MULTI-RESOURCE ALLOCATION
ACROSS MULTI PROJECTS BY SUBCONTRACTOR

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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This document is dedicated to my lovely grandparents in the remote country. And it is also dedicated to my family for their unconditional support.

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Due to the limitation of resources on construction projects, the subcontractor will shift multi resources fluidly within projects or across projects to meet resource demands. During the multi-resource allocation procedure, some factors influencing the cost have to be considered such as the change to existing conditions and the collaboration across projects.

The research has been conducted in this area. Some influence factors are identified to establish a model to figure out productivity change and help allocate various resources. Then the original resource allocation schedule can be improved so as to reduce the subcontractor's total construction cost.

The objectives of this thesis are to discuss the effects of multi-resource allocation and determine how to reach a better multi-resource allocation approach by a mathematical model.

CHAPTER 1
INTRODUCTION

General

The construction industry is one of the driving industries in the economy. Through the first ten months of 2004, the total construction on an unadjusted basis came to $495.3 billion, up 9% from the same period in 2003. The 9% increase for the total construction during the January-October period of 2004, compared to 2003, was due to this performance by sector – residential building, up 16%; non-residential building, up 3%. By geography, the total construction in the first ten months of 2004 was the following—the South Atlantic, up 13%; the West, up 12%; the Northeast and South Central, each up 7%; and the Midwest, up 4% (Dodge, 2005).

Recognizing the economy growth rate in 2004 has settled to 4.4 percent that is above the historical trend, a booming construction market is expected in the year 2005. Residential improvements are forecast to remain strong, fueled by higher new home prices, and a scarcity of buildable land in many markets. The nonresidential segment will accelerate to a growth rate of 6.0 percent in 2005, equaling the growth rate in the residential markets. On the other hand, inflation is back on the radar screens of both the central bank and the financial markets. The Consumer Price Index (CPI) jumped up 2.0 percent toward the end of 2004, the highest reading of the year. Prices for construction products and materials became a major issue throughout 2004. The cost of certain steel products and wood panel products rose by 150 percent or more, with limited availability. Gypsum, structural lumber, cement, copper, and PVC all showed major increase. In the

case of steel, a strong foreign demand (e.g., from China), limited domestic capacity, coke shortages, and a limited number of available ships will keep up price pressures. Similarly, a shortage of cement is expected to result in the price going even higher (Giggard, 2005). So for the subcontractors, construction resource allocation optimization has a significant impact on the ability to achieve success in the implementation of construction projects.

Although research in construction management and practitioners in the construction industry realize the importance of resource allocation across construction projects, there is still a divergence of opinion on how much effort should actually be invested in construction resource allocation activities to obtain a better performance during the construction period, and how much benefit the subcontractor may obtain through these reallocated resource activities. Moreover, even now some subcontractors are indeed reallocating resources at some degree in construction, they just make decisions with their experiences, without a systematic method that can take into account the actual external conditions as much as possible, and then can assist subcontractors to adjudge the situation impersonally.

The objective of construction resource allocation is to find a way that is consistent with specified resource limits, as well as profiting subcontractors the furthest and matches up with the schedule. It is necessary for the subcontractor to plan overall plans for multi projects and take all factors into consideration to obtain the maximum profits. Sometimes they would have to change the existing resource allocation plan. The result of planning as a whole is that some projects may not have the shortest construction duration; meanwhile other projects may take too much resource than the average level. The

subcontractor's ultimate objective however is to lower construction costs, and improve profit margin, with a fixed total amount of resources.

In this thesis, an attempt is made to develop a practical approach that presents a near-optimum solution to allocating finite construction resources among projects in the standpoint of the subcontractor. The thesis starts with a brief description of the resource allocation problem. The impact of resource allocation on construction cost is then proposed, approaching consequent tardiness and overtime costs. Followed by optimization applications in both single project and multi-projects, parametric models are addressed to figure out the productivity change and the corresponding results in different costs and profits, taking into consideration the resource situations. The multi-resource project's guideline is evolved by the optimization implementation. The performance of the proposed approach is then evaluated, and recommendations made.

Introduction of Scheduling Optimization Concepts

As we know, scheduling is a matter of great concern in construction. Resource allocation is one of the scheduling optimization methods. Optimization problems in construction scheduling are traditionally classified into the following categories depending on the objectives: (1) time-cost tradeoff; (2) resource leveling; and (3) resource allocation (Hegazy, 1999). What is the difference? What specific characters for resource allocation?

Time-cost tradeoff is concerned with minimizing the project cost while maintaining the desired project duration. Resource leveling is concerned with minimizing peak resource requirements and period-to-period fluctuations in resource assignment while maintaining the desired project duration. Resource allocation is concerned about minimizing project duration without exceeding the available resource limits.

Normally the subcontractor has more than one project to work ongoing. Each construction project is composed of a network of activities. Each activity in a project has a corresponding duration. The project duration is usually measured in integral increments of time called independent subsets (that will be elaborated in Chapter 2 – Literature Review) each of which consist of certain activities. The normal duration of an activity refers to the time required to complete that activity under normal circumstances. Meanwhile the construction cost of an activity or a project is somewhat associated with its construction duration. Normally, corresponding to the reduction in activity/project duration is an increase in direct cost, and in contrast a decrease in indirect cost. For some activities and projects, it is possible to reduce their duration below the normal duration. This is done through some measures called crashing. Some ways by which crashing is achieved include overtime, additional manpower, equipment and/or other resources, and the use of better skilled men and/or improved technology. Crashing with resource allocation is done as a tradeoff between resource, duration, and cost. But on the basis of limited resources, considering both the direct cost and the indirect cost in construction, the comprehensive total cost maybe maintained at the same level, perhaps even lower, with shorter activity duration. This study is to determine the best one during the period of optimizing resources.

On the other hand, resource allocation attempts to reschedule the project tasks so that the existing resources can be efficiently utilized while keeping the modified construction schedule does not exceed the required construction duration. At present few companies can remain competent in today’s highly competitive construction industry

environment without effectively managing their resources, particularly the allowable adjusted resources.

Concerning the resource allocation, the basic PERT (Program Evaluation and Review Technique) and CPM (Critical Path Method) scheduling techniques in practice have proven to be helpful only when the project deadline is not fixed and the resources are not constrained by either availability or time, assuming that the resources are neither able to flow from one activity to another activity, nor flow among different projects. As this is not practical even for smaller sized projects, the resources in construction are basically fixed in quantity, and resource allocation has been used to achieve a near-optimum result in relation to practical considerations, allowing the resources to shift among activities and projects.

An activity or a project can have any duration between the normal and crash duration. However, one subcontractor normally has a cluster of ongoing activities or projects. The subcontractor needs to comprehensively analyze the different resource allocation schemes, then find a most profitable one and work out the lowest construction cost accordingly.

Due to the complexity of construction projects, time-cost tradeoff and resources allocation have been dealt with as two distinct sub-problems that cannot guarantee optimum solutions. In this thesis, a proposal is addressed to time-cost tradeoff and resource allocation, considering both aspects simultaneously. In other words, resource allocation is used to adjust the schedule and solicit the optimal tradeoff between the duration and the cost, so that the final objective is to find the schedule by which the

contractor is able to supply the project in demand as well as reach the maximum profit at a lower cost.

Problem Statement

The goals of this study include the following:

- Presenting a thorough literature review on the effect of resource allocation on the schedule duration and the construction cost.
- Identifying the relevant external influence factors.
- Presenting some hypothetic models and conduct case studies to demonstrate validity of the models.
- Outlining the future extensions.

Scope and Limitations

Due to limited time and access of information, the initial study focused particularly on some major kinds of resources. The other resources are not mentioned in this thesis. Also the case studies only happened to subcontractors with labor allocation.

Since resource allocation may follow different development steps and patterns in other countries, the literature review focused on scheduling the development and application of methods in the United States.

Responding to the above-mentioned restrictions, the scope of this study has been set as the following:

- The literature review reflects construction resource allocation characteristics and its applications in the United States. Other possible characteristics that may seem evident in other countries are not included.
- Because of a variety of resources depending on the specific fields, this thesis only addresses the problem of some sorts of major resources often encountered in construction projects. The other possible resources are not analyzed in detail. The hypothetical model is established on the basis of these major resources.
- The case study was only done to subcontractor located in Florida and Arizona. The viewpoints will be more applicable if more subcontractors are investigated.

