sim uniform\ (5, 10)$
Review duration of the project	$R_j \sim uniform\ (1, 5)$
Project due time	$DD_j = 0$
Activity's duration	$P_a \sim uniform\ (10, 30)$
Demand of non-renewable resource	$Q_{jk} \sim uniform\ (10, 100)$
Suppliers for one type of non-renewable resource	$s \sim uniform\ (3 * project\ size, 5 * project\ size)$
Supplier's capacity	$C_s \sim uniform\ (300, 600)$
Supplier's release time	$R_s \sim uniform\ (10, 20)$
Unit cost from supplier to project	$c_{sj} \sim uniform\ (8, 12)$

Shipping time from supplier to project	$\tau_{sj} \sim uniform\ (1, 7)$

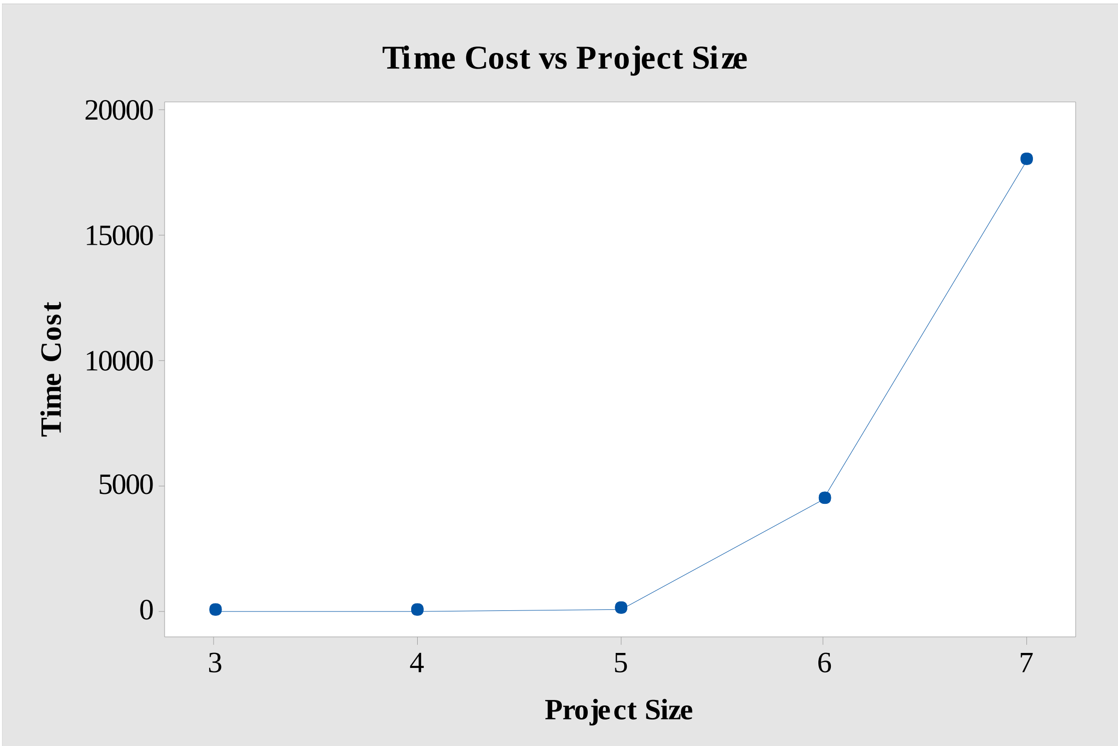

Figure 3.2 Parameter of project size and its computational time.

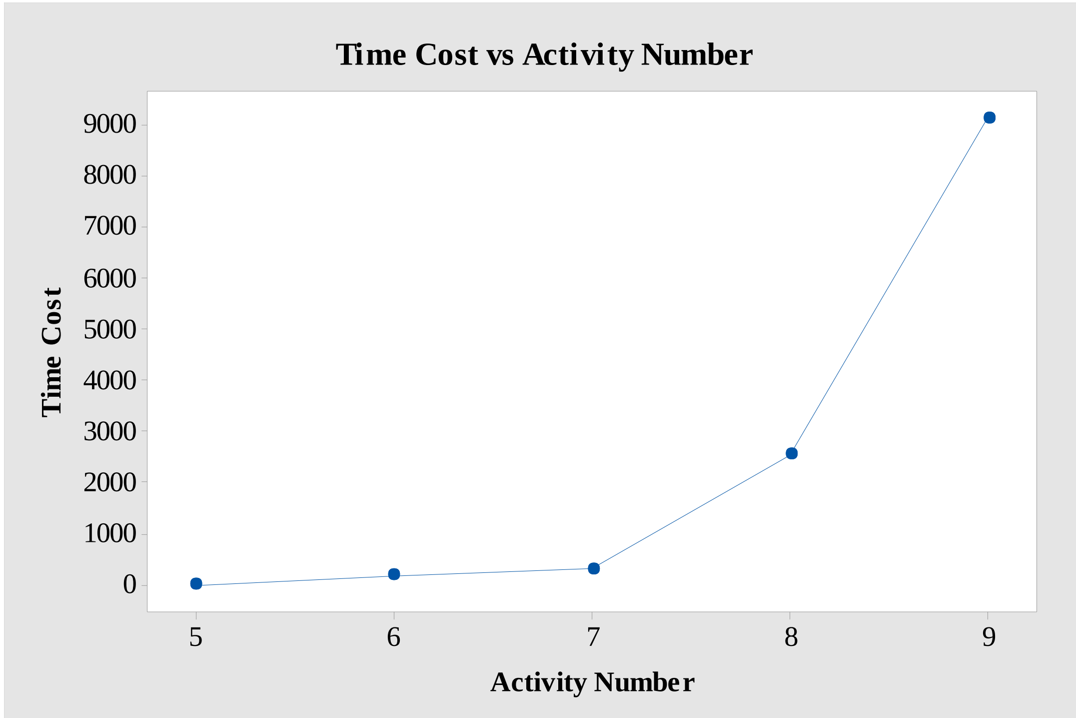

Figure 3.3 Parameter of activity number and its computational time.

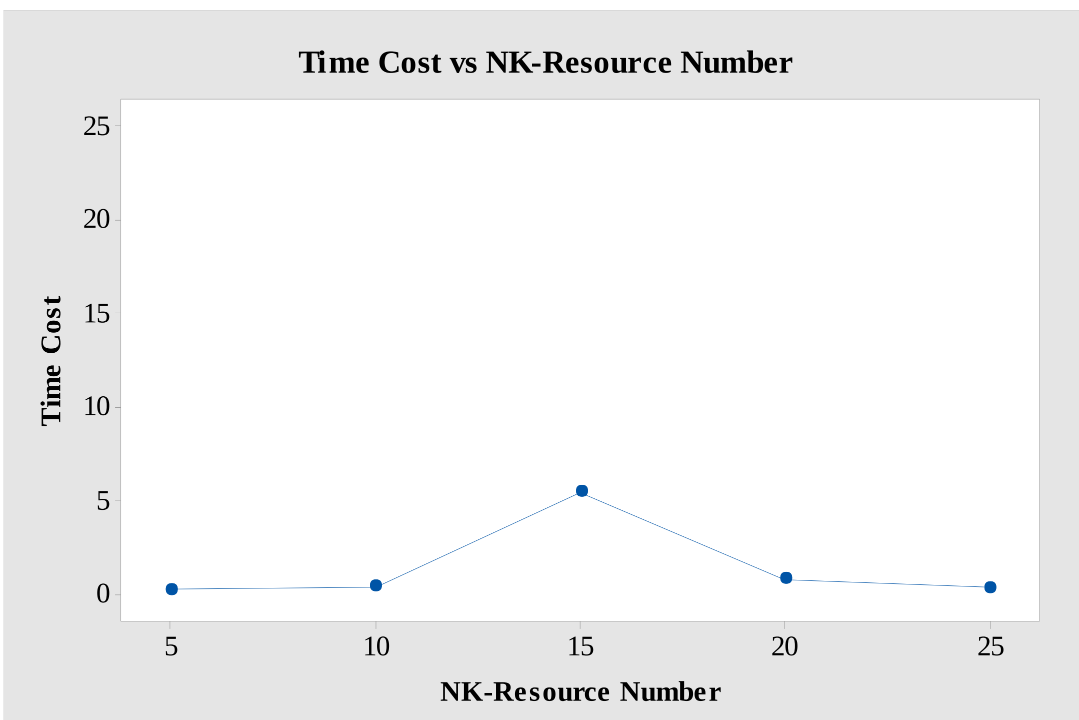

Figure 3.4 Parameter of non-renewable resource number and its computational time.

Figure 3.2 – 3.4 report the results of the impact of project size, activity number, and non-renewable resource on the computational time (in CPU seconds). In Figure 3.2, the curve increases intensely from the point of the project size is equal to 6 until the project size is equal to 7 where the computational time is over 5 hours CPUT time. In Figure 3.3, we can see that the computational time dramatically increases when the activity number is equal to 8, using about 2500 CPU seconds; when the activity number is equal to 9, the computational time is over 9000 CPU seconds. The scatterplot line in Figure 3.4 is smooth with the computational time range from 0.2 to 5.5 CPU seconds. According to the results, we conclude that the project size and the activity number are the most influential parameter to the computational time.

Chapter 4

Heuristic Solution Approach

In this chapter, we first discuss the structure of sub-problems of problem **P**. Naturally, the problem can be decomposed into three easier sub-problems, namely, supplier selection, project activity scheduling, and project review sequencing (as presented in Figure 4.1). Subsequently, we develop a mathematical programming-based heuristic for solving this problem, exploring the special structure.

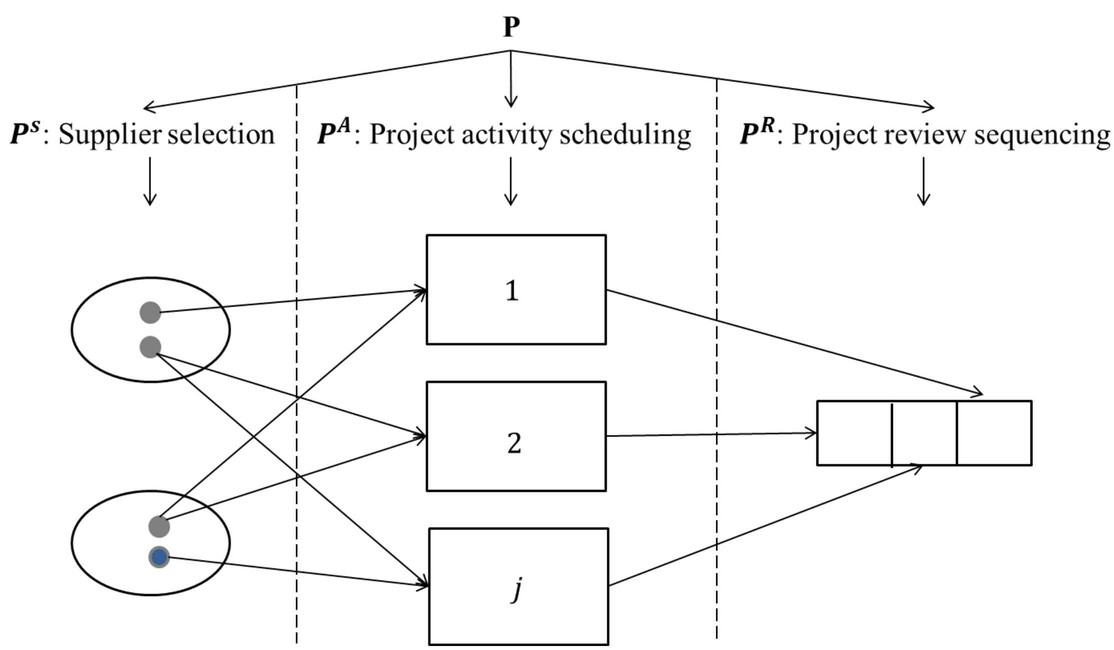

Figure 4.1 Sub-problems of problem **P**.

It is observed that, for each project $j \in J$, once the supplier for each required non-renewable resource $k \in K(j)$ is determined, the earliest available time of resource k for project j, AT_{kj}, can be easily computed. Given AT_{kj}, the subproblem is then to schedule the activities for each project. Without considering the downstream project review sequencing, the project activity scheduling can be decomposed in to $|J|$ independent problems. That is, for each project j, we solve the following MILP. The objective is to minimize the completion time of this project.

$$\min CT_j \tag{19}$$

$$ST_a \geq AT_{kj} \qquad \forall k \in K(a), a \in A(j) \tag{20}$$

$$ST_a + P_a \leq ST_b \qquad \forall a, b \in E(j) \tag{21}$$

$$ST_a + P_a - M \cdot (1 - y_{ab}) \leq ST_b \qquad \forall a, b \in AL(l), a \neq b, l \in L(j) \tag{22}$$

$$ST_b + P_b - M \cdot y_{ab} \leq ST_a \qquad \forall a, b \in AL(l), a \neq b, l \in L(j) \tag{23}$$

$$CT_j \geq ST_a + P_a \qquad \forall a \in A(j) \tag{24}$$

This project activity scheduling sub-problem, denoted as $\mathbf{P^A}$, is much easier to solve due to the reduced size. The main difficulty of solving sub-problem $\mathbf{P^A}$ lies in the sequencing to avoid conflicts for the shared renewable resources, captured by Eqs. (22) and (23). In practice, each non-renewable resource is shared among a subset of activities, whose size is much smaller than the full set of activities for each project. For example, some activities in interior systems require the workers who specialized construction craft, such as floor and wall installation. In that case, we can first drop Eqs. (22) and (23), and solve the remaining problem, which is a LP problem, using linear programming or the critical path method (CPM) (Rardin, 1998). Then, based on the critical path and schedule slack (the gap between the earliest and latest start time for each activity), we can make minor adjustments of the schedule to resolve the conflict of shared non-renewable resources.