CHAPTER 2
LITERATURE REVIEW

The objective of this literature review is to define the basic concepts in this thesis, and introduce methods and models proposed in earlier literature that would be a starting point for this research about resource allocation. This chapter will also try to collect information on the application and development of resource allocation in both single-resource and multi-resource projects in reviewing the relevant application of optimization by the methods in kinds of resource allocation. At the end of this literature review, research needs will be generalized to start the research methodology design, data analysis, and conclusion in a later chapter.

Basic Concepts

The research in the past decades supplied a large number of publications about the resource allocation and the construction cost change as a consequence of resource allocation. Some basic concepts resulting from this past research are relevant to the study in this thesis. It is necessary to discuss them first.

Resource Constraints

Typical resources that have appeared in construction include a rented piece of equipment that needs to be returned early, a number of skilled workers or crews who need to be hired for the job, some amount of material that needs to be used in the project, and proper working spaces where the project can be operated, and so on.

For complexity reasons, construction scheduling is a critical process of assigning activities to resources in time. However, a variety of constraints affect this process, so

that scheduling actually is a decision-making process—the process of determining a schedule. Normally a project construction is affected by constraints as follows: activity durations, release dates and due dates, precedence constraints, transfer and set-up times, resource availability constraints (shifts, down-time, site conditions, working spaces, etc.), and resource sharing. These constraints define the space of admissible solutions.

It has been acknowledged that the use of constraint-based techniques and tools enables the implementation of precise, flexible, efficient, and extensible scheduling systems: precise and flexible as the system can take into account any constraint. Critical Path Method (CPM) is the basic scheduling solution and widely applied to the construction field. But CPM scheduling computations do not take into consideration resource constraints. However we can see that in most practical situations the availability of resources is limited. The assumption of unlimited resources is unrealistic and may result in unfeasible solutions. In addition to the CPM approach, the Time-Cost Trade-off (TCT) approach is criticized for being incapable of representing the capacity costs and constraints of subcontractors and suppliers to resolving changes in schedule. Capacity constraints and poor site conditions cause subcontractors and suppliers real costs, which managers should take action to mitigate, and also suggested incorporate site conditions and capacity constraints into construction planning and scheduling techniques (O’Brien and Fischer, 2000).

Other scheduling methods such as resource leveling, overtime, etc. also have this shortcoming mentioned above. As a matter of fact, resources are flexible and allowed to shift in a reallocating method. If resources are superfluous at some time period, slack resources can be shifted to other activities or projects where more resources are needed so

as to save money for the subcontractor as well as speed up the lagging projects. Actually even when resources are not excessive, they still may be allocated to critical activities or projects where time can be bought cheapest while maintaining resource feasibility. Efficient reallocation of resources for construction planning activities possibly may reduce the duration of activities below the normal duration even in a lower cost.

Resource Allocation

Resource allocation is one of the new scheduling approaches developed in the past decades. It constitutes another important class of scheduling methods. Through mobilization and shift of constrained resources across activities in construction projects, even across different projects, it is an attempt to seek a more realistic scheduling method, having the minimization of both project duration and total project cost as its goals.

In the practical construction environment that subcontractors operate within, resources must be allocated to multiple jobs in activities, even to multiple projects because of limited resources. Very often resources must be allocated in conditions of competing demand and uncertainty about project schedule. Subcontractors will shift resources fluidly among the jobs, activities, or across projects to meet demands, trying to find low cost allocations within a project or across projects.

Because resource allocation is supposed to solve a more practical schedule, incurring a substantial portion of the cost of the project and significantly affecting its duration, it has therefore received a great deal of attention from researchers. So resource allocation is becoming a very popular measure to control total construction costs, especially preferred by subcontractors. Many scholars mentioned resource allocation as a scheduling optimization method in the huge volume of literature over the years. Birrell (1980) was the first author to consider the implication for project uncertainty and change

on the cost and resource allocation of subcontractors and suppliers and the need for consideration of resource constraints when coordinating schedule alternatives. Subsequent empirical work has demonstrated that subcontractors and suppliers routinely reallocate resources among jobs, activities, and projects on a daily basis (O'Brien and Fischer, 2000). Hegazy (2000) developed solutions that mathematically illustrate scheduling with certain constrained resources.

Construction Costs

The final objective of scheduling and resource research is to determine which resource allocation will give the best overall economical solution. Then what are the compositions of project costs? The costs caused by construction activities are easily understood as the *direct cost*, which may be expected to dominate each operation in the form of material costs, labor costs, equipment costs, etc. Especially with the contract system, direct cost is critical when the work may be completed at the lowest total cost. However, the project direct cost does not represent the full cost of the work. Besides direct cost, the total cost must be added to all the other *indirect costs* of the project such as overhead charges, payment to office staff, etc.

Because both direct cost and indirect cost are associated with the complete execution of the work, and proportional to time, they jointly elaborate the derivation of the total project cost curve. The solution to the cost problem is: all costs vary with duration and direct costs tend to decrease if more time is available for an operation, but indirect costs will increase with time (Antill and Woodhead, 1982). See Fig. 2-1 for an illustration of this point.

For the direct cost, the least duration will result in the highest cost while the lowest costs will be spent with the available longest project duration. Moreover, the direct cost

curve is concave and the magnitude of its slope decreases monotonically with increased project duration (Chaker, 1973). Any project schedule is feasible between the least time duration and the normal duration, even the duration with tardiness.

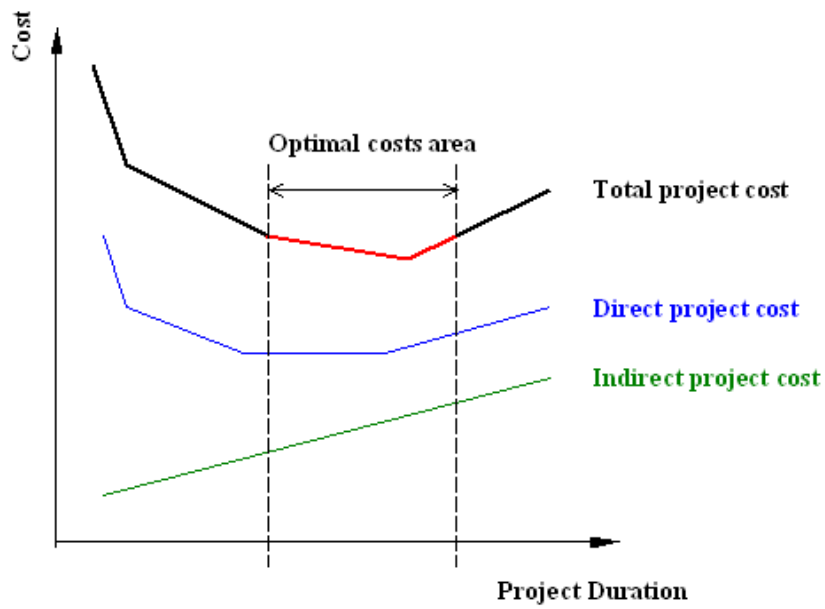

Figure 2-1. Construction costs composition. Total construction cost consists of direct cost and indirect cost. Indirect cost is basically linear proportional to project duration. Extremely short or excessively long project durations make direct cost higher.

The indirect costs are estimated by the planner in a conventional way and vary with different project completion times. Usually they vary almost directly with project duration. Only making out the needed indirect costs for the normal or tardiness duration solution and for one other duration such as the least time duration solution, a straight line variation will be derived between these two points.

In general, the project total cost curve may be figured out by simply adding two cost curves at any desired duration on the diagram. Of course the direct cost curve has a fluctuation range with the different resource conditions and other constraints. Then from Fig.1, a minimum total project cost is immediately found. This is the most economical

solution for the project. In practice, it is unlikely that a subcontractor can always reach this optimal point. If construction cost is within a range adjacent to the minimum point, the projects will be profitable enough. In other words, the objective of allocating resources across projects is to make sure the cost is in such a scope; also, the corresponding durations are acceptable.

Independent Subset

It was mentioned before that the project duration is usually measured in integral increments of time called independent subsets, each of which consist of certain activities or projects. The notion of independent subset was introduced to effectively avoid the disorder possibly aroused by coincidence of too many activities or projects (Yang et al. 2002). It is necessary to arrange so many activities and projects, which happened on a subcontractor and interlaced to each other, in order of time.

They proposed an approach that assumed that all activities or projects carried out by a subcontractor are not absolutely available for processing effectively at time zero. They took into account the project planning and activities sequences controlling. A subcontractor generally has several ongoing projects, and a practical construction project consists of dozens or even hundreds of activities. Every activity or project has its duration, resources needed in construction, and costs used to guarantee the processing of this activity/project. Considering the possibility of processing many activities, even many projects at the same time, everything will be interlocked if activities are assumed to be available along the scheduling horizon. It will become too complicated and desultory to allocate resources across activities or projects, and further to work out the resulting duration and costs. So the tone is set for the basic research entity—*Independent Subset.*

For any schedule of projects, an independent subset of project satisfies three definitions: (1) the release date of the first job in the subset is strictly greater than the completion date of the job's immediate predecessor; (2) the completion date of the last job in the subset is strictly less than the release date of its immediate successor; (3) no unscheduled regular time exists between the start of the first job in the subset and the completion of the last job in the subset. (Yang et al. 2002). See Fig. 2-2 for property of the independent subset.

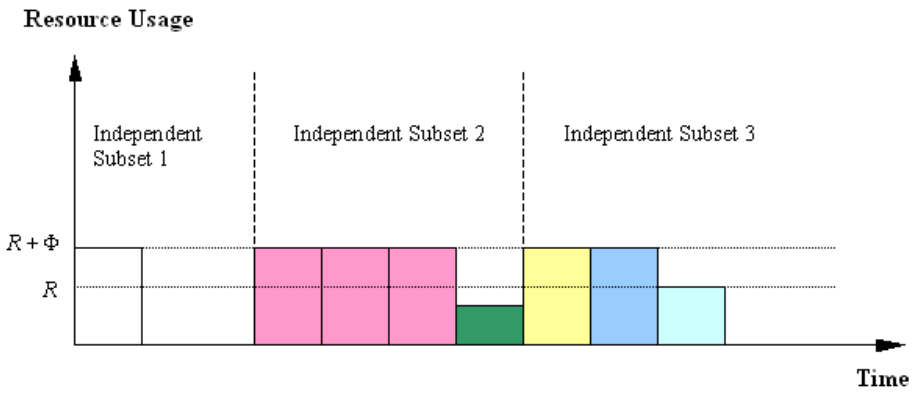

Figure 2-2. Graphic illustration of property of independent subset (Yang et al. 2002).

In Fig.2-2, the time horizon length represents the schedule time for a specific resource. Independent subsets on this time horizon actually are a series of activities or projects applicable to one kind of resources. Once the duration and costs of every independent subset—activity or project—are obtained, the necessary duration and construction costs with this specific resource will consequently be received. Each independent subset, i.e., the block along the time horizon, is composed of several activities or projects. All of them are processed in accordance with a predetermined sequence. For example, we have scheduled the first project in an independent subset to complete on day t_1, and the next job in the sequence, i.e., the second project, has a release

date of t_2, with $t_2 = t_1 + k$, where k is a nonnegative integer greater than 1, then no jobs are scheduled on days $t_1 + 1$, $t_1 + 2$, …, $t_1 + (k-1)$ in the original schedule, and so on. After reallocating the resource within the independent subset, several adjustments must be made. Some jobs have longer durations, but some of them have shorter construction durations. Accordingly the independent subset's durations and costs will change for the whole project as well.

It is important to note that the definition of an independent subset does not preclude an independent subset consisting of a single job or an independent subset consisting of all jobs to be scheduled, which occurs, for example, when all release time equals zero. For instance in the case illustrated in Fig. 2-2, there is only one activity/project in Independent Subset 1. But Independent Subset 2 comprises 4 activities/projects, and 3 activities/projects in Independent Subset 3.

In Fig.2-2, R represents regular processing time, and Φ represents overtime. These two notations may be regarded as a form of construction resource in this thesis. They are shifted across activities or projects so as to optimize the original schedule and make more profits. The problem is to schedule a finite set of activities or projects with a single resource during some finite time horizon of length T. Here the processing time is used to elaborate the concept of independent subset. Each activity or project has an available processing time of R during regular time, plus an additional amount of time Φ, for overtime. Both of them are period independent. So the total amount of processing time available in a given period can be expressed as R+Φ.

Assuming that the resource is set available in each period R+Φ, the original schedule consists of m independent subsets, where m is a positive integer. Suppose index

these subsets in order of increasing start time (i = 1, 2, …, m). If m = 1, then simply apply resource allocation among jobs within this subset. If m > 1, then apply resource allocation individually to jobs of each independent subset, then apply to all independent subsets to one another from 1 to m.

Some independent subsets are flexible. They are possibly combined into a new independent subset under a certain condition. This procedure may be realized through two phases—compacting phase and relaxing phase. Firstly compacting phase is to fully utilize all available overtime in any period to make out a corresponding schedule. Then in relaxing phase, the total amount of overtime used in every period (beginning with the latest scheduled job that uses overtime and working backwards in time) is sequentially decreased. Except subset m, other independent subsets may become “blocked” in applying the relaxing phase to an independent subset, when the completion time of the last job in the subset reaches the period immediately before the starting period of the next independent subset, and also exhausts all regular time in the period. If independent subset i does become blocked by subset i +1, then the two subsets i and i + 1 merge into a single new subset. The new merged subset must satisfy the conditions required in the definition of an independent subset. Figure 2-3 below provides an example of one independent subset blocking another in the resource allocation phase, producing a new independent subset.

The above figure provides an example of one independent subset blocking another in the phase of reducing overtime, producing a new independent subset. The utilization of other kinds of construction resources such as materials, labors, etc. is somewhat analogous to that of processing time expatiated above.

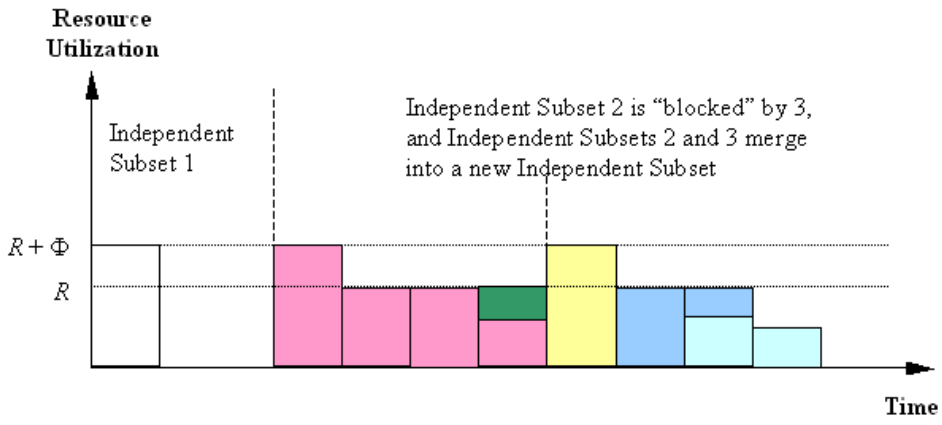

Figure 2-3. Graphic illustration of formation of a new independent subset from two consecutive independent subsets. Independent subset 2 is blocked by independent subset 3, and then merged with independent 3 into a new bigger independent subset.

Perspectives of Application to Multi Projects By Subcontractor

The study of this thesis focuses on the resource allocation application to multi projects constructed by subcontractor. It is believed that the resource allocation is exerting markedly on multi projects, particularly by subcontractor.

Why Multi Projects

Because of the resources finites, subcontractors need to maintain a resource demand balance across many projects. The environments and projects require the allocation of materials, labor, equipment, and other resources to complete a set of construction projects that change over time.