Once the earliest activity completion time for each project, CT_j, is determined, the downstream project review sequencing sub-problem, denoted as $\mathbf{P^R}$, is then to optimize the review sequence of the projects. This sub-problem is captured by the following MILP.

$$\min \sum_{j \in J} \omega_j \cdot TD_j \tag{25}$$

$$TD_j \geq DT_j - DD_j \qquad \forall j \in J \tag{26}$$

$$DT_j \geq CT_j + R_j \qquad \forall j \in J \tag{27}$$

$$DT_j \geq DT_i - M \cdot \left(1 - z_{ij}\right) + R_j \qquad \forall i, j \in J, i \neq j \tag{28}$$

$$\sum_{i \in \{0\} \cup J, i \neq j} z_{ij} = 1 \qquad \forall j \in J \tag{29}$$

$$\sum_{j \in J} z_{0j} = 1 \tag{30}$$

$$\sum_{j \in J, j \neq i} z_{ij} \leq 1 \qquad \forall i \in J \tag{31}$$

As shown in the proof of Theorem 1, this sub-problem is NP hard. For large-scale problems, heuristics can be developed to solve this sub-problem efficiently. Such heuristics include, but are not limited to, genetic algorithm (Mitchell, 1998), tabu search (Cvijovi´c and Klinowski, 1995), ant colony optimization (Dorigo et al., 1999), and nested partitions (Chen and Shi, 2013).

The following proposition serves as a formulation for the proposed heuristic.

Proposition 2. *Given a feasible supplier selection for all projects (fixing x_{sj}), the earliest available time of each resource for each project, $AT_{kj}, \forall k \in K(j), j \in J$, is then subsequently fixed. Then, the following two approaches result in the same objective value.*

1. Solve problem $\boldsymbol{P}$ *with* x_{sj} *fixed. Denote the optimal objective in Eq. (1) as* TTD^*.

2. First, solve sub-problem$\boldsymbol{P^A}$ *(19) – (24) for each project* $j \in J$ *given* AT_{kj}*, and obtain the earliest activity completion time for each project j,* CT_j^**; next, solve sub-problem* $\boldsymbol{P^R}$ *(25) – (31) by setting* $CT_j = CT_j^*$*. Denote the optimal objective value in Eq. (25) as* TTD'.

That is, $TTD^* = TTD'$.

Proof. The proof of this proposition is simple. Given a fixed supplier selection solution, denote the completion time of all activities for project *j* in the optimal solution of problem **P** as $\widetilde{CT}_J$. Obviously, $\widetilde{CT}_J \geq CT_j^*$ for all $j \in J$, since $CT_{\hat{j}}^*$ is the earliest possible activity completion time for project *j* given AT_{kj}. Therefore, the optimal objective value of subproblem $\mathbf{P^R}$ (25) – (31) with given $CT_j = CT_j^*$ is no worse than that of $\mathbf{P^R}$ with $CT_j = \widetilde{CT}_J$. Notice that the former objective value is TTD', while the latter is TTD^*. That is, $TTD' \leq TTD^*$. On the other hand, the solution correspondent toTTD' is a feasible solution of problem **P**, resulting $TTD' \geq TTD^*$. Hence, $TTD^* = TTD'$.

Proposition 2 states that if a feasible supplier selection is determined, solving the remaining problem **P** is equivalent to solving J subproblems $\mathbf{P^A}$ and then sub-problem $\mathbf{P^R}$. The benefit of the latter approach is that each subproblem is much smaller in size than the original problem **P**, and thus the computational time can be substantially less when the problem size is large. However, the difficulty remains that different supplier selection solution may result in different AT_{kj}, and subsequently impacts the results of project activity scheduling and project review sequencing. Intuitively, when multiple projects require a same non-renewable resource, it may be beneficial for some projects to receive the resource as early as possible, since the activity that requires this resource may be on the critical path for these projects. While for some other projects, time to receive the resource may not be as critical since it will be used in the later stage of the project. Hence, the coordinated supplier selection can optimally choose the supplier for each resource of each project according to the urgency of receiving the resource, as well as the quantity and cost.

The following proposition provides a basic rule on selecting suppliers for each resource of each project.

Proposition 3. *Given two feasible supplier selection solutions, x_{sj}^1 and x_{sj}^2, denote their respective earliest available time for resource k of project j as AT_{kj}^1 and AT_{kj}^2, for all $k \in K(j), j \in J$. If $AT_{kj}^1 \leq AT_{kj}^2$ for all $k \in K(j), j \in J$ and $AT_{kj}^1 < AT_{kj}^2$ for at least one set of index (k, j), the optimal objective value in Eq.* (1) *obtained by solving problem* $\boldsymbol{P}$ *with $x_{sj} = x_{sj}^1$ (denoted as TTD^1) is no worse than that obtained by solving* $\boldsymbol{P}$ *with $x_{sj} = x_{sj}^2$ (denoted as TTD^2).*

Proof. According to Proposition 2, TTD^1 and TTD^2 can be obtained alternatively using the second approach in Proposition 2 by setting $AT_{kj} = AT_{kj}^1$ and $AT_{kj} = AT_{kj}^2$, respectively. For any project $j \in J$, since $AT_{kj}^1 \leq AT_{kj}^2$ for all $k \in K(j)$, it is seen that $CT_j^{1*} \leq CT_j^{2*}$ by solving sub-problem $\mathbf{P^A}$ with $AT_{kj} = AT_{kj}^1$ and $AT_{kj} = AT_{kj}^2$ for all $k \in K(j)$, respectively. Here, CT_j^{1*} and CT_j^{2*} are the earliest activity completion time for project j in Eq. (25). It follows readily that $TTD^1 \leq TTD^2$, by solving sub-problem $\mathbf{P^R}$ with $CT_j = CT_j^{1*}$ and $CT_j = CT_j^{2*}$, respectively.

According to Proposition 3, supplier selections solution x_{sj}^1 is dominated by x_{sj}^2. Or equivalently, AT_{kj}^1 is dominated by AT_{kj}^2. Therefore, we only need to search among those supplier selection solutions x_{sj} such that the resulting AT_{kj} is not dominated. Consequently, we construct a problem as follows, which is a multiobjective optimization problem.

$$\min AT_{kj} \qquad \forall j \in J, k \in K(j) \tag{32}$$

$$\textstyle\sum_{j \in J} q_{sj} \leq C_s \qquad \forall s \in S(k) \tag{33}$$

$$\textstyle\sum_{s \in S(k)} q_{sj} \geq Q_{jk} \qquad \forall j \in J, k \in K(j) \tag{34}$$

$$q_{sj} \leq \mathrm{M} \cdot x_{sj} \qquad \forall s \in S(k), k \in K(j), j \in J \tag{35}$$

$$\textstyle\sum_{s \in S(k)} x_{sj} = 1 \qquad \forall j \in J, k \in K(j) \tag{36}$$

$$\textstyle\sum_{s \in S(k)} r_s + \tau_{sj} \cdot x_{sj} \leq AT_{kj} \qquad \forall j \in J, k \in K(j) \tag{37}$$

$$\textstyle\sum_{j \in J} \sum_{s \in S(k)} c_{sj} \cdot q_{sj} \leq B \tag{38}$$

Furthermore, the weighted sum method can be used to convert the multiple objectives in Eq. (32) into a single objective (Miettinen, 1999):

$$\min \sum_{j \in J} \sum_{k \in K(j)} r_{kj} AT_{kj} \tag{39}$$

where $r_{kj} > 0, \forall j \in J, k \in K(j)$, and $\sum_{j \in J} \sum_{k \in K(j)} r_{kj} = 1$. Further called the problem (33) – (39) the supplier selection sub-problem $\mathbf{P^S}$.

Theorem 4. *There exist a set of weights* $r_{kj}^* > 0$ *for all* $j \in J, k \in K(j)$, *where* $\sum_{j \in J} \sum_{k \in K(j)} r_{kj}^* = 1$, *such that the optimal solution of problem* $\boldsymbol{P}$ *can be obtained using the following approach:*

1. *Solve sub-problem* $\boldsymbol{P^S}$ (33) – (39), *with* $r_{kj} = r_{kj}^*$ *for all* $j \in J, k \in K(j)$. *Denote* AT_{kj}^* *the optimal solution obtained.*
2. *For each project* $j \in J$, *solve subproblem* $\boldsymbol{P^A}$ (19) – (24), *with* $AT_{kj} = AT_{kj}^*$ *for all* $k \in K(j)$. *Denote* CT_j^* *the optimal solution obtained.*
3. *Solve sub-problem* $\boldsymbol{P^R}$ (25) – (31), *with* $CT_j = CT_j^*$ *for all* $j \in J$.

Proof. Since the feasible region of the multi-objective optimization problem (32) – (38) is convex, any element of the optimal Pareto frontier of the problem can be found by changing the weights r_{kj} in the corresponding single-objective optimization problem $\mathbf{P^S}$ (33) – (39) (Miettinen, 1999). That is, any non-dominated set of AT_{kj} can be found by changing the weights r_{kj} and solve problem $\mathbf{P^S}$. Form Proposition 3, there exist a set of weight r_{kj}^*, whose corresponding solutions of problem $\mathbf{P^S}$ are denoted as AT_{kj}^* and x_{sj}^*, such that the optimal solution of problem **P** can be obtained by solving **P** with $x_{sj} = x_{sj}^*$. On the other hand, from Proposition 2, solving **P** with $x_{sj} = x_{sj}^*$ is equivalent to executing steps 2 and 3 of the above approach with $AT_{kj} = AT_{kj}^*$. The theorem is therefore proved.

Based on the above theoretical results, we now propose a heuristic algorithm to efficiently solve problem **P**.

The basic idea of Algorithm 1 is to heuristically improve the weights r_{kj} iteratively, and hopefully when the algorithm stops, r_{kj} will be close to r_{kj}^* in Theorem 4. Eq. (40) holds the key for a heuristic search toward r_{kj}^*. The shadow price pr_j^l represents the impact of each unit of decrease in CT_j^l on the decrease in TTD^l; if $pr_{kj}^l = 0$, decreasingCT_j^l does not change TTD^l, indicating that it is less important to minimize AT_{kj}^l for all $k \in K(j)$ in subproblem $\mathbf{P^S}$. Similarly, the maximum shadow price $\max_{a \in A(j)} pa_{akj}^l$ represents the impact of each

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Algorithm 1 A heuristic for solving problem **P**

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1. Set iteration counter $\boldsymbol{l = 1}$. Set weights $\boldsymbol{r_{kj}^l = 1}$ for all $\boldsymbol{j \in J, k \in K(j)}$ and normalize $\boldsymbol{r_{kj}^l}$ such that $\boldsymbol{\sum_{j \in J} \sum_{k \in K(j)} r_{kj}^l = 1}$. Set $\boldsymbol{d_1}$ and $\boldsymbol{d_2}$.
2. Given $\boldsymbol{r_{kj}^l}$, solve three subproblem sequentially as follows.

   (a) Solve sub-problem $\mathbf{P^S}$ (33) – (39), with $\boldsymbol{r_{kj} = r_{kj}^l}$ for all $\boldsymbol{j \in J, k \in K(j)}$. Obtain the resulting optimal solution of variables $\boldsymbol{AT_{kj}}$ for all $\boldsymbol{k \in K(j), j \in J}$, denoted as $\boldsymbol{AT_{kj}^l}$.

   (b) For each project $\boldsymbol{j \in J}$, solve subproblem $\mathbf{P^A}$ (19) – (24), with $\boldsymbol{AT_{kj} = AT_{kj}^l}$ for all $\boldsymbol{k \in K(j)}$. Obtain the resulting optimal solution of variables $\boldsymbol{CT_j}$ for all $\boldsymbol{j \in J}$, denoted as $\boldsymbol{CT_j^l}$. Then, fix all integer variables to the optimal values attained, resolve the remaining LP and record the shadow price for each

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constraint (20), denoted as $\boldsymbol{pa_{akj}^l}$.

(c) Solve sub-problem $\mathbf{P^R}$ (25) –(31), with $\boldsymbol{CT_j = CT_j^l}$ for all $\boldsymbol{j \in J}$. Obtain the resulting optimal objective value, denoted as $\boldsymbol{TTD^l}$. Then, fix all integer variables to the optimal values attained, resolve the remaining LP and record the shadow price for each constraint (27), denoted as $\boldsymbol{p_j^l}$.

3. If stop criteria are reached, e.g., the optimal objective value $\boldsymbol{TTD^l}$ has not improved for the past $\boldsymbol{M}$ generations, output the optimal solution and exit; otherwise, continue to the next step.

4. Update weights as follows.

$$\boldsymbol{r_{kj}^{l+1} = r_{kj}^l \left(1 + d_1 (d_2 + pr_j^l) \max_{a \in A(j)} pa_{akj}^l \right)} \qquad (\mathbf{40})$$

where $\boldsymbol{d_1 > 0}$ and $\boldsymbol{d_2 \geq 0}$. Normalize $\boldsymbol{r_{kj}^{l+1}}$. Set $\boldsymbol{l \leftarrow l + 1}$, and got to step 2.