Subcontractors will shift resources fluidly across projects to meet demand, seeking to optimize productivity across projects. Choices about resource allocation are perhaps the most important operational decision that subcontractors make. The ability to shift resources across projects is a key component of flexibility. Subcontractors, unlike suppliers, have limited ability to buffer production by producing ahead of schedule and respond to changes on projects by reallocating resources (O'Brien, 2000). A parametric

model relating productivity, site conditions, and resource allocation to a work package was described, and implications of the model were discussed when considering multi-project resource allocation.

Due to increasingly intense international competition, construction firms are constantly undertaking multiple projects while they might leverage their resource investments in order to achieve economical benefits. Accordingly, the perspective of multiple projects scheduling has become a critical issue for competition. Regardless of the number of projects, the final objectives for all projects are to strive for minimum total completion time, minimum total costs, and maximum resource usage efficiency.

Generally speaking, multiple project scheduling is an area where traditional methods and techniques appear to be less adequate.

Why Subcontractor

Subcontracting has become prevalent in the construction industry, and presented as an organizational alternative for some economic activities. Construction firms are dispersing their jobs more and more, as subcontracting becomes a basic part of the work organization.

The reasons why subcontracting prevails may be summarized as follows: increasing sophistication and specialization of trades, which requires long-term investment in personnel and equipment; increasing prefabrication off site, which similarly requires large-scale investment in fixed facilities; fluctuating demand for services of general construction contractors, which demands agility in adjusting capacity (Sacks, 2003).

Nowadays, in order to reduce costs, construction firms do not need to have control of all the value string. By subcontracting, they are able to externalize non-strategic

activities, realizing the aim of costs reducing. Building firms are organized into a consistent operating core based on their individual capabilities. More and more construction companies are becoming construction managers or contractor managers after transferring construction jobs to specialists. Meanwhile, subcontractors are specialists in the execution of a specific task. They may supply manpower, materials, and equipment as well as designs and techniques.

In the United States, currently in many projects, it is common for 80-90% of the construction work to be performed by subcontractors. They perform construction work that requires skilled labor from one or at most a few specific trades and for which they have acquired both special-purpose resources and process know-how.

Other Literature

The project scheduling literature contains a variety of work dealing with multi-project and subcontractors' problems. Not meant to be exhaustive, this review is limited to some relevant technologies about resource allocation. While some research considers only one type of resource, some models are only with stated resource constraints, some with single resource, and some with multi resources, and the diversity reflects the complexity of the reality. This chapter tries to tie together widely scattered ideas and to assess a resource allocation model in a simple and generalized form.

Sacks (2003) proposed a model of a multi-project and multi-subcontracting paradigm. He tried to identify ways to align a subcontractor's benefit and better understand workflow from the subcontractors' point of view. Adopting the subcontracting, and researching problems faced by subcontractors, the ultimate goal is the total amount of benefit achievable by both general contractors and subcontractors across multiple projects.

O'Brien (2000) presented a model associated with site conditions, resource allocation and productivity, allowing quantitative assessment of the impact of shifting resources across projects. Use of the model for multi-projects resource allocation decision was discussed, and several implications for subcontractor and site management were developed.

Hegzy (2000) addressed the algorithm for scheduling with multi-skilled constrained resources. Hegzy (2001) also presented Subcontractor Information System that supports the estimating and project control functions of subcontractors.

Models of Subcontractor's Construction Costs

Tardiness and Overtime Cost Model

Flexible preference constraints characterize the quality of scheduling decisions. These preferences are related to due dates, productivity, frequency of changes, inventory levels, overtime, etc. Since preference constraints may conflict with one another, the resolution of a scheduling problem also consists in deciding which preferences should be satisfied and to what extent others should be relaxed.

In practice, however, preference constraints are often either combined into a unique evaluation or cost function to maximize or minimize, or compiled into evaluation heuristics to favor candidate solutions that satisfy the preferences.

A heuristic approach was tried to minimize weighted tardiness and overtime costs in single resource scheduling. The tardiness costs and overtime costs, as the constraints, are collaborative and considered to satisfy while the scheduling solutions are eventually gained (Yang et al. 2002). A solution to the scheduling problem is a set of compatible scheduling decisions (such as performing the project as soon as possible after tardiness

and overtime costs are generated), which guarantee the satisfaction of the constraints, i.e., minimizing the sum costs of both constraints.

The previous literature normally assumed each job took a certain fixed amount of time on the resource, and that both processing times and resource usage can be measured in some continuous time increments, also an assumption exists that the cost of processing activities is the same no matter when the activities are processed, the amount of available processing time in each processing period is fixed. In the paper mentioned above, Yang, Geunes, and O'Brien thought the primary method the contractors employ to meet due dates of the project was through the use of overtime. So they tried to overcome the defects in the previous research to direct the construction with a tradeoff of tardiness cost versus the use of overtime (Yang et al. 2002).

A model was made to simulate the overtime-tardiness problem. In the model, compacting was the first step that made out a corresponding schedule by fully utilizing all available overtime in any period. The created schedule guarantees the minimum total tardiness costs under the fixed sequence, but with a high overtime costs. Then a relaxing phase was carried out—sequentially decreasing the total amount of overtime used in that very period (beginning with the latest scheduled job that uses overtime and working backwards in time). The total amount of relaxed overtime is a function of whether the relax phase produces a lower total cost schedule, so that the optimal sequence of jobs, the start date, finish date, and overtime usage for each job were able to be determined.

Basically the overtime cost is the increment with a fixed amount every overtime unit (hour, day, week, month…). So it can be seen that the overtime cost is linear in overtime resources utilization. For the tardiness cost, it keeps stable within one time

interval, e.g., the daily penalty or the weekly penalty is a fixed amount within one day/week. The construction term of the project will not be reduced by one day or one week unless the accumulated overtime utilization reaches a certain amount. That means the tardiness cost decrease is a stepwise decrease to total overtime usage instead of a linear relationship to the overtime usage. Therefore, the total cost function is the sum of a linear function and a stepwise decreasing total tardiness cost function. The resulting total cost curve is shown as the saw-tooth curve in the following Fig. 2-4.

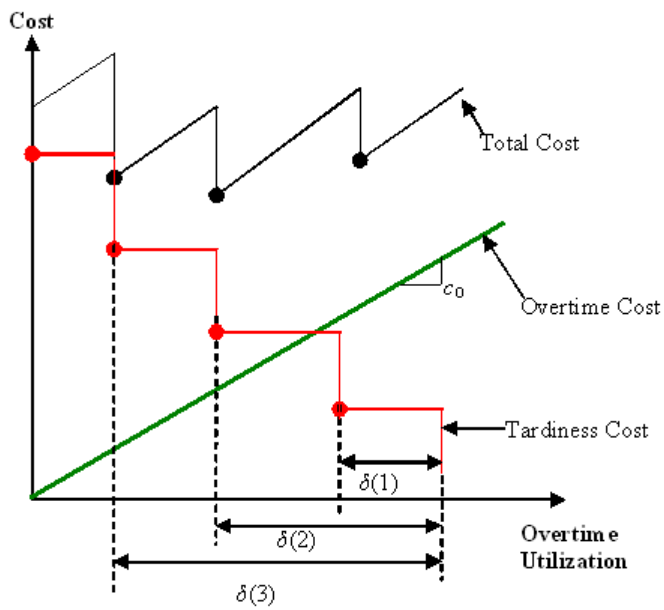

Figure 2-4. Total cost curve as a function of overtime utilization under the compact and relax procedure. (Yang et al. 2002)

The tardiness cost for an activity determines the amount of cost decrease at each of the steps in the curve, while the overtime cost per unit time, c_O, determines the rate of increase after each step. The compact and relax algorithm evaluates the cost at the bottom of each spike on the saw-tooth curve, then finally a minimum total cost for the predefined sequence of jobs might be obtained.

Overtime and due date were presented for the representation of constraints and subsequently a solution was figured out to satisfy these constraints, by resource allocation, proper usage of overtime, and tardiness (Yang et al. 2002).

Parametric Influence Model

When subcontractors make resource allocation choices, they have to take into account some influence factors. O'Brien (2000) addressed these considerations in his literature— "Multi-project Resources Allocation: Parametric Models and Managerial Implications". He proposed a productivity model with which subcontractors allocate resources. He stated that subcontractors must consider the switching and logistics costs of moving resources across projects, the affect of altering the balance of different classes of resources, and the ability of a project to absorb and loan resources with regard to productivity and completion dates.