---

unit of decrease in AT_{kj}^l on the decrease in CT_j^l; if $\max_{a \in A(j)} pa_{akj}^l = 0$, decreasing AT_{kj}^l does not decrease CT_j^l, indicating that it is not critical to minimize AT_{kj}^l in subproblem $\mathbf{P^S}$. Therefore, in Eq. (40), if $\max_{a \in A(j)} pa_{akj}^l > 0$, the corresponding weight r_{kj}^l will be increased in the next iteration, emphasizing the importance of minimizing AT_{kj}. This weight increase is further boosted if $pr_j^l > 0$. In our experiments, we set $d_1 = 100$ and $d_2 = 0.1$.

4.1. Numerical Experiments

We studied the impact of three types of networks: those with different project sizes, activity numbers, and non-renewable resource types on the computational performance of the Gurobi solver in Chapter 3. In this section, we focus on the project size and the activity number to observe their computational performance of the proposed heuristic approach, and compare the performance with the Gurobi optimizer. The parameter values are summarized in Table 3.2.

4.1.1. Performance of Projects and Activities with Small Sizes Networks

When the performance of project size is tested, we fix the numbers of activities at $a = 5$ and the types of non-renewable resources at $l = 5$. In this case, when the project sizes are small, i.e., $|J| \leq 6$, the Gurobi solver is able to find the optimal solution within the given CPU time limit of 3600 seconds; whereas, when the project sizes are relatively large, i.e., $|J| \geq 7$, the Gurobi solver fails to find the optimal solution within the time limit. In contrast, the proposed heuristic approach is able to find the optimal solution within 3600 seconds CPU time until the project size is as large as $j = 16$. Furthermore, the derived objective value of the proposed heuristic approach is same as that of the Gurobi solver when $|J| \leq 15$. Figure 4.2 reports an example, which makes a comparison of the computational time (the average result of five tests) between the proposed heuristic approach and the Gurobi solver of sizes $j = \{3, 4, 5, 6, 7 ,8 \}$. The results of the example illustrate that as the project size $|J|$ increases, the required CPU time of the proposed heuristic approach are minimal, while the Gurobi solver increases intensely.

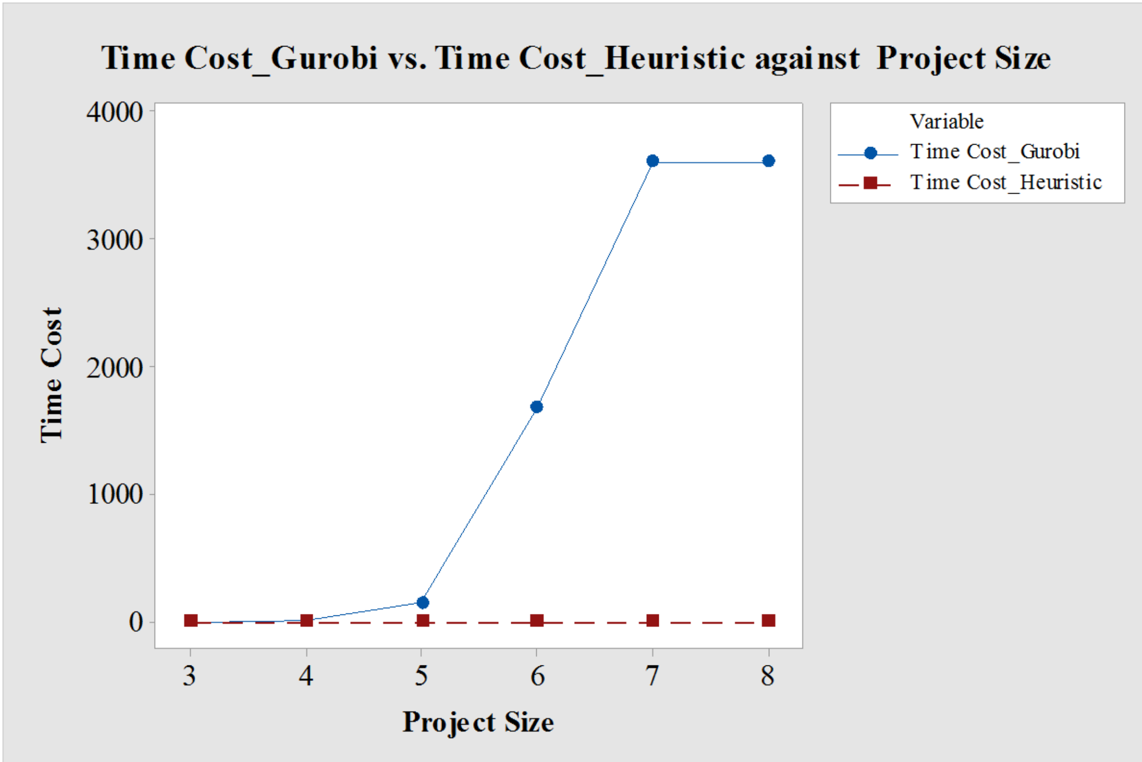

Figure 4.2 Computational time of the proposed heuristic approach and GUROBI against project sizes.

We also investigate the impact of activity numbers on the computational performance of the proposed heuristic approach and the Gurobi solver. In this case, we fix the sizes of projects at $j = 3$ and the types of non-renewable resources at $l = 5$. According to the results of the experiment (the average result of five tests), we conclude that the Gurobi solver fails to find the optimal solution within 3600 seconds of CPU time limit when the numbers of activities $a \geq 8$. However, the proposed heuristic approach is able to find the best optimal solution as the Gurobi solver does within the time limit when the activities $a = 15$. The tests with the activities $a = \{5, 6, 7, 8, 9, 10\}$ are used to illustrate the computational time of the proposed heuristic approach and the Gurobi solver, which is shown in Figure 4.3. As we can see, the computational time of the proposed heuristic approach remains shortly, while the computational time of the Gurobi solver increases sharply when the number of activities is equal to 8.

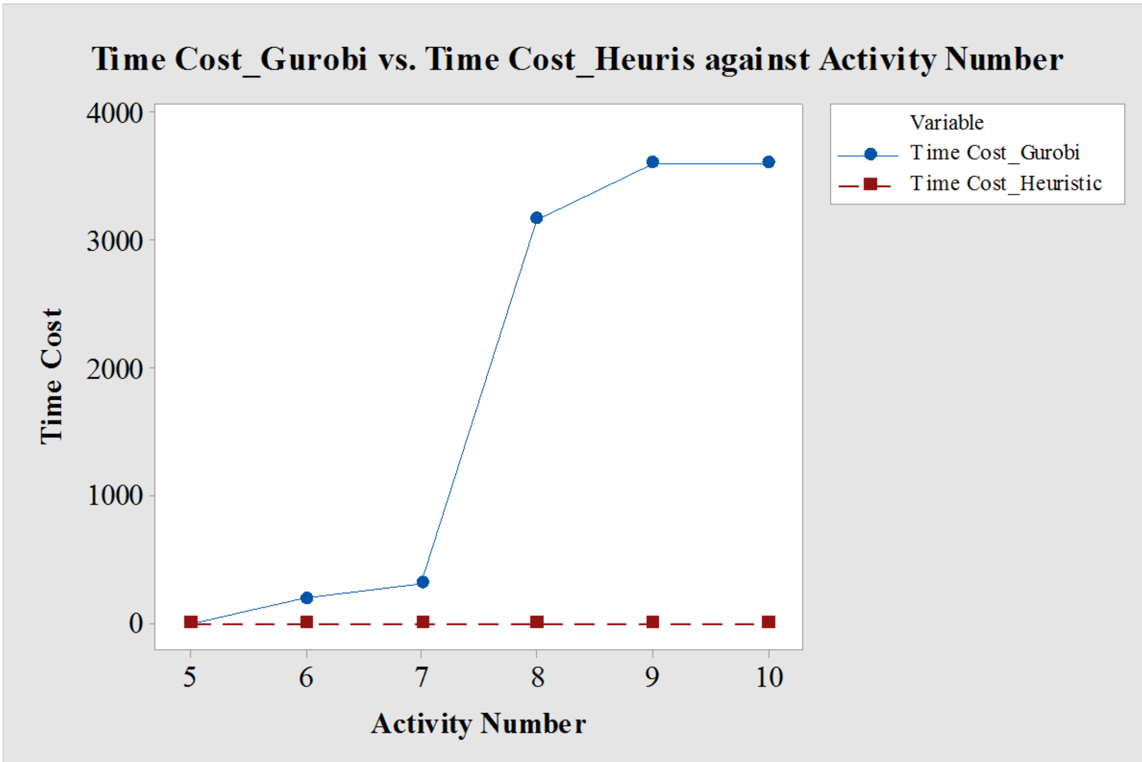

Figure 4.3 Computational time of the proposed heuristic approach and GUROBI against activity numbers.

4.1.2. Performance of Projects and Activities with Larger Sizes Networks

For the relatively larger sizes of projects, we conduct the tests with the project sizes of $j = \{5, 10, 15, 20, 25\}$ and the activity numbers of $a = \{5, 7, 9, 11\}$. In this case, we compare the computational time and the derived gap of the two methods within 3600 seconds CPU time limit. The *empirical error gaps (EEG)* are collected and used to measure the performance, which can be defined as

$$EEG = \frac{(G^H - G^*)}{G^*} \times 100\%$$

where G^H and G^* stand for the best objective value obtained by the proposed heuristic approach and the Gurobi solver within 3600 seconds of CPU time limit, respectively. The results of the experiment are shown in Table 4.1 – 4.4, which demonstrates the performance of the network with $|J| \in \{5, 10, 15, 20, 25\}$ when the numbers of activities of $a = 5, a = 7, a = 9,$ and $a = 11$, respectively.

Table 4.1

Performance of the project networks with the activities $a = 5$.

$(\boldsymbol{a} = \mathbf{5})$	**EEG**		**CPU time (seconds)**		
$\boldsymbol{\lvert J \rvert}$	Average	Standard Deviation	Average (G)	Average (H)	Standard Deviation (H)
5	0.00%	0.00%	192.08	1.77	0.06
10	0.00%	0.00%	3600.36	2.42	0.06
15	-0.20%	0.26%	3600.89	8.89	0.86
20	-0.60%	0.40%	3601.41	205.15	0.13
25	-4.11%	1.48%	3601.74	248.49	56.62

Table 4.2

Performance of the project networks with the activities $a = 7$.

$(\boldsymbol{a} = \mathbf{7})$	**EEG**		**CPU time (seconds)**		
$\lvert\boldsymbol{J}\rvert$	Average	Standard Deviation	Average (G)	Average (H)	Standard Deviation (H)
5	0.00%	0.00%	3751.62	2.00	0.12
10	-0.03%	0.04%	4241.33	2.61	0.09
15	-0.34%	0.58%	3601.57	7.23	0.56
20	-1.89%	2.18%	3602.21	247.24	55.99
25	-3.67%	1.63%	3602.37	292.63	46.54

Table 4.3

Performance of the project networks with the activities $a = 9$.

$(\boldsymbol{a} = \mathbf{9})$	**EEG**		**CPU time (seconds)**		
$\lvert\boldsymbol{J}\rvert$	Average	Standard Deviation	Average (G)	Average (H)	Standard Deviation (H)
5	0.00%	0.00%	3798.05	3.74	0.15
10	-0.45%	0.51%	3672.07	7.44	0.55
15	-3.35%	1.79%	3601.61	47.22	5.51

20	-5.28%	1.02%	3602.11	209.55	0.90
25	-6.89%	1.89%	3602.26	276.99	58.16

Table 4.4

Performance of the project networks with the activities $a = 11$.

($\boldsymbol{a = 11}$)	**EEG**		**CPU time (seconds)**		
$\boldsymbol{\lvert J \rvert}$	Average	Standard Deviation	Average (G)	Average (H)	Standard Deviation (H)
5	0.00%	0.00%	3600.22	2.82	0.12
10	-1.93%	0.93%	3600.80	38.46	4.68
15	-5.86%	0.91%	3601.77	156.30	41.18
20	-9.69%	1.28%	3602.05	424.78	3.29
25	-10.28%	2.51%	3602.45	463.78	93.6

As the Table 4.1 – 4.4 shown, the proposed heuristic approach is able to find the better optimal solution compared to the Gurobi solver within the time limit. In addition, the computational time of the proposed heuristic approach increases constantly as the sizes of the projects increase, and it is significantly less than the computational time of the Gurobi solver.

To be better illustrating the performance of the proposed heuristic approach and the commercial solver against the activity numbers, we summarize the results of the average empirical error gaps $|G^H - G^*|/G^*$ in Figure 4.4 as shown below. According to the figure, we note that the empirical error gap increases when the activity numbers and the project sizes increase.

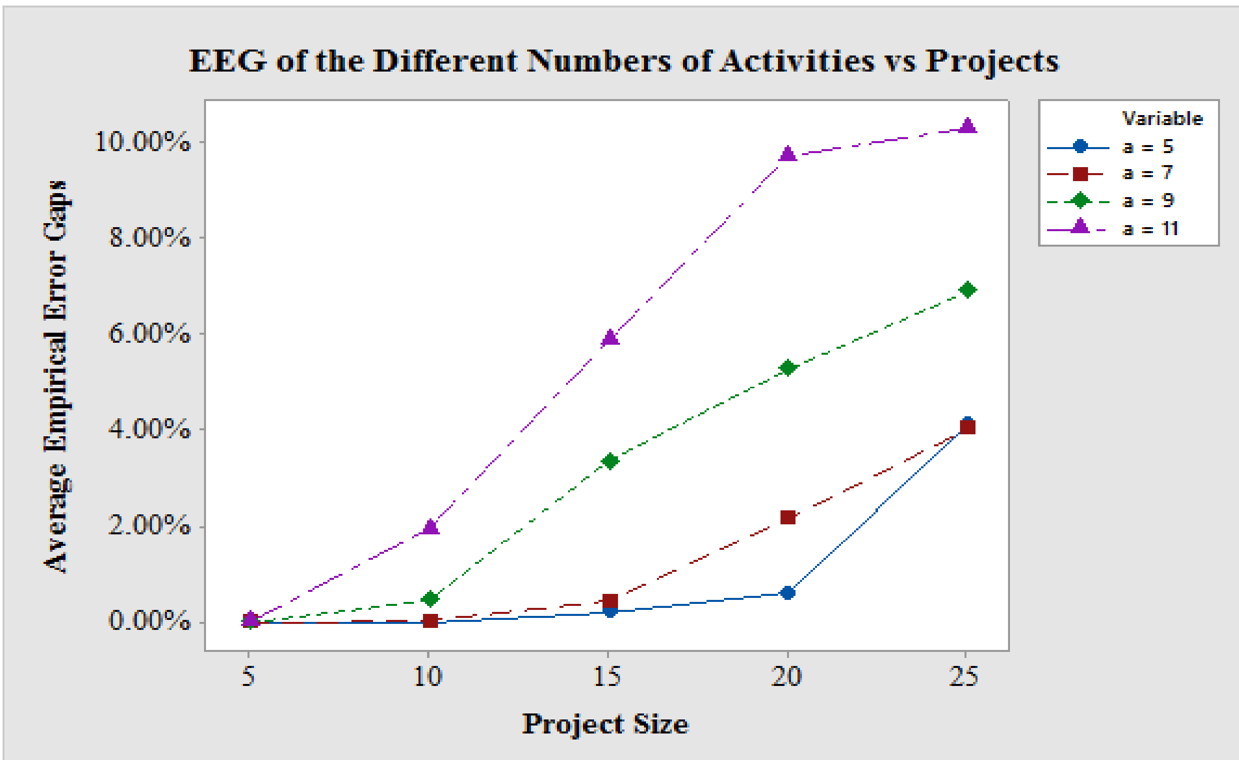

Figure 4.4 Average empirical error gaps of different activities.

Chapter 5

A Study on Project Scheduling Policies under Uncertainty

In Chapters 3 and 4, we study a project management and supply chain management integrated problem of resource-dependent project network with final project review sequencing on the tactical and operational levels. In contrast to the traditional management approach – in which projects are assigned to different project managers and managed on a one-for-one basis – the new problem proposes that projects share non-renewable resource suppliers and that they are managed as a network in a collaborative way. All the studies in the previous chapters are based on deterministic information. That is, all the activity durations, supplier shipping times, and project review times are known as constant values. However, in real project management practices, these are rarely the case. For example, defective work or additional machinery and material needed to complete task can cause a delay of the activity duration (Chester & Hendickson, 2005). Therefore, it is critical to study the impact of uncertainty to project management, and find optimal policies for some important cases.

In this chapter, we will extend our problem toward two directions in strategic terms. First, we examine two project review assignments: the batch mode slot assignment and the sequential mode slot assignment under two policies that either work with collaboration or work without collaboration. Second, we will propose a strategy for resource allocation based on time-resource tradeoff problem with uncertain activity durations. This strategy can be used to provide project managers with the incentive to improve the project performance when they encountered such problem. Findings of these two problems will be discussed in Chapter 5.1 and 5.2, respectively. Note that the projects discussed in this chapter are applicable to the construction projects mentioned in the previous chapters, but can be extended beyond the construction industry. For example, in a concurrent computing system with *n* parallel processors; projects submitted to each processor are processed locally on a first-come-first-serve basis, and, as a result, each has an expected due time d_i. The processing of a project requires the use of both a local resource (e.g., CPU and I/O) and a system resource (e.g., communication bandwidth). One issue with the management of such a system is how to allocate the bandwidth to projects to minimize the total delay in computation and communication (Lee & Lei, 2001).

5.1. Project Review Scheduling with/without Collaboration

In this chapter, we investigate the impact of inter-project collaboration for project review scheduling. Recall that, in Chapter 3, each project is subject to final quality inspection (or review) after the initial completion of all activities of this project. In Chapter 3, the final review is scheduled based on the predicted time of project initial completion times, since all activity durations and review durations are known and unchanged. In this chapter, the uncertainty in activity durations will be taken into consideration. Furthermore, we consider two types of project review assignments: the batch mode slot assignment and the sequential mode slot assignment. In other words, for each assignment, we will make a comparison of both policies based on the project review time, that is, the difference between the project initial completion time (the time when all activities are completed) and the project final delivery time (the time when the project passes the final quality review).

To this end, the final project completion time is affected by three primary points: (1) project start time, (2) project duration, and (3) project review time. The project start time is determined by the latest arrival time of required non-renewable resources, which includes the supplier's release time and transportation time between the supplier and the project site. The project duration consists of multiple activities that are determined by the activities' precedence and the random activity duration depicted by certain probability distribution. Finally, the project review time is subject to the chosen policy, either with collaboration or without collaboration. A specific description is given in Section 5.1.1 and 5.1.2, respectively. A simulation study in MS-EXCEL is used for performing the experiments. One of the most important elements of this technique is to identify appropriate probability distribution for the input data. In this case, both uniform distributions and normal distributions are used, according to the expert's judgment.

5.1.1. Batch Mode Slot Assignment

In practice, all the completed projects need to be reviewed by the Quality Inspection Committee and only those projects that qualify can be submitted to the client. When a number of projects finish at about the same time, the review time has to be considered more carefully. After all, an efficient review scheduling method can reduce the total completion time of the project. In this case, we will consider that several projects are completed during the same period of time, and some of them are located close to each other; under those conditions, they can be reviewed together by one Quality Inspection

Committee. Under the no-collaboration policy, every project has a designated review slot with a specific review starting time. If the project cannot be reviewed at the review starting time, the designated review slot is wasted, and that project has to be reviewed along with a slot of late projects at a later date. In contrast, with the collaboration policy in place, whenever a project is completed it can be reviewed at the next available review starting time, in the corresponding slot. Figure 5.1 illustrates the batch mode slot assignment in detail in an example. There are 15 projects in total, and every 5 projects are assigned to one batch mode slot (the Quality Inspection Committee).

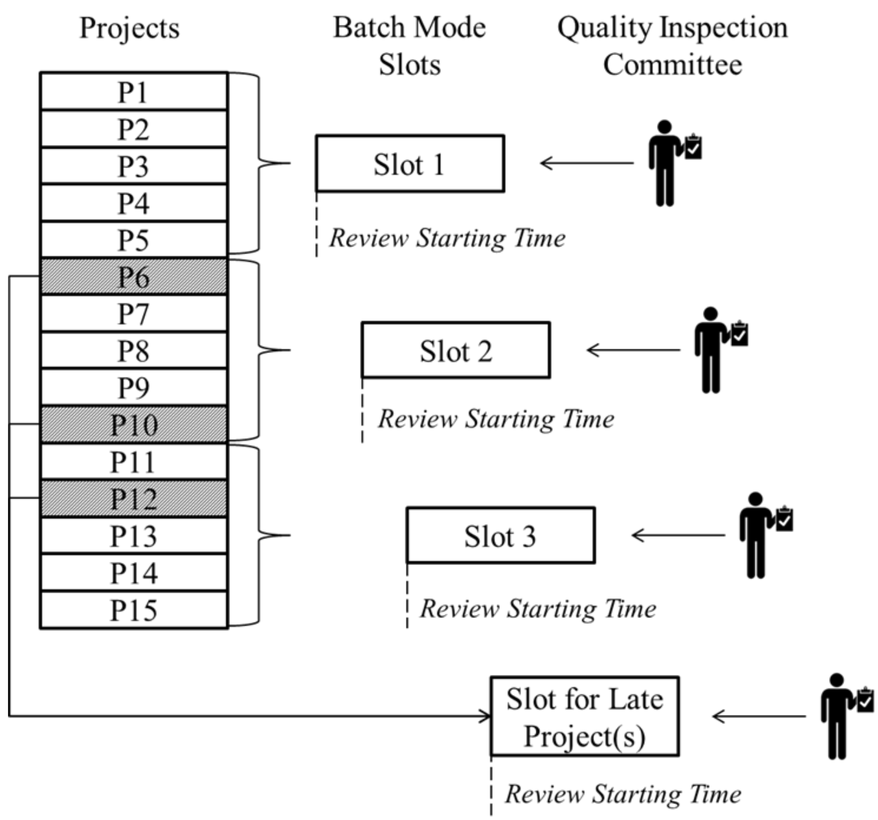

Figure 5.1 Batch mode slot assignment (3 slots and 5 projects are designated in one slot).

The procedures we use for simulating the projects are described below, based on the project network with 25 projects. In addition, two Project Review Committees are assumed to review the 25 projects.

Step 1. Identify project start time ST_j.

List all types of nonrenewable resources $k, k \in K$ and all the suppliers $s, s \in S$ for each type of resource. Given the release time r_s for each supplier, randomly generate the transportation time τ_{sj} from supplier s to project $j, j \in J$ follow uniform distribution. Calculate the sum of the release time and the transportation time $r_s + \tau_{sj}$. Since we assume that any supplier's capacity is sufficient, we randomly choose one sum from every type of resource k as the arrival time of the correspondent resource $k, k \in K$. Determine the latest arrival time, i.e. $\max(r_s + \tau_{sj})$, for all types of resources as the corresponding project start time ST_j.

Step 2. Calculate project completion time P_j.

Given a precedence of activities $a, a \in A(j)$ in a project, each activity's completion time is $CT_b = P_a + P_b \sim Uniform/Normal\ Distribution$ following the precedence from the start (the result from step 1) until the project completion at CT_j.

Step 3. Get project review staring time and project final completion time.

Policy 1: Project without collaboration. In this case, each project $j, j \in J$, has its own designated Project Review Committee and a predetermined review starting time equal to a given time. The project review end time is equal to the project starting time plus the review time duration (Uniform distribution). For example, given 25 projects and the predetermined review starting time equal to 20, for $j = 1,2, \dots, 15$, or 25, for $j = 16, \dots, 25$. In addition, the project review time duration for each project is Uniform (5, 10). In other words, if $CT_j \leq 20$ (for $j = 1,2, \dots, 15$), then the review committee starts the project review at 20. If $CT_j \leq 25$ (for $j = 16, \dots, 25$), then the review committee starts the project review at 25. Otherwise, if $CT_j > 20$ (for $j = 1,2, \dots, 15$), then the review committee may not start the project review until $CT_j + \text{Uniform}\,(7,21)$. If $CT_j > 25$ (for $j = 16, \dots, 25$), then the review committee may not start the project review until $CT_j + \text{Uniform}\,(7,21)$. Here, Uniform (7,21) represents a random delay caused by missing a designed review slot. After review, a project may have to be reworked (if it failed the review) on part of the project using a different percentage. If the project failed, then an additional several days are needed. For example, the chance pass is 60% and the chance to fail is 40%. If the project failed, then an additional 10 days are needed. Finally, we obtain the average on the difference between each project final completion time T_j and its project duration CT_j.

Policy 2: Project with collaboration. In this case, whenever a project j completes, take the next available review starting time, e.g., either 20 or 25. For example, if a project is completed at 23, then the project can be reviewed at 25. For the late project that neither can be reviewed at 20 nor 25, which is assigned to the slot of late project(s) and the review starting time of it would therefore be $CT_j +$

Uniform $(7, 21)$. As with the non-collaboration model, the difference between project final completion time T_j and project duration CT_j is used to compare with the result of Policy 1.

We use an example to examine the results of these two policies on batch mode slot assignment. We assume 15 projects, with each project j consisting of 19 activities $a_{1,2,\dots,19}$ following the precedent as see in Figure 5.2. In addition, there are a total of 14 types of non-renewable resources and for each type of resource there are 12 suppliers. Each individual supplier has a given release time and a randomly generated transportation time according to uniform distribution. Based on Step 1, we can determine the project start time ST_j, and compute the project completion time CT_j followed Step 2. In Step 3, for the no-collaboration policy, we first set three slots for all 15 projects and each slot concludes 5 designated projects. The review staring times for the three slots are 365, 370, and 375 respectively. Furthermore, an additional slot is set for the late projects at time $CT_j + \text{Uniform } (5,10)$. The review time for each project is a constant 2, that is, the final project completion time $T_j = Review\ start + 2$. Finally, we get the differences between T_j and CT_j . The procedures are shown in Table 5.1. For Step 3 of the collaboration policy, a project can be reviewed at 365, 370, or 375, as long as it is completed. Otherwise, the project would be reviewed at $CT_j + \text{Uniform } (5,10)$. The simulation procedures and results are shown in Table 5.2.