The parametric model was defined as:

$$Pi = (a_j^{\ T}\ y)CW$$

The productivity model was described as an ideal productivity with complementarity. For the construction method j, the rate per unit of flexible resources (such as labor, small tools and equipment that are often used by single workers), a, multiplied by the number of flexible resources, y, gives the ideal productivity rate. Complemented by flexible-fixed resources ratio (fixed resources were defined as heavier equipment that serves crews rather than individuals) C and work area productivity modifier W, the final actual productivity rate was gained.

When there is an ideal ration of flexible to fixed resources, complementarity modifier C reaches a maximum value of 1. As the ratio varies, the value of C will decrease towards zero as shown in the Fig.2-5.

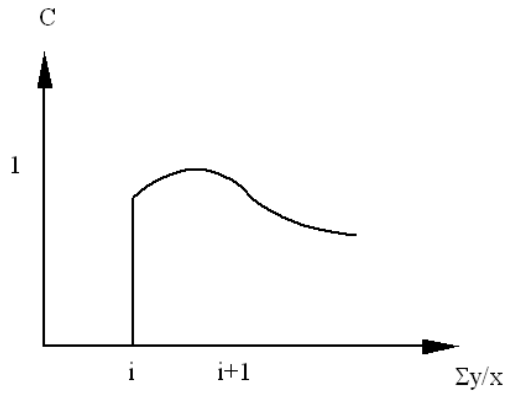

Figure 2-5. Complementarity (flexible/fixed resources ratio) modifier curve

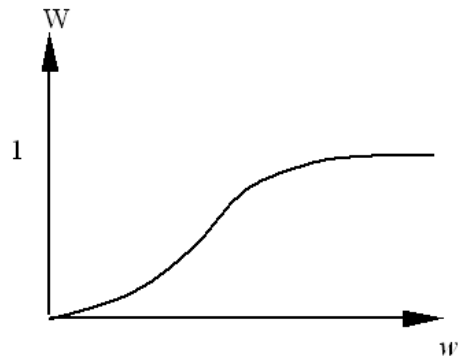

Figure 2-6. Work area modifier curve

Work area modifier W is a function of the size of work area *w*. W is zero when there is no available work area. That means there is no possible production. As work area increases, productivity increases too.

O'Brien's model provides the subcontractor with insight as to how to allocate the resource. Such a model may become the criteria for subcontractors in determining project operating decisions, making contracts and developing schedules.

Summary

Critique and Current State of Literature

In the above-mentioned literature about tardiness and overtime cost, there was a presumption of solution approach that job preemption on the resource was not allowed,

i.e., once a job is started it must proceed to completion before any other job can be started (Yang et al. 2000).

In a practical construction project, the original construction schedule is allowed to adjust and change in order to match the time schedule well and ensure the financial situation in the budget. Sometimes activities would be started in advance and at other times postponed a little. Consequently one resource might be preempted by another job instead of the scheduled job. Moreover, many projects keep changing even in the process of construction, particularly in the design-build projects that become more and more popular in this industry. The designer, the owner, and the contractor need to cooperate closely, and frequently change their plans and timetable in accordance with the requirements.

Furthermore, compacting phase is to set the resource availability to the hard time, i.e., the regular time plus overtime. For the algorithm proposed in this paper, the relaxing phase is to begin with the last scheduled job after the compact phase of the algorithm. This relaxing procedure is repeated backwards till the first scheduled job. In this phase, the overtime costs are going down to zero while the decrease of working time possibly results in the tardiness costs.

In practice, few contractors will complete the project later than the project due date requested by the owner. It is about not only the cost problem, but also the reputation of the contractors. So the contractors are unlikely to make out a schedule longer than the required completion days. The contractor has to keep the record and reputation good in order to get more projects. They definitely would rather increase the investment such as increase the overtime to ensure the completion date than consider if the tardiness costs

are lower than the overtime costs. Normally subcontractors will try their best to prevent tardiness from happening. So it is significant to study projects with presumption of normal durations.

Research Needs

The final target of a subcontractor's multi-project resource allocation research is to complete the project in time and in demand desired, meanwhile with possibly lower comprehensive total costs. The project duration may be adjusted to be shorter or longer within an allowed scope through resource allocation. Considering indirect cost, a fluctuation in total cost curve can be achieved. The lowest point of this fluctuation curve is the optimum solution to subcontractors (to be explained in chapter 4). However, due to the complexity of construction, the total cost and project duration vary by complicated situation such as the disturbance caused by relevant activities to one another. So the case studies with calculations of both cost and duration will focus on a single resource project in this thesis. However, the implications of project uncertainty and change on the cost and resource allocation of subcontractors in multi-project will also be discussed.

Through the literature review, the relevant information and basic concepts necessary for resource allocation resolution in my thesis are collected and explained. Different from overtime usage or other time-cost tradeoff methods, resource allocation is absorbing more attention in the construction field because of its property of being flexible and being prone to construction cost reduction, constructability improvement, and better project quality.

Starting from the basic entity—independent subset in a single resource project, resource allocation optimization will be analyzed and extended to further prospect. In my study I will seek the cost curve related to resource allocation, and create some models

that relate to site conditions, resource allocation, productivity, and other influence factors. In view of the perspectives of resource allocation application in multi-project, the project scheduling problems will be discussed in detail.

CHAPTER 3
SINGLE RESOURCE ALLOCATION ACROSS PROJECTS

This chapter discusses the basic concepts on which a model for resource allocation in a single-resource project is built. Components of construction cost are explained and a parametric model used to optimize the resource allocation is introduced as well. Two case studies are used to help understand the application of single resource allocation that establishes the base for development of multi-resource allocation.

Presumption

Resource Shifting Within Independent Subset

According to the concepts of independent subsets elaborated in chapter 2, the project duration is measured in integral increments of time of independent subsets. Independent subsets are accrual units that chronicle along the time horizon. The allowed adjustable resource such as labors, materials, equipment, etc. can be shifted among the activities or projects within one independent subset. After obtaining the durations and corresponding costs of affected activities or projects, they may evolve into data of a series of independent subsets. Then the subcontractor's total project costs associated with this specific kind of resource may be evaluated.

In practice, activities or projects within one independent subset occur simultaneously. These activities or projects are using the resources at the same time. They integrate together to form a complete independent subset. Within an independent subset, every activity or project is allowed to adjust respectively, i.e., with resource reallocation across these activities or projects. All of the subcontractor's work is divided

into many independent subsets in the time order of activities or projects. On the basis of Fig. 2-2, we can illustrate the resource reallocation within an independent subset as shown in Fig.3-1.

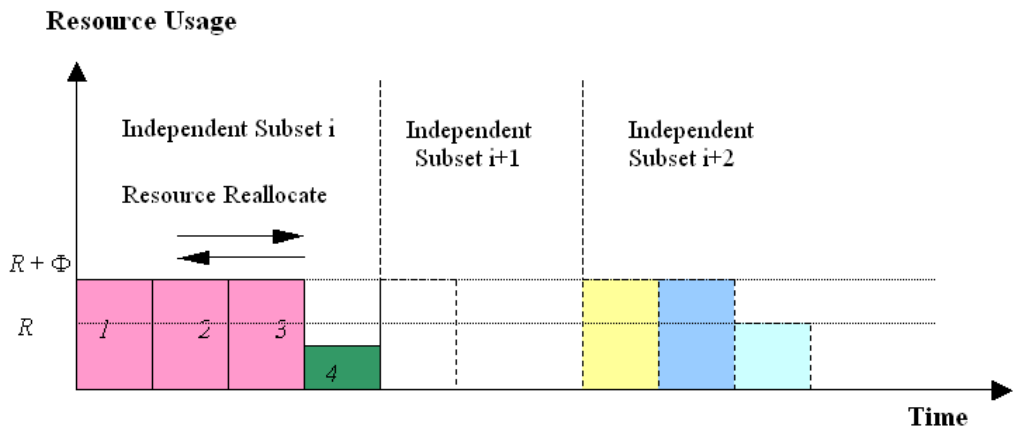

Figure 3-1. Illustration of resources shift in the independent subset

In Fig.3-1 above, the first activity—independent subset i— consists of 4 jobs, numbered from 1 to 4. Independent i+1 includes several jobs, and independent i+2 has 3 jobs, and so on. Every independent subset has a fixed construction period that has been decided in the schedule. In independent subset i, job 1, 2, and 3 fully utilize the available processing time, the sum of overtime Φ and regular time R. Job 4 just utilizes a part of regular time. Under this situation, we assume the construction cost is X that includes the indirect cost and direct cost (refer to Literature Review). Indirect cost is fixed because it basically is positively proportional to construction period time. Direct cost should cover the expenses that have occurred in both overtime and regular time. Through resource allocation, we may reach another situation. The work time for job 1, 2, and 3 may fall down to a level lower than the regular time, and in contrast the working time of job 4 increases. The new situation will result in a new construction cost Y, and the composition

of Y is the same as that of X. Comparing X with Y, the contractor certainly prefers a lower one, and meanwhile the activity completion due time will still be guaranteed.