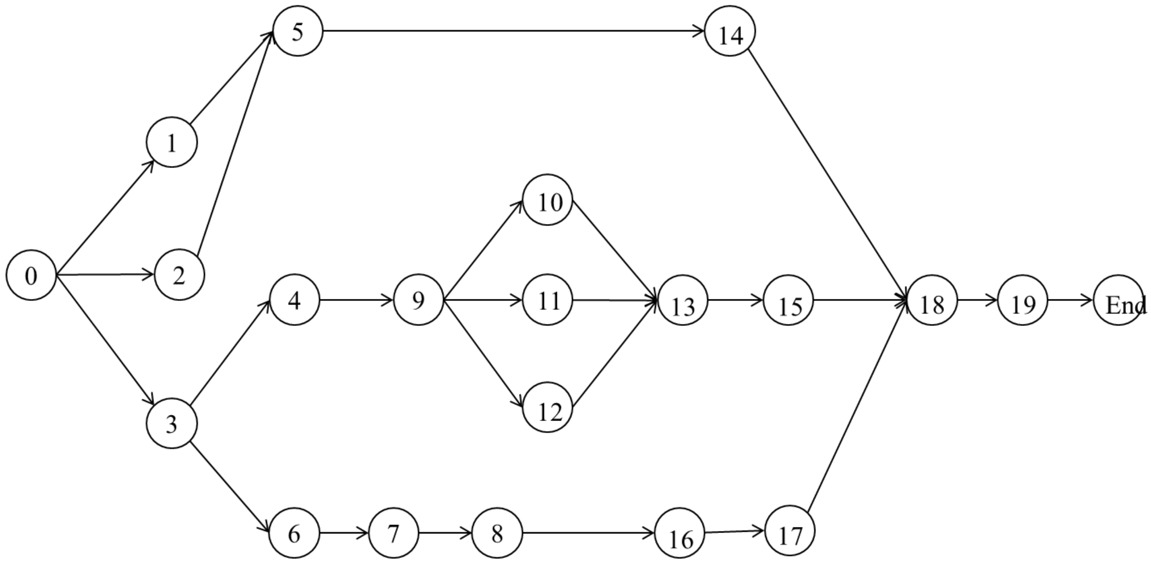

Figure 5.2 Precedent of 19 activities in a single project.

Table 5.1

Batch mode slot assignment: results of projects without collaboration.

j	ST_j	a_1	$a_{2,3,\dots 18}$	a_{19}	CT_j	Slot Review Start	Review Start	Review End	T_j	$T_j - CT_j$
1	21	25	⋯	352	352	365	365	367	367	15
2	25	29	⋯	361	361	365	365	367	367	6
3	25	28	⋯	376	376	365	383	385	385	9
4	22	26	⋯	363	363	365	365	367	374	11
5	20	24	⋯	361	361	365	365	367	374	13
6	23	28	⋯	377	377	370	386	388	388	11
7	25	28	⋯	367	367	370	370	372	372	5
8	24	28	⋯	350	350	370	370	372	372	22
9	30	34	⋯	370	370	370	381	383	383	13
10	21	24	⋯	355	355	370	370	372	372	17
11	21	26	⋯	374	374	375	375	377	384	10

12	20	25	⋯	366	366	375	375	377	377	11
13	20	23	⋯	372	372	375	375	377	377	5
14	26	29	⋯	359	359	375	375	377	377	18
15	24	29	⋯	356	356	375	375	377	377	21
							Average of T_j - CT_j :			**12**

Table 5.2

Batch mode slot assignment: results of projects with collaboration.

j	ST_j	a_1	$a_{2,3,\ldots 18}$	a_{19}	CT_j	**Slot Review Start**	**Review Start**	**Review End**	T_j	$T_j - CT_j$
1	21	25	⋯	352	352	365	365	367	367	15
2	25	29	⋯	361	361	365	365	367	367	6
3	25	28	⋯	376	376	365	383	385	385	9
4	22	26	⋯	363	363	365	365	367	367	4
5	20	24	⋯	361	361	365	365	367	367	6
6	23	28	⋯	377	377	370	389	391	391	14
7	25	28	⋯	367	367	370	370	372	372	5
8	24	28	⋯	350	350	370	365	367	367	17
9	30	34	⋯	370	370	370	375	377	377	7
10	21	24	⋯	355	355	370	365	367	367	12
11	21	26	⋯	374	374	375	375	377	377	3
12	20	25	⋯	366	366	375	370	372	372	6
13	20	23	⋯	372	372	375	375	377	377	5
14	26	29	⋯	359	359	375	365	367	367	8
15	24	29	⋯	356	356	375	365	367	374	18
							Average of T_j - CT_j :			**9**

By running Table 5.1 and Table 5.2 100 times (10 times in each set, 10 sets in total), we get the mean on the final contract completion time for both policies, as presented in Figure 5.3. The results show that Policy 2 of projects with collaboration having a shorter review duration than Policy 1 of projects without collaboration.

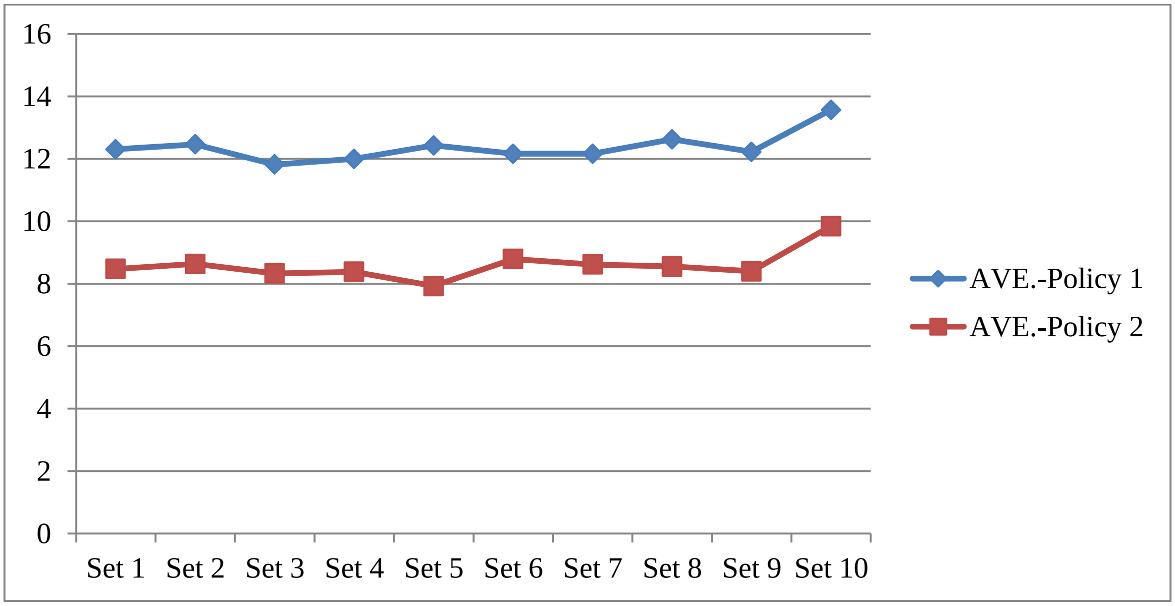

Figure 5.3 Results of comparison of the mean between Policy 1 and Policy 2.

5.1.2. Sequential Mode Slot Assignment

The sequential mode slot assignment is designed for projects that are waiting to be reviewed by only one review team, which is based on the mean of project completion time. In a practical case, the mean can be calculated in accordance with the planned project completion time computed from historical data or based on expert opinions. In a bid process, the planned project completion time is an especially important element to consider in terms of whether the company can win the bid. Therefore, the planned completion time has to be relatively accurate, practicable, and have a competitive advantage over other bidders. In this case, we use the mean of the planned completion time to set the review starting time of each slot. For the no-collaboration policy, every project has a designated review slot with the review starting time scheduled based on the mean time. If the project missed the review starting time, this project has to be reviewed later, during a slot of late projects. For the collaboration policy, there is a review sequence of all the slots, determined by an optimal sequencing of the mean of the project completion time. In addition, when a project misses the sequential slot review start time, it can be reviewed during a late project slot in a first-come-first-serve basis. Figure 5.4 illustrates the sequential mode slot assignment in detail. There are 15 projects in total, and each project has a review slot assigned based on the mean of its completion time.

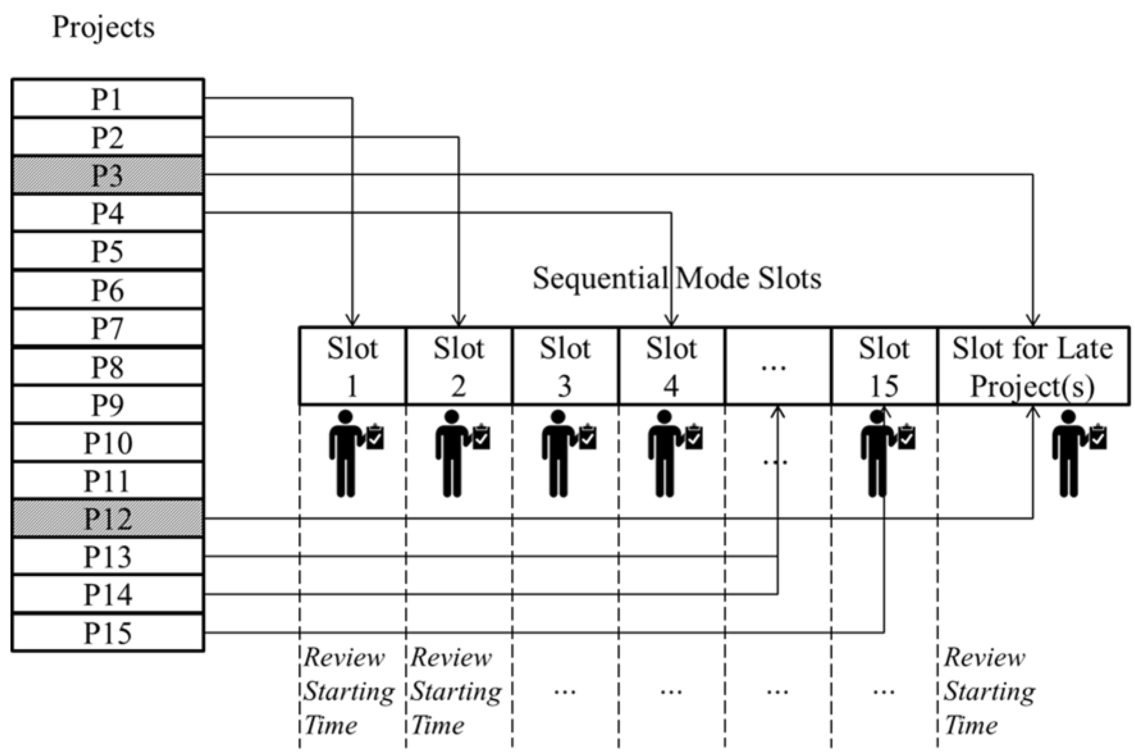

Figure 5.4 Sequential mode slot assignment.

We also use an example to illustrate the sequential mode slot assignment here, as shown in Table 5.3 and 5.4. Under this assignment, we run the simulation 100 times and get the mean based on the project completion time CT_j. For the project that missed the review start time, it is reviewed at $\max(CT_j) + Unifrom\ (10, 15)$ after all the projects finishing the review. It should be noted that we first make a sequence of the mean based on the projects' completion time. According to the mean sequence, we determine the review stating time of each slot, where the latest reviewed starting time is greater than the largest number of the mean. However, for Policy 1, the starting time of each assigned slot is fixed. Each completed project can only be reviewed at the corresponding slot. For Policy 2, although the review starting time of all the slots are same as that of Policy 1, but we sort the project completion time in an order from small to large as the mean's sequence. In this case, the project can be reviewed when it completes.

Table 5.3

Sequential mode slot assignment: results of projects without collaboration.

j	ST_j	a_1	$a_{2,3,\dots 19}$	CT_j	Mean	Mean Sequence	Sequential Slot	Review Start	Review End	T_j	$T_j - CT_j$
1	21	25	⋯	361	356.67	357	359	394	396	396	34
2	25	29	⋯	360	358.54	359	360	390	392	392	31
3	25	28	⋯	367	372.89	359	361	390	392	392	24
4	22	26	⋯	361	372.06	364	362	362	364	364	3
5	20	24	⋯	362	364.45	364	363	363	365	365	3
6	23	28	⋯	367	364.35	364	364	393	395	395	28
7	25	28	⋯	379	368.32	364	365	392	394	394	15
8	24	28	⋯	365	364.01	364	366	366	368	368	3

9	30	34	⋯	368	365.80	366	367	394	396	396	27
10	21	24	⋯	365	366.10	366	368	368	370	377	12
11	21	26	⋯	375	370.72	368	369	394	396	396	21
12	20	25	⋯	363	370.28	370	370	370	372	372	9
13	20	23	⋯	360	364.36	371	371	371	373	373	13
14	26	29	⋯	357	358.53	372	372	372	374	374	17
15	24	29	⋯	369	363.97	373	373	373	375	375	6
									Average of $\boldsymbol{T_j}$ - $\boldsymbol{CT_j}$:		**17**

Table 5.4

Sequential mode slot assignment: results of projects with collaboration.