So we may create a series of different situations through different resource allocation methods. Finally the lump sum of every shortest activity construction period time is the construction term most beneficial to subcontractors.

Total Construction Costs

As described in the Literature Review section of this thesis, the total construction cost is the lump sum of direct construction cost and indirect construction cost. The direct cost curve in the Literature Review shows that the solution for direct cost must be somewhere between the two extremes of the least-cost solution and the least-time solution, and the direct cost tends to decrease if more time is available. In contrast, the indirect cost varies almost positive directly with project duration. The blend of direct cost curve and indirect cost line presents the change fluctuation of the total project construction cost, and also supplies the information for determination of lower cost and corresponding project duration.

We now move from the study vision to the independent subset—the epitome of activities or projects performed by a subcontractor. The whole construction cost and project duration are accruements of all independent subsets. Each independent subset has a series of activities/projects. The data are required for every possible method of carrying out each activity or project. How much resources allocated for each job, how much time scheduled, and so on, are all related to resource allocation, so it becomes the only influence factor to generate different total construction curve.

Since the indirect cost just has a simple relationship with the activity period, we pay attention to the direct cost. Direct cost curve is pivotal because it can have any

duration between different normal and least duration, then a range of possible durations and corresponding costs based on its utility data is available for each activity. Accordingly, different combinations of possible durations for the activities can be associated with the project.

Because all individual activities are assumed to have valid continuous cost curves, the curve in Fig. 3-2 implies that any project schedule is feasible between the least-time duration and the all-normal duration.

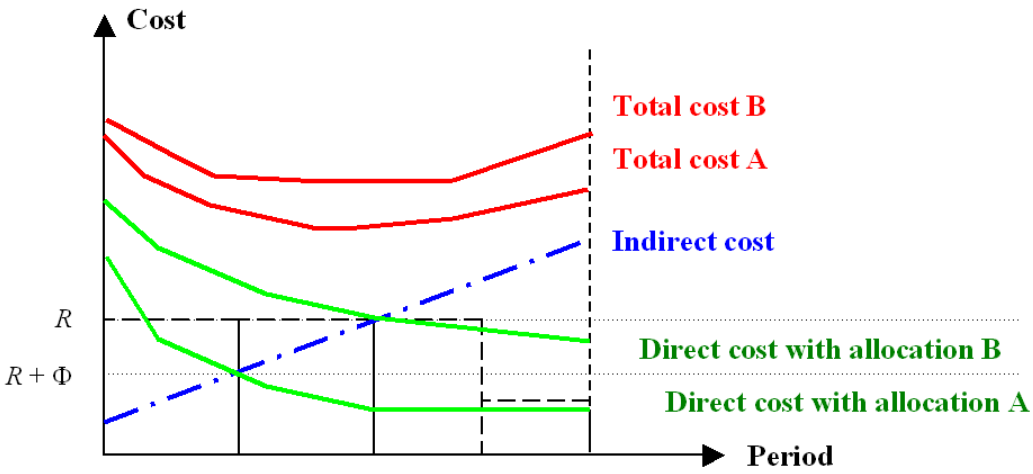

Figure 3-2. Construction costs in independent subset i

The data such as construction schedule and resource allocation scheme set the limits of the cost and duration of an activity. Usually the contractor determines these data before starting the activities. It is to indicate that a different method of performing the same activity may define a different set of data. Consequently, it may have a different utility curve, such as the two direct cost curves caused by different resource allocations.

The indirect cost curve is plotted on the same graph as the direct cost curve and then summed up to give the total cost curve so as to determine the final cost curve. The

project total cost curve is plotted by simple addition of the two other costs at any desired duration on the graph.

Then it is immediately clear that a minimum total project cost exists. This is the most economical solution for the project, i.e., the duration for the least total cost. In practice, contractors wish to pursue this most economical solution if they possibly can. Even they cannot always achieve the idealistic point. Also contractors will have the intrinsic property of construction cost as a helpful reference. By different construction methods through adjusting resource allocation, contractors then will work out a feasible cost solution that is most profitable to them.

Parametric Models of Single Resource Allocation

We just focus on one independent subset to analyze the single resource allocation influence on activity construction cost. In the independent subset i, the construction cost is composed of two portions—direct cost and indirect cost. The parametric models in this thesis try to find a way to determine the cost of loaning or absorbing resources on a particular work area, meanwhile only single resource is allowed to separately allocate in the models, no matter what resource it is, labor or material.

Indirect Cost and Direct Cost

As explained in Literature Review, a productivity function formula has been developed as follows:

$$P_i = (a_j{}^T y)CW \qquad \text{(O'Brien, 2000)} \qquad \text{Equation 3-1}$$

In Equation 3-1, P_i is the actual productivity rate for all resources applied, a_j is ideal productivity rate per unit of flexible resource for construction method j, y is units of flexible resources applied, C is complementarity productivity modifier, and W is work area productivity modifier.

Equation 3-1 allows us to calculate activity duration.

$$T_i = Q_i/P_i \qquad \text{Equation 3-2}$$

Where Q_i is the construction quantities of activity i, and T_i is the deduced activity duration of activity i.

With computation of activity duration through Equation 3-2, we will easily access the construction costs by multiplying duration by unit cost.

Indirect cost includes the overhead, project management expense, and so on. It is basically a linear relationship along the activity construction time. So we may figure out the indirect cost by the following Equation 3-3.

$$C_{ind} = mT_i + n \ (m>0, n\geq 0) \qquad \text{Equation 3-3}$$

Here C_{ind} represents the indirect cost of activity i; m represents the unit indirect cost; and n represents the start-up cost at the beginning of activity i.

Direct cost is the money invested directly to the activity's construction. Its change curve depends on the different source allocation ways as described in section of total costs analysis. Under a certain resource allocation situation, the direct cost C_d can be divided into regular part and overtime part. Two parts have different unit cost. The direct cost of the overtime part does not exist in case the activity may be completed within the time without any overwork. In addition, we ignore the possible rewards for early completion and the possible penalties for tardiness.

Either in regular time or in overtime, we have to take into account costs caused by both applied flexible resources and applied fixed resources.

$$C_r = S_{ry}yR + S_xxR \qquad \text{Equation 3-4}$$

$$C_o = S_{ry}'y\Phi + S_xx\Phi \qquad \text{Equation 3-5}$$

where

C_r – direct cost occurred in regular time

C_o – direct cost occurred in overtime

S_{ry} – unit cost in regular time for one certain flexible resource

S_x – unit cost for one certain fixed resource

S_{ry}' – unit cost in overtime for one certain flexible resource

y – units of flexible resources in regular time

x – units of fixed resource in regular time

R – regular time

Φ – overtime

Addition of Cr and C_o will result in the equation for direct cost C_d:

$$C_d = C_r + C_o$$

$$= S_{ry}yR + S_xxR + S_{ry}'y\Phi + S_xx\Phi$$

$$= S_{ry}yR + S_{ry}'y\Phi + S_xx(R + \Phi) \qquad \text{Equation 3-6}$$

The lump sum of R and Φ is the maximum available processing time T_i for the activity i that is deduced by Equation 3-2. In case the working time T_i is less than the regular time R with productivity rate P_i, there is no over time Φ. Otherwise, a certain amount of overtime will be used in activity i. The quantities of flexible resource y and fixed resource x will be determined by the concrete resource allocations.

Therefore, the total construction cost C_T is:

$$C_T = C_{ind} + C_d \qquad \text{Equation 3-7}$$

Different resource allocations result in different cost point. Connecting all points, the total cost curve can be plotted.

Other Costs

When building the picture of total cost of resource allocation, there are other considerations needed to be included. Shifting cost for moving flexible or fixed resources from site-to-site, training expenses for new added unskilled labors, the cost for being familiar with the new equipment, etc. will happen in the resource allocation periods. Those costs are likely to be different for each resource allocation, and for each activity. They vary depending on the conditions environments supplied by the sites. The tougher terrain conditions or longer distance may increase the shifting costs. Few numbers of new added workers will keep the training costs lower.

In this thesis, we will not discuss those costs due to the variety of activity individuality. Furthermore, it is not difficult for contractors to respectively estimate those costs according to concrete situations.

As for the material cost, because the quantities needed to complete the activity basically are constant and can be found in the estimate, they will not be discussed here.

Case Study

Two cases will be discussed in this section. They respectively study construction cost with labor allocation, and equipment (flexible small tools) allocation. In order to simplify the problem, we assume every activity in the following models has only one job, and the ideal unit productivity remains same no matter how the resources are reallocated.

Model 1 – Labor (crew) allocation

For a 12,000 sq. ft. plastic roofing work, the construction period is 15 days. One standard crew to do this work includes 2 sheet metal workers and 2 building laborers. Their unit cost is $ 600 per day in regular time, and $ 900 per day in overtime. The ideal

productivity rate of one crew is 600 sq. ft. per day. On the job site, 5,000 sq. ft. of the working area and one PVC machine are supplied for roofing.

We assume that the PVC machine requires at least one crew (2 sheet metal workers and 2 building workers) to operate, so the function drops to zero at one. However, the machine is not fully productive with one crew and it can exert all its power with 2 crews. More crews greater than two can affect little on overall productivity. So the complementarity modifier C is illustrated below in Fig.3-3.

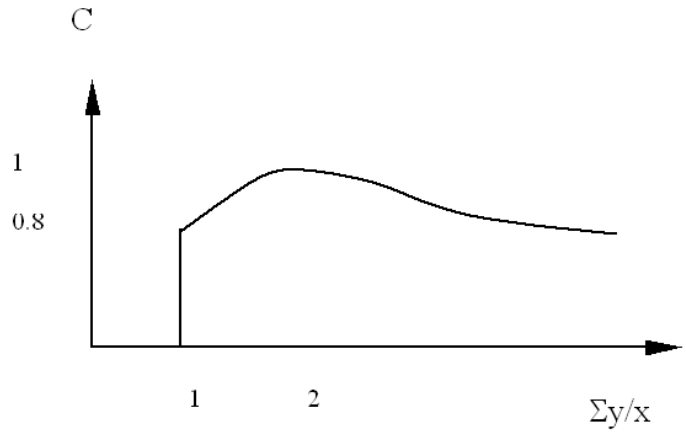

Figure 3-3. Complementarity modifier C in Model 1

For each crew, they need 5,000 sq. ft. of working area to guarantee the maximum productivity rate. Smaller working area will result in conflicts in construction. On the other hand, they have to spend extra time on mobilization with a too large working area. So the work area productivity modifier may be plotted as in the following Fig.3-4.

With these conditions, how many crews do we need to complete this roofing work and yet be most economical? We may work it out by equations set up in section.

Firstly we compute the cost with 2 crews. Because 2 crews are using one PVC machine, the complementarity modifier C is 1. The average working area for each crew is only 2,500 sq. ft., so the work area modifier W is only 0.63. The ideal productivity rate

for each crew is 600 sq. ft. per day, and the flexible resource quantity y, i.e., the number of crews is 2. Then the actual productivity rate for this activity comes out.

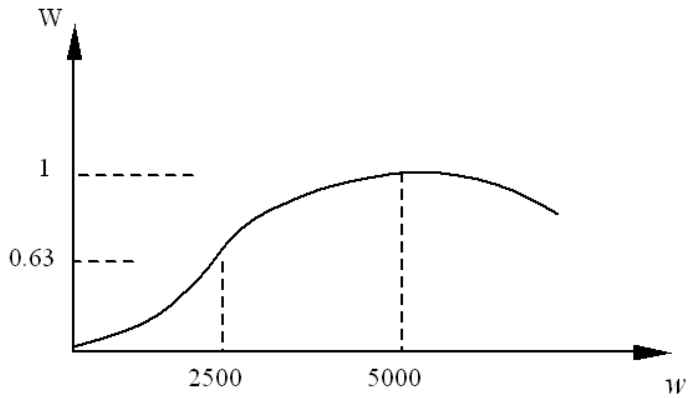

Figure 3-4. Work area productivity modifier W in Model l

$$P = (a_j\ y)CW = 600 \times 2 \times 1 \times 0.63 = 756 \text{ sq. ft. /day}$$

By Equation 3-2, the working time for this activity is:

$$T = 12{,}000/756 = 15.87 \text{ days}$$

Because the project is required to finish within 15 days, the overtime is 0.87 days.

$$R = 15 \text{ days}$$

$$\Phi = 0.87 \text{ days}$$

In this case, the indirect costs include management fees, overhead costs, etc. in addition to daily cost $ 100, $ 500 basic cost is needed at the beginning of the activity. That means:

$$m = 100 \qquad n = 500$$

Therefore:

$$C_{ind} = mT + n = 100 \times 15 + 500 = 2000 \text{ dollars}$$

Using equation 6, we may work out the cost both in regular time and cost in overtime. Because the daily cost for a fixed resource, which is for the PVC machine here, does not change, we just compare the cost for labor.

$$C_d = S_{ry}yR + S_{ry}'y\Phi = 600 \times 2 \times 15 + 900 \times 2 \times 0.87 = 19{,}566 \text{ dollars}$$

Equation 7 tells us how much the total cost is:

$$C_T = 2000 + 19566 = 21{,}566 \text{ dollars}$$

Then we consider the situation with only one crew. The complementarity modifier turns to 0.8, but the work area modifier raises to 1.

$$P = (a_j\, y)CW = 600 \times 1 \times 0.8 \times 1 = 480 \text{ sq. ft. /day}$$

$$T = 12{,}000/600 = 25 \text{ days}$$

$$R = 15 \text{ days}$$

$$\Phi = 25 - 15 = 10 \text{ days}$$

$$C_{ind} = mT + n = 100 \times 15 + 500 = 2000 \text{ dollars}$$

$$C_d = S_{ry}yR + S_{ry}'y\Phi = 600 \times 1 \times 15 + 900 \times 1 \times 10 = 18{,}000 \text{ dollars}$$

$$C_T = 2000 + 18{,}000 = 20{,}000 \text{ dollars}$$

So that the comparison results are concluded in the table below:

Table 3-1. Resource allocation comparison in Case 1

	Duration	Overtime	Indirect cost	Direct cost	Total cost
2 crews	15	0.87	2000	19,566	21,566
1 crew	15	10	2000	18,000	20,000

In this model, it shows that decreasing the numbers of the crew from 2 to 1 seems beneficial to contractors. Using one crew comes into better effect, and the contractors should reallocate the superfluous crew to other activities or projects.

Model 2 – Equipment (flexible resource) allocation

Hydraulic excavators and cranes are used to cooperate to do 1,000 cubic yards trenching activity without exact construction time limitation (8 working hours per day). A total of 3,000 sq. ft. of working area is available. The hydraulic excavators are flexible, but the cranes are fixed resources. With one crane already working on the job site, the contractor cares about how many excavators they should allocate to this activity in order to achieve the most economical effect.

The curve of Productivity complementarity C shows 2 excavators working with one crane are fully productive. Although the productivity rate will drop off 30% when only one excavator is used, a crane requires at least one excavator to operate, and thus the function drops to zero.