$\boldsymbol{j}$	$\boldsymbol{ST_j}$	$\boldsymbol{a_{1,\ldots 19}}$	$\boldsymbol{CT_j}$	$\boldsymbol{CT_j}$ **Sequence**	**Mean**	**Mean Sequence**	**Sequential Slot**	**Review Start**	**Review End**	$\boldsymbol{T_j}$	$\boldsymbol{T_j - CT_j}$
1	21	⋯	361	357	356.67	357	359	359	361	361	4
2	25	⋯	360	360	358.54	359	360	392	394	394	34
3	25	⋯	367	360	372.89	359	361	361	363	363	3
4	22	⋯	361	361	372.06	364	362	362	364	364	3
5	20	⋯	362	361	364.45	364	363	363	365	365	4
6	23	⋯	367	362	364.35	364	364	364	366	366	4
7	25	⋯	379	363	368.32	364	365	365	367	367	4
8	24	⋯	365	365	364.01	364	366	366	368	368	3
9	30	⋯	368	365	365.80	366	367	367	369	369	4
10	21	⋯	365	367	366.10	366	368	368	370	370	3
11	21	⋯	375	367	370.72	368	369	369	371	371	4
12	20	⋯	363	368	370.28	370	370	370	372	372	4
13	20	⋯	360	369	364.36	371	371	371	373	373	4
14	26	⋯	357	375	358.53	372	372	391	393	393	18

15	24	···	369	379	363.97	373	373	394	396	396	17
									Average of T_j - CT_j :	**7**

Figure 5.5 presents the results of the mean with 100 simulation runs (10 runs in each set, and 10 sets in total) for each policy. In summary, the average number of review days of Policy 2 is shorter than that of Policy1 in 4 days approximately.

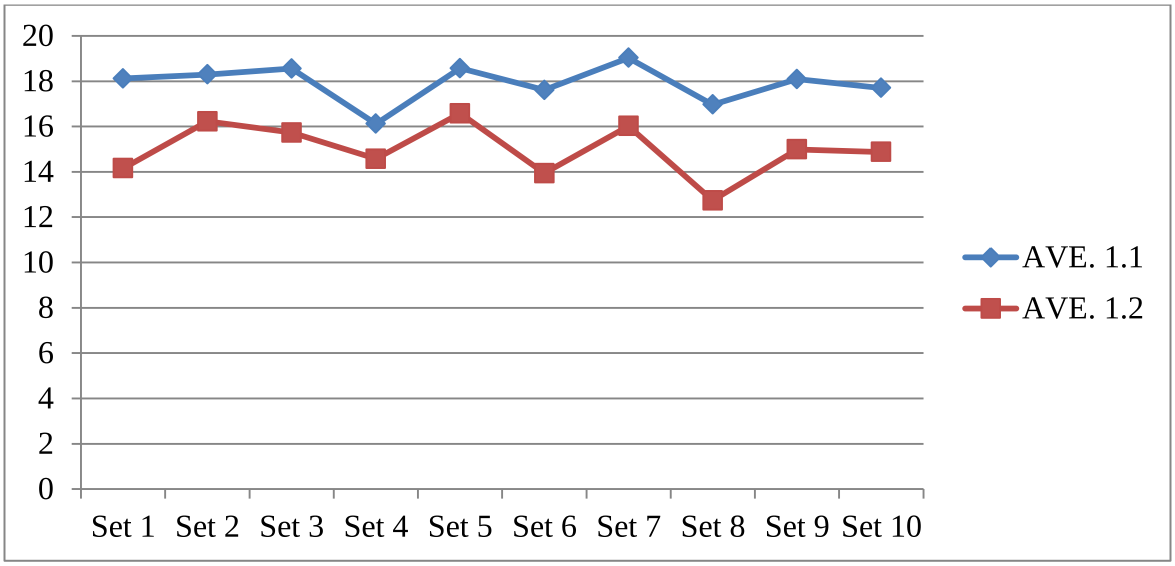

Figure 5.5 Results of comparison of the mean between Policy 1 and Policy 2.

5.2. A Resource Allocation Strategy under Uncertainty

5.2.1. Background of the Problem

Resource availability is a crucial juncture for reducing the project duration and costs. In the event of a scheduling problem, the presence of additional resources may help reduce the project duration. This is what is called time-resource tradeoff problem. For example, sometimes a project is behind the schedule to that it needs a crash to meet the time deadline for the project. In this case, the project manager usually schedules overtime work such as weekend and evening shifts to increase the productivity and thereby reduce the project completion time. Such time-resource tradeoff solutions can also be used in construction project management, which “provide project managers with information on how much each resource’s consumption (or its cost) will be increased if project duration is decreased by one time unit” (Pulat & Horn, 1996).

A number of papers have investigated the time-resource tradeoff problem in project scheduling. For instance, Talbot (1982) describes and defines the time-resource trade-off problem using a zero-one integer programming approach. The objective is to find the schedule of jobs that minimizes project completion time and project cost. A two-stage computationally tractable integer programming approach is introduced to solve a general class of non-preemptive resource-constrained project scheduling problems, setbacks in which the duration of each job is a function of the resources committed to it.

Pulat and Horn (1996) examine the time-resource tradeoff problem with regard to a given project network with a set of tasks to be completed according to some precedent relationship. The objective is to determine efficient project schedules for a range of project realization times. A multiple objective linear programming (MOLP) model is utilized. This methodology assumes that the project manager’s utility function over the resource consumption costs is linear, with unknown weights for each resource. In addition, enumerative and interactive algorithms utilizing Geoffrion’s $P(\lambda)$ approach are presented as solution techniques.

Problems related to time-resource tradeoffs can be also found in Kabarati et al. (1995), which addresses a discrete resource allocation problem in a deterministic flow line for various performance criteria. The research assumes the processing times are convex and non-increasing in the amount of resources allocated to the machines. A branch-and-bound procedure of approximate and iterative solution procedure is then presented. Armstrong et al. (1998) propose an efficient algorithm based on an analysis on the primal and Lagrangian dual solutions for solving a defined series-parallel graph of the two resource allocation problem based on a time-resource tradeoff. The objective is to minimize the length of the longest path on the graph. Shabtay and Steiner (2007) study a supply chain scheduling problem, assuming that the job-processing times are either a linear or a convex function of the amount of a continuous and nonrenewable resource that is to be allocated to the processing operations. A polynomial-time algorithm is also provided to minimize an integrated objective function, i.e., the weighted number of tardy jobs, and due date assignment, makespan, and total resource consumption costs.

Lee and Lei (2001) study some solvable cases of multiple-project scheduling with controllable project duration and hard resource constraints based on the time-resource tradeoff relationship. Two types of problems are presented in their research. The Type I problem considers the duration of each project, including a constant and a term that is inversely proportional to the amount of resources allocated. The Type II problem involves the duration of each individual project as a continuously decreasing function of the amount of resources allocated. Lee and Lei pointed out that the general resource constrained project/machine scheduling problem is hard to solve and it is even harder in practice because the actual conditions under which a schedule will be executed change over time. For this reason, special case solutions may serve as a decision-making tool for quick estimations in a highly dynamic project management environment and may lead to the design of quality heuristic scheduling algorithms.

5.2.2. Problem Statement and Formulation

To the best of our knowledge, existing research works on resource allocation in project management are based on known and deterministic project/activity durations (Wiest, 1964; Elmaghraby, 1990; Russell and Ranasinghe, 1991; Leach, 1999; Vonder et al., 2005), and such problem has been studied in a PERT newtwork (Hagstrom, 1988; Hagstrom 1990). However, as it is well known in real-world project management practices, project/activity durations rarely follow a deterministic time (Radermacher, 1985; Tsai and Gemmil, 1998; Scholl, 2001; Stork, 2001). In this section, we will study the resource allocation problem with a time-resource tradeoff, which subjects to uncertainty in activity durations.

More specifically, a project management team manages a set of n projects simultaneously. These projects can start simultaneously and be executed in parallel. The project management team has a set of renewable resources, e.g., laborers or machines, which can be allocated to each project. To simplify the problem, we will assume that only one renewable resource, i.e., laborer, is in consideration for purposes of this study. In short, the project management team has only a fixed number of laborers, denoted by B, to share among these n projects. The hypothetical resource allocation network is presented in Figure 5.6.

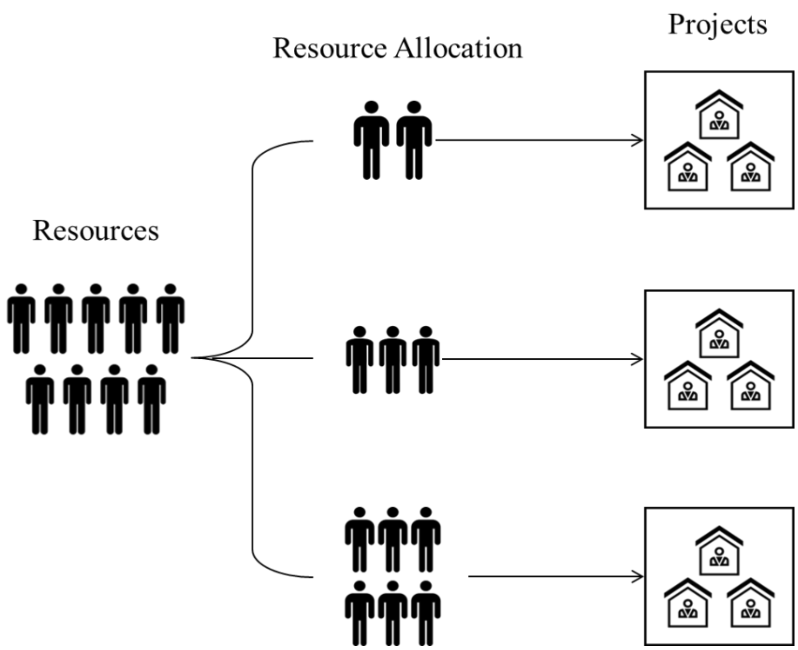

Figure 5.6 A hypothetical resource allocation network (laborers).

Each project has a set of activities with predetermined precedent constraints, as discussed in Chapter 3; Figure 5.2 in Section 5.1 represents one for such example. The work efficiency and, consequently, the duration for each activity in a project depend on the number of allocated laborers (or other chosen resource under investigation). For example, Table 5.5 shows the relationship between assigned laborers and mean activity durations for the project shown in Figure 5.2.

Table 5.5

Relationship between assigned laborers and mean activity durations.

Assigned Laborers	**Mean Activity Duration**					
	Activity 1	**Activity 2**	…	**Activity 16**	**Activity 17**	**Activity 18**

3	8.84	9.40	⋯	113.65	110.68	115.68
4	6.51	7.07	⋯	86.22	84.17	90.44
5	5.15	5.49	⋯	68.54	66.48	72.15
6	4.44	4.72	⋯	57.26	55.57	61.51

Even though the mean activity durations can be described as decreasing functions of the assigned laborers, each realized activity duration can vary and be subject to uncertainty. Such uncertainty can be best modeled as a random noise following certain probability distributions. Denote the labors assigned to project i (i = 1, 2, …, n) as x_i, which are decision-making variables to be made by the project management team. Note that the total assigned laborers are subject to the total availability, that is, $\sum_{i=1}^{n} x_i \leq B$. For each project i, given that x_i laborers are assigned to the project, the duration for each activity j, denoted as $l_{ij}(x_i)$, is a random variable following a probability distribution. For example, activity 1 in Table 5.5 can follow different distributions, with the parameters being functions of x_i, for example, $l_{11}(4)\sim Normal(98.5, 5)$, $l_{11}(5)\sim Normal(244.5, 30)$, and $l_{11}(6)\sim Uniform(35, 45)$.

Given a random realization of activity durations, the project completion time can be subsequently determined based on the project network. For example, if the project in Figure 5.2 is assigned$x_i = 5$, two different random realizations of the activity durations can lead to rather different critical paths and hence different project completion times, as illustrated in Figure 5.7 and Figure 5.8, where critical paths are shown in bold arrows.

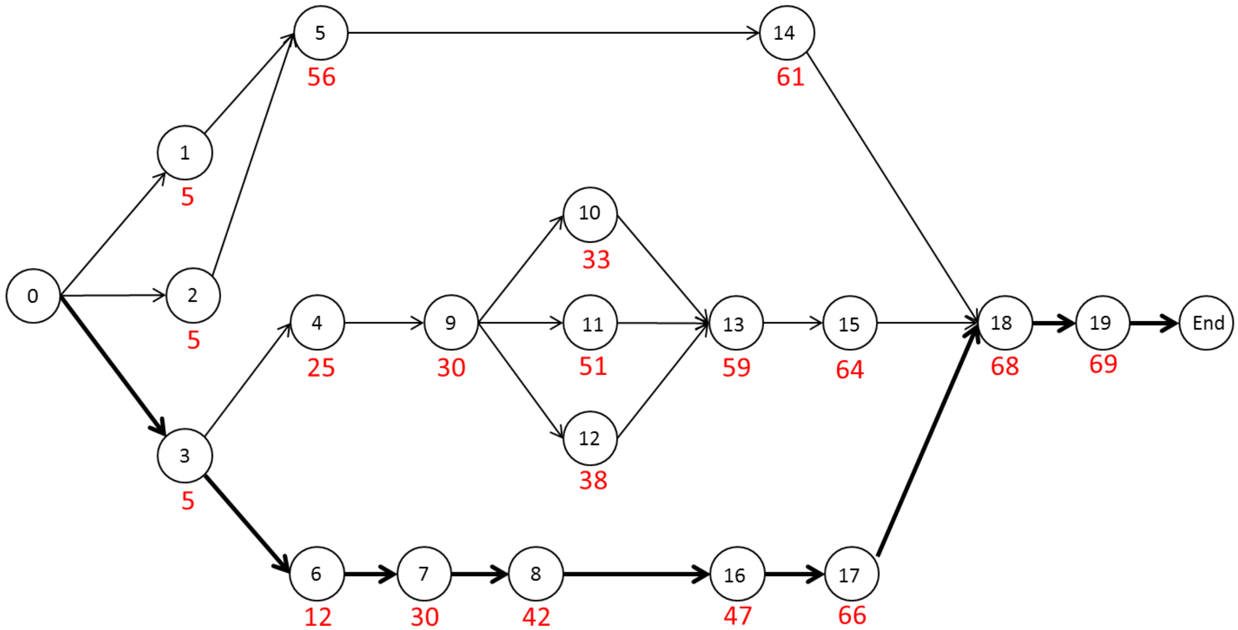

Figure 5.7 Critical path with a random realization of the activity durations (completion time: 69) – 1.

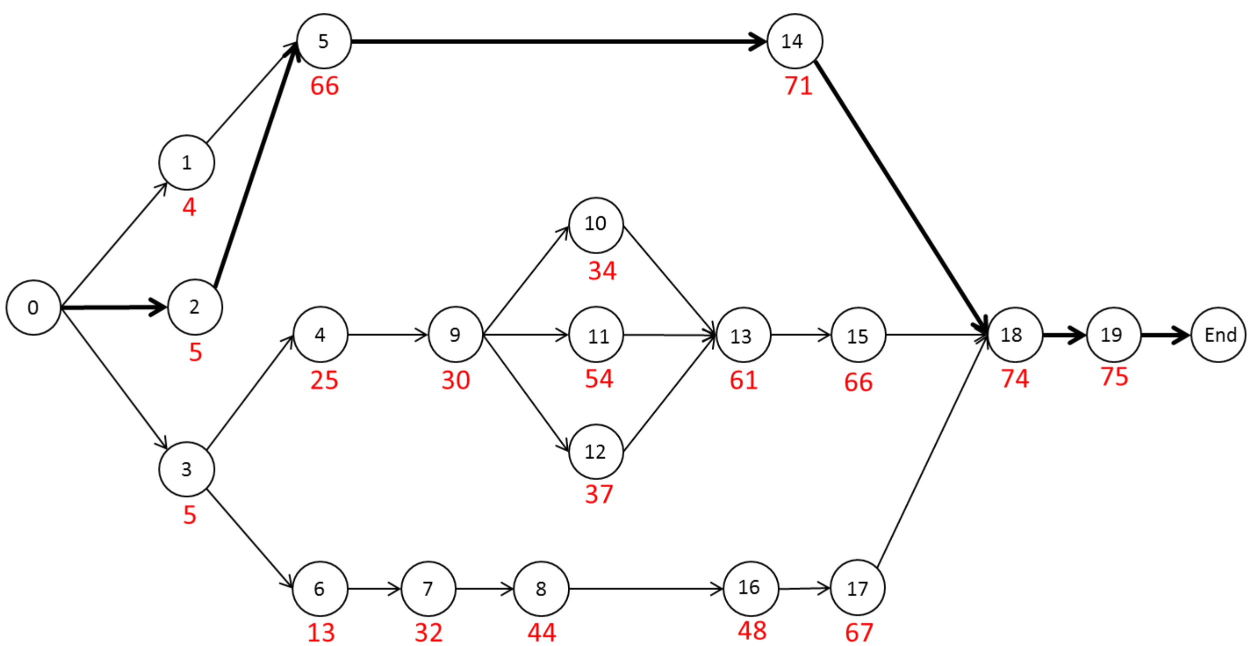

Figure 5.8 Critical path with a random realization of the activity durations (completion time: 69) – 2.

Therefore, the project completion time can be expressed as a function of x_i, denoted as $t_i(x_i)$. $t_i(x_i)$ is a random variable, and its value depends on the random realizations of activity durations $l_{ij}(x_i)$. The problem under study here is then to minimize the total weighted tardiness for completing all projects, subject to the resource limitation. That is,

$$\min_{x} \sum_{i=1}^{n} \omega_i \max(0, t_i(x_i) - d_i)$$

$$s.t. \quad \sum_{i=1}^{n} x_i \leq B$$

where d_i is the due date of project i, ω_i is the weight of project i, and B is the total resource (e.g., labor) available.

Since $t_i(x_i)$ does not typically admit a closed form expression (due to varied network structure and precedency constraints), its statistics (mean and variance) can be estimated using simulation. However, the number of designs can be quite large, and thus it is usually not realistic to compute the statistics of all available designs. We aim to find the best design (i.e., the optimal values of x_i) given a limited simulation budget. Hence, this problem falls into the well-established branch of statistics known as Ranking & Selection (R&S).

The Ranking and Selection (R&S) problem has significantly expanded over recent years (for reviews see Branke et al., 2007; Kim & Nelson, 2007; and Xu et al., 2015). For instance, Nelson et al. (2001) propose some simple procedures for selecting the best simulated system when the number of alternatives is large. Chen et al. (2000) investigate the simulation budget allocation for further enhancing the efficiency of ordinal optimization. Chick and Inoue (2001a) examine the new procedures for identifying the best simulated system using common random number. Moreover, Chick and Inoue (2001b) study a two-stage and sequential procedures for selecting the best simulated system. Last but not least, Kim and Nelson (2001) propose a fully sequential procedure for indifference-zone selection in simulation. The above approaches have also been extended to find the optimal subset of designs (i.e., top-*m* designs where *m*>1). For example, Chen et al. (2008) formulate a problem of maximizing the probability of correctly selecting all of the top-*m* designs in ranking and selection, which subject to a constraint on the total number of samples available. An asymptotically optimal allocation and an easy-to-implement heuristic sequential allocation procedure have been proposed. Gao and Chen (2016) study a problem of selecting the top-*m* (*m*>1) designs from a finite set of k design alternatives. Given the total simulation budget constraint, the purpose of the selection problem is to maximize the Probability of Correct Selection (PCS). In addition, an approximation for the correct selection probability and then derived an asymptotically optimal selecting procedure is developed.

Any algorithms developed for solving R&S problems can be used to solve the problem under study here. However, it should be noted that since the number of possible designs (i.e., combinations of values of x_i) is usually quite large, even the most efficient R&S algorithm will require a large simulation budget to reach a satisfactory confidence level. Meanwhile, our numerical experiments showed that the distributions of $t_i(x_i)$ sometimes admit simple trends as x_i increases. We will therefore focus on a special case of the general problem under investigation.

5.2.3. Solving a Special Case

We observed through numerical experiments that the mean activity duration typically takes the following form: $l_{ij}(x_i) = a_{ij} + \frac{c_{ij}}{x_i} + \delta$, where a_i and c_i are positive constants, x_i is the amount of resource allocated to project i, and δ is the randomness factor. In essence, activity duration includes a constant and a term that is inversely proportional to the amount of resources allocated, which is further subject to uncertainty. Therefore, based on this special structure, we can solve a special case of the problem proposed in Chapter 5.2.2.

To illustrate the special case, we show an example including 5 projects with a total budget $B = 25$. In other words, the sum of all the resources that are allocated to the 5 projects equals to 25. In this simulation experiments, each activity duration takes the form $l_{ij}(x_i) = a_{ij} + \frac{c_{ij}}{x_i} + \delta$, where the parameters for each activity are generated randomly as follows: project due time $d_i \sim Uniform(15, 20)$, $a_i \sim Uniform(10,15)$, $c_i \sim Uniform(20, 30)$, and $\delta \sim Uniform(1,5)$.

Then, we conduct an empirical study to testify whether project duration fits the function under this hypothetical circumstance. In this empirical study, we are given the precedent of activities shown in Figure 5.2. The parameters are described in Table 5.6. For a certain amount of resources x_i allocated to the project, 100 simulation runs have been performed; and for each μ_i 10 simulation runs have been performed. Thus, 1,000 observations have been obtained for the project duration and resource allocation. The procedures to perform the experiment are described below:

Step 1. Randomly generate a_{ij}, c_{ij}, and randomness δ in a given range and let $x_j = x$, for $j = 1,2, \dots, n$.

Step 2. Define the precedent σ of activity j for project i. The project starts at $t_0 = 0$. Based on the precedent σ, calculate the duration of each activity j which is defined by $l_{ij} = (a_{ij} + c_{ij}/x_i) + \delta + l_{ij-1}$, until we get $t_i, i = 1,2, \dots, n$.

Step 3. Run step 1 and 2 *m* times and we will get *m* project duration t_i. Next, get mean μ_i of $\forall t_i$, $i = 1,2, \dots, n$.

Step 4. Repeat steps 1-3 with an increased x, for example, $x_i = x'$, where $x' > x$. For this x', we will have a corresponding μ_i' for $\forall t_i$, $i = 1,2, \dots, n$. As before, we will get a decreasing project duration curve of μ_i for $\forall t_i$ when resource x increases.

Table 5.6

Range of the parameter's value.

$\boldsymbol{x_i}$	$\boldsymbol{a_i}$	$\boldsymbol{c_i}$	$\boldsymbol{k_i}$	**Performance Times**
$\boldsymbol{x = 3}$	Rnd(10,20)	Norm(300,10)	Rnd(1,5)	100
$\boldsymbol{x' = 4}$	Rnd(10,20)	Norm(300,10)	Rnd(1,5)	100
$\vdots$	Rnd(10,20)	Norm(300,10)	Rnd(1,5)	100
$\boldsymbol{x^n = 13}$	Rnd(10,20)	Norm(300,10)	Rnd(1,5)	100

Table 5.7

Results of project duration corresponding to different resource allocations.

x_i	μ_j −*High*	μ_j −*Low*	μ_j −*Ave.*
3	939	928	933
4	741	730	734
5	618	605	612
6	537	530	535
7	484	472	477
8	437	431	434
9	406	397	401
10	378	368	373
11	357	346	350
12	335	327	332
13	322	317	320

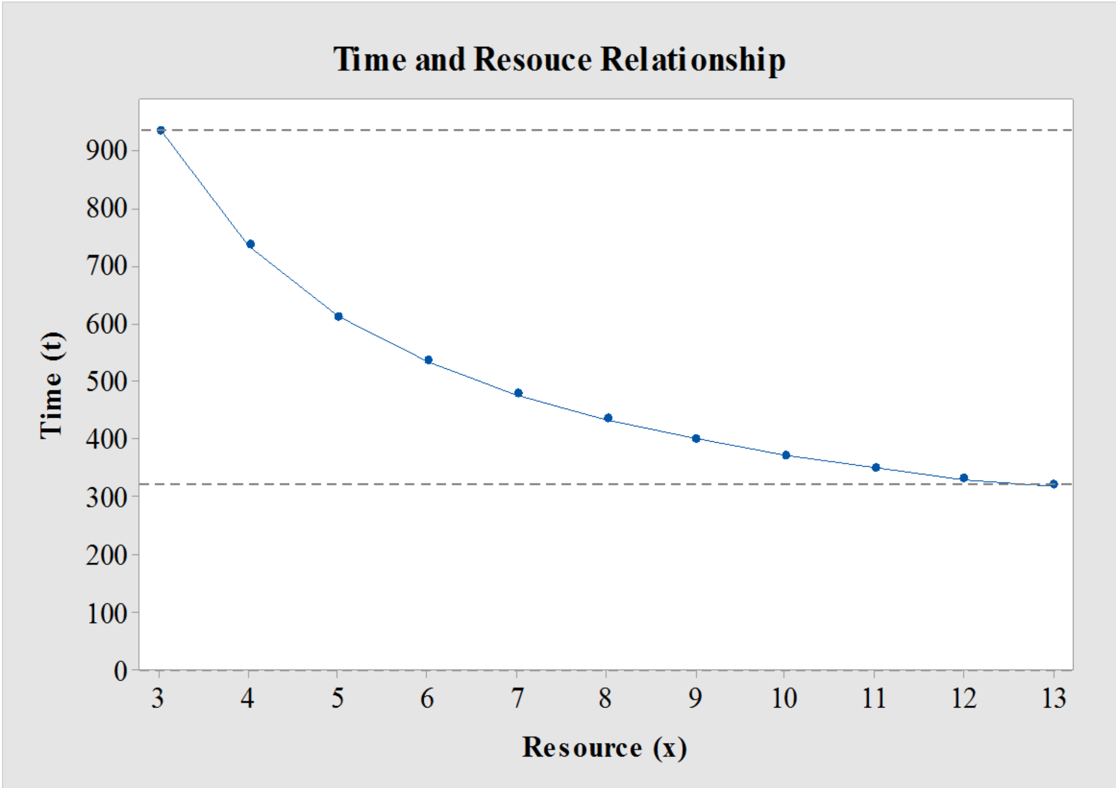

Figure 5.9 Curve of the relationship between time and resource.

The result shown in Table 5.7 and Figure 5.9 demonstrates that the project duration follows the function $t_i = a_i + c_i/x_i$ when activity duration fits $l_{ij}(x_i) = a_{ij} + \frac{c_{ij}}{x_i} + \delta$.

The performance is measured in accordance with the tardiness of project which can be expressed as $\sum_{i=1}^{n} \max\{0, a_{ij} + c_{ij}/x_i - d_i\}$ as shown in Table 5.8 (run 1,000 times in MS-EXCEL). In addition, the table shows three different resource allocations, and the resulting different tardiness. Therefore, finding the optimal resource allocation combination $(x_1, x_2, \ldots, x_n)$, subject to the resource constraint$\sum_{i=1}^{n} x_i \leq B$.

Table 5.8

Comparison of different resource allocations.

		Case I		Case II		Case III	
Project *i*	d_i	x_i	t_i	x_i	t_i	x_i	t_i
1	17	5	20.5	2	28.0	5	20.4
2	18	5	20.5	4	21.7	3	23.7
3	18	5	20.4	5	20.4	4	21.7
4	17	5	20.6	6	19.9	8	18.7
5	18	5	20.5	8	18.6	5	20.5
Total tardiness		14.5		20.6		17	

In Lee and Lei (2001), the researchers present that given n independent projects and a budget B for a nonrenewable resource, each project, say i, $1 \leq i \leq n$, has a controllable project duration that includes a constant and a term that is inversely proportional to the amount of resource allocated

$$t_i = a_i + \frac{c_i}{x_i},$$

where a_i and c_i are the given constants, and x_i is a decision variable representing the amount of resource allocated to project i. Parameter a_i is called the minimum project duration or "fixed cost", that is $t_i \to a_i$ when $x_i \to \infty$. By constrained project scheduling with nonrenewable resources, they mean that

$$\sum_{i=1}^{n} x_i \leq B, \text{where } x_i > 0, i = 1, 2, \dots, n,$$

must be satisfied by any feasible project schedule. In Lee and Lei (2001), problems with regular performance measure are considered. Namely, that the objective function is an increasing function of project completion times. The structure of t_i implies that they have $\sum_{i=1}^{n} x_i \leq B$ at the optimal solution.

In this case, we use Lee and Lei (2001) as a reference to solve the resource allocation problem with a time-resource tradeoff, while realizing that it is subject to uncertainty in activity durations. The problem assumes that all *n* projects must start at the same time that each has a project duration that depends on the amount of resources allocated, and that each has a customer-specified due date. The problem is to allocate the resources to the n projects so that the total weighted tardiness is minimized. The following theorem in Section 1.2 of Lee and Lei (2001) provides a theoretical guarantee on how to solve our special case.

Theorem 3. If $d_i \leq a_i, \forall i$, then the optimal solution of (P_1) is given by

$$x_i^* = \frac{\sqrt{\omega_i c_i}}{\sum_{i=1}^{n} \sqrt{\omega_i c_i}} B, \quad i = 1,2, \ldots, n.$$

Based on Theorem 3, the following algorithm is proved to solve our special case to optimality (cite Prof. Lei's paper).

Algorithm 1. Step 0. Let $N = \{1,2, \ldots, n\}$ be the set of projects to be considered.

Step 1. If $N = \emptyset$, then stop.

Else, let

$$\lambda = \frac{\left(\sum_{i\in N}\sqrt{\omega_i c_i}\right)^2}{B^2}, \quad x_i = \sqrt{\frac{\omega_i c_i}{\lambda}}, \quad \forall i \in N.$$

which ensures that $\omega_i c_i/x_i^2 = \omega_j\, c_j/x_j^2\,, \forall i, j$.

Step 2. Let Π_1 and Π_2 be two subsets of N such that

$$\Pi_1 = \left\{i \in N: a_i + \frac{c_i}{x_i} \le d_i\right\}, \qquad \Pi_2 = \left\{i \in N: a_i + \frac{c_i}{x_i} > d_i\right\}.$$

If $\Pi_1 = N$ or $\Pi_2 = N$, then stop. Else, reduce x_i to x_i' so that $a_i + c_i/x_i' = d_i$, $\forall i \in \Pi_1$, and go to step 3.

Step 3. Set $N = \Pi_2$ and $\mathrm{B} = \sum_{i\in\Pi_2} x_i + \sum_{i\in\Pi_1}(x_i - x_i')$, and go to step 1.

Evidently, algorithm 1 stops in no more than n iterations. To see this, consider that we have a total of n projects. At the end of each iteration, either the size of N is reduced by at least one if $\Pi_1 = \emptyset$, or a termination condition is satisfied if $N = \Pi_2$. In the later case, the algorithm stops in less than n iterations. Since the complexity of each iteration is $\mathrm{O}(n)$, the total complexity is bounded by $\mathrm{O}(n)^2$. The optimality of algorithm 1 is based on the following observation.

Finally, a numerical example performed by MS-EXCEL is given to explain the above algorithm. Given 10 projects and a total budget $B = 40$ for one type of nonrenewable resource, other parameters are as shown in Table 5.9.

Table 5.9

Parameters of a numerical example for resource allocation strategy

Project i	**Due date** d_i	**Minimum duration** a_i	**Constant in var. duration** c_i	**Weight** ω_i
1	114	20	335	3
2	105	16	342	4
3	110	13	351	4
4	92	13	347	3
5	107	18	362	3
6	105	16	349	5
7	94	19	342	2
8	112	19	342	5
9	100	20	356	5
10	98	17	353	2

Based the above parameters, the steps to find the best resource allocations are described as below.

Step 1.	**Initially, we have N** $= \{\mathbf{1}, \mathbf{2}, \ldots, \mathbf{10}\}$**.**
$\boldsymbol{\lambda}$	$\lambda_{1,2,\ldots 10} = \dfrac{(\sqrt{\omega_1 c_1} + \sqrt{\omega_2 c_2} + \cdots + \sqrt{\omega_{10} c_{10}})^2}{B^2} = 76$
$\boldsymbol{x_i}$	$x_1 = \sqrt{\frac{\omega_1 c_1}{\lambda_{1,2,\ldots,10}}} = 4, x_2 = \sqrt{\frac{\omega_2 c_2}{\lambda_{1,2,\ldots,10}}} = 4\ , x_3 = 4, x_4 = 4, x_5 = 4, x_6 = 5, x_7 = 3, x_8 = 5, x_9 = 5, x_{10} = 3$
$\boldsymbol{C_i}$	$C_1 = a_1 + \frac{c_1}{x_1} = 112 < d_1, C_2 = a_2 + \frac{c_2}{x_2} = 97 < d_2, C_3 = 95 < d_3, C_4 = 107 > d_4, C_5 = 114 > d_5, C_6 = 89 < d_6, C_7 = 133 > d_7, C_8 = 91 <$

	$d_8, C_9 = 94 < d_9, C_{10} = 133 > d_{10}$

Step 2.	**Get two subsets of N.**
Π	Set of early projects $\Pi_1 = \{1, 2, 3, 6, 8, 9\}$
	Set of tardy projects $\Pi_2 = \{4, 5, 7, 10\}$
$\boldsymbol{x_i'}$	$x_1' = \dfrac{c_1}{d_1 - a_1} = 4, x_2' = \dfrac{c_2}{d_2 - a_2} = 4, x_3' = 4, x_6' = 4, x_8' = 4, x_9' = 4$

Step 3.	**Set $\boldsymbol{N = \Pi_2}$ and $\boldsymbol{B}$, and go to step 1.**
$\boldsymbol{B}$	$\mathrm{B} = x_4 + x_5 + x_7 + x_{10} + (x_1 - x_1') + (x_2 - x_2') + (x_3 - x_3') + (x_6 - x_6') + (x_8 - x_8') + (x_9 - x_9') = 17$
$\boldsymbol{\lambda}$	$\lambda_{4,5,7,10} = \frac{(\sqrt{\omega_4 c_4} + \sqrt{\omega_5 c_5} + \sqrt{\omega_7 c_7} + \sqrt{\omega_{10} c_{10}})^2}{B^2} = 48$
$\boldsymbol{x_i}$	$x_4 = \sqrt{\frac{\omega_4 c_4}{\lambda_{4,5,7,10}}} = 5, x_5 = 5, x_7 = 4, x_{10} = 4$
$\boldsymbol{C_i}$	$C_4 = a_4 + \frac{c_4}{x_4} = 88 < d_4, C_5 = 94 < d_5, C_7 = 110 > d_7, C_{10} = 109 > d_{10}$

Step 4.	**Get two subsets of N.**
Repeat Step 2.	
Π	Set of early projects $\Pi_1 = \{4, 5\}$
	Set of tardy projects $\Pi_2 = \{7, 10\}$
$\boldsymbol{x_i'}$	$x_4' = 4, x_5' = 4$

Step 5.	**Set $\boldsymbol{N} = \boldsymbol{\Pi_2}$ and $\boldsymbol{B}$, and go to step 1.**
Repeat Step 3.	
$\boldsymbol{B}$	$\mathrm{B} = x_7 + x_{10} + (x_4 - x_4') + (x_5 - x_5') = 10$
$\boldsymbol{\lambda}$	$\lambda_{7,10} = \frac{(\sqrt{\omega_7 c_7} + \sqrt{\omega_{10} c_{10}})^2}{B^2} = 38$
$\boldsymbol{x_i}$	$x_7 = \sqrt{\frac{\omega_7 c_7}{\lambda_{7,10}}} = 4,\ x_{10} = 4$
$\boldsymbol{C_i}$	$C_7 = a_7 + \frac{c_7}{x_7} = 100 > d_7, C_{10} = 99 > d_{10}$

Step 6.	**Since both projects 7 and 10 are tardy under the new resource allocation (i.e., $\boldsymbol{\Pi_2 = N}$), we stop. The minimum total weighted tardiness is**
	$\omega_1 \cdot 0 + \omega_2 \cdot 0 + \omega_3 \cdot 0 + \omega_4 \cdot 0 + \omega_5 \cdot 0 + \omega_6 \cdot 0 + 2 \cdot (100 - 94) + \omega_8 \cdot 0 + \omega_9 \cdot 0 + 2 \cdot (99 - 98) = 14$

Chapter 6

Conclusion and Future Research

This research addresses an integrated problem of coordinated supplier selection and resource-dependent project management with final project review sequencing that encountered by a real-life case in construction industry. We formulate the problem to a mixed integer linear program (MILP) model, which contributes the literature as a new mathematical model that describes a common operational problem emerged in coordinating the project resource allocation, the activity schedule, and the final project review operations.

Furthermore, we propose a heuristic approach that decomposes the MILP model into three sub-problems aforementioned, which can be solved independently and consecutively. The benefits of such decomposition are twofold: (1) each sub-problem is much smaller in size than the original problem, and hence can be solved quickly by a standard MILP solver; and (2) the resulting project activity scheduling can be solved at an individual project level, enabling the use of parallel computing for all projects. The overall objective is improved by updating a weight vector in the supplier selection sub-problem, where the shadow prices of some constraints in the project activity scheduling sub-problem and project review sequencing sub-problem are utilized to guide the weight updates. Our empirical studies show that the proposed heuristic is capable of generating near-optimal solutions in a short computational time.

Last but not least, we extend our problem toward two directions in strategic terms. First, we examine a collaboration policy on final project review, both under batch mode slot assignment and sequential mode slot assignment. Second, we study a resource allocation strategy based on time-resource tradeoff subjects to uncertainty of activity durations. The results and observations obtained from this part of studies contribute to the literature of stochastic project management and confirm the power of collaboration in project management practices. In addition, this strategy can be used to provide project managers with the incentive to improve the project performance when they encountered such problem. Note that both problems can be applicable to the projects in construction or other industries.

In future study, we have two major extensions on this research: (1) *Constrained project scheduling with renewable and nonrenewable resources.* Project scheduling, especially constrained by the co-existing renewable resources (e.g., equipment, labor, utility, and skilled technicians, etc.) and non-renewable resources (e.g., monetary, construction material supplies, and contractor hours), is both computationally challenging and practically appealing. Even in its simplest version, this problem reduces to the well-known bin-packing problem, a computationally intractable problem (NP hard). In the current literature, there is a significant lack of solution methodologies. Several results obtained from this dissertation can be extended toward that end. (2) *Project scheduling with inspection requirement and multiple objectives.* Project scheduling with inspection requirement and multiple objectives is another common problem encountered in the practices of construction supply chains. Objectives that should be considered simultaneously by a construction manager could include minimizing the variations in the workforce level over a project period, maximizing the customer satisfaction (by ensuring each individual project to complete close to the target completion time) and the suppliers' satisfaction (by minimizing the suppliers cost to fulfill the supply contract). While project scheduling with a single objective and relaxed project review and suppliers' capacity have been studied for many years, the generalized version of this problem has scarce results in the academic literature. (3) *Supplier assumption.* First, the assumption that a supplier can only provide one type of non-renewable resource can be extended to that one project can use multiple suppliers to represent as one supplier. Second, third party or 4PL can be considered with the application in practice. The algorithm could be used by an overall multi-project coordinative firm, similar to a 3PL or 4PL. (4) *Sustainability application.* Integrate the Green Building in to the current tool from the perspectives of supplier selection, project scheduling, and project quality inspection. There is a lack of a systematic tool in current literatures to solve an integrated problem of the supply chain management and project scheduling in construction industry. (5) *Alternative decomposition schemes of the heuristics*. In this research, we develop a mathematical programming-based heuristic based on three decomposed sub-problem: supplier selection $\mathbf{P^S}$, project activity scheduling $\mathbf{P^A}$, and project review sequencing $\mathbf{P^R}$. Alternative heuristics can be developed using other decomposition schemes.

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