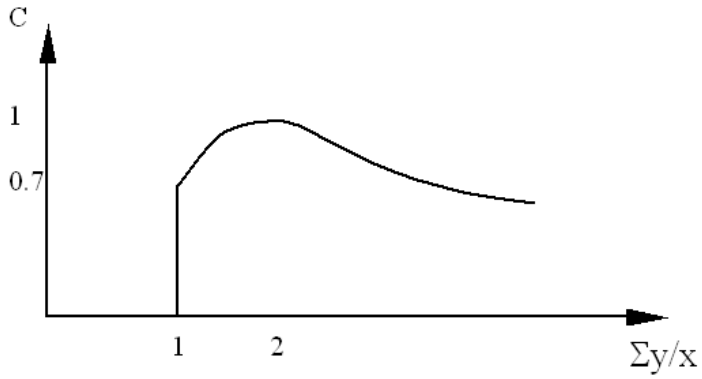

Figure 3-5. Complementarity modifier C in Model 2

One excavator needs 2,000 sq. ft. to become most productive. Smaller or bigger areas all decrease its behavior, shown in Fig. 3-6.

The ideal daily output of each excavator is 50 cubic yards, and the hourly cost is $40. The cost for fixed resource—crane—should be taken into consideration because the construction time is varying. The hourly cost for the crane is $50.

If we use only one excavator, the related parameters are computed according to the processes shown in model 1.

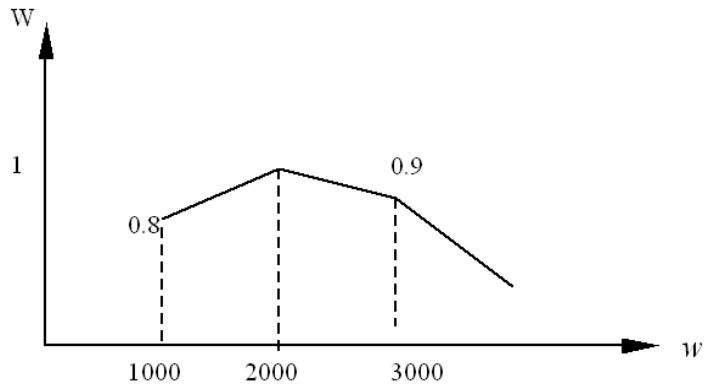

Figure 3-6. Work area modifier W in Model 2

$P = (a_j\ y)CW = 50 \times 1 \times 0.7 \times 0.9 = 31.5$ cubic yard /day

$T = 1000/31.5 = 31.75$ days

$R = 31.75$ days

$\Phi = 0$ days

$C_{ind} = mT + n = 100 \times 31.75 + 500 = 3{,}675$ dollars

$C_d = S_{ry}yR + S_x x\Phi = 50 \times 1 \times 37.5 \times 8 + 40 \times 1 \times 37.5 \times 8 = 22{,}860$ dollars

$C_T = 3675 + 22860 = 26{,}535$ dollars

And then if we add one more excavator in this activity, y units of flexible resources becomes 2, and the x—units of fixed resource—still maintain as 1. The average for each excavator is 1500 sq. ft. Assume that the work area modifier W can be interpolated, W is 0.9 under the situation with 2 excavators.

$P = (a_j\ y)CW = 50 \times 2 \times 1 \times 0.9 = 90$ cubic yard /day

$T = 1{,}000/90 = 11.1$ days

$R = 11.1$ days

$\Phi = 0$ days

$C_{ind} = mT + n = 100 \times 11.1 + 500 = 1{,}610$ dollars

$C_d = S_{ry}yR + S_x x\Phi = 40 \times 2 \times 11.1 \times 8 + 50 \times 1 \times 11.1 \times 8 = 11{,}544$ dollars

$C_T = 1610 + 11544 = 13{,}154$ dollars

The comparison table is shown as follows:

Table 3-2. Resource allocation comparison in Case 2

	Duration	Overtime	Indirect cost	Direct cost	Total cost
1 crew	31.5	0	3675	22860	26535
2 crews	11.1	0	1610	11544	13154

On the contrary, adding one more excavator to model 1 will accelerate the project greatly, and with less costs. Using the same method, the contractor may compute the costs for 3 excavators, or more, until they find a solution that is sound for them.

Summary

Although the equations and models are established only within a single resource allocation scope, they still reveal the relationships between construction cost and resource allocation to a certain extent. As a main method to control cost and set down the schedule, resource allocation plays an important role. In accordance with the specific conditions of different activities or projects, it is not difficult to simulate the above analysis and establish models on the computer, and then further electrolyze the data processing. We just discussed two resource allocation methods for each model, but the computer may repeat the same processes to calculate many allocations. With the electrical results, the cost curve, including the direct cost curve and the direct cost curve will be easily plotted. That will be the right-hand guidance to subcontractors.

This analysis method can be further developed in multi-resource projects. The possible influence and the perspective will be discussed in chapter 4.

CHAPTER 4
MULTI-RESOURCE ALLOCATION ACROSS MULTIPLE PROJECTS

On the basis of elaboration of single resource allocation, the concept of independent subsets and the parametric cost model are introduced in the application of the subcontractor's multi-resource allocation in this chapter. The implementation of multi-resource allocation encompasses consideration of mutual impacts caused by allocation itself to the subcontractor as a whole, of certain combinations of resource utilization. Two examples of subcontractors, taken from an investigation in Florida and Arizona, are presented in this thesis on their resource allocation measures. The evaluation of their allocations is also addressed.

Environment for Multi-resource Allocation Across Multi Projects

Due to increasing sophistication and specialization of work, which creates a more complex work environment, the subcontractor is likely to grow to encompass more trade, invest more in personnel and equipment, and be able to confront tough work conditions with a tighter schedule. Increasing prefabrication off site and more complicated construction on site require multifarious fixed facilities too. Under this kind of environment, the subcontractor has to consider the deployment of each resource in the meantime other than a schedule with a single resource. Reasonable multi-resource allocation across projects is necessary to take advantage of resources and also complete all projects as required. Multi-resource allocation across multi projects in the context of construction is the assessment of the real inputs for any of the subcontractor's projects or

programs of construction and the identification of the action necessary to ensure that there is a balance between requirements and availability.

With the resource constraints, some of projects will be prioritized and the others not. What are the criteria? Most of the subcontractors normally prioritize their projects with multi-resource on customer priority, stakeholders' interest, corporate portfolio, product roadmap, business strategy, and project budget (Faniran et al. 1999). The single most significant factor is the return of investment. Other prominent reasons used to allocate resources across projects are reliant on the subcontractor's core business. Utility, construction, and government industry prioritize projects based on regulatory requirements, legislative mandates, emergencies, and political demands in addition to above-mentioned criteria. From the standpoint of a subcontractor, the return of investment, i.e., the construction cost, is the only concern in this thesis. In order to maximize the profits, multi-resource allocation is necessary, on the one hand, to improve the efficiency, and on the other, to plan all projects as a whole so as to reduce the cost as much as the subcontractor can manage to do so.

Multi-resource allocation involves much more than merely crunching numbers in a mathematical calculation. In the single resource allocation hypothesis, the resources are allocated in the chronological order based on project priorities. If resources are insufficient then there may well be decreases in the labor productivity, thus possibly prolonging project durations with the risks of project tardiness, and increasing the construction cost as well. Also there may be some kinds of excessive resources at some projects that damage the balance of process causing inability to fully exerting other resources and a rise in price through a change in the correlation. So the resolution is to

shift the extra resources from the projects where fewer resources are required to reach the optimum efficiency to the projects that need more resources to speed up the progress.

But in the typical multi-resource allocation, the resources are allocated simultaneously to sets of activities or projects, rather than to individual activities or projects in a sequential manner. With multi-resources allocation across multi projects, the subcontractor possibly does not save money on some projects, and even has to endure the loss to some degree, but meanwhile gain profits from other projects. In other words, some projects are sacrificed to create favorable resource conditions for other prioritized projects, then benefit from them, and eventually profit the subcontractor in the entire plan.

The first step in the process of moving to a strategic resource-allocation perspective is to determine where current strengths exist, where the weakness exists, and where the priority will be set to build upon these answers. In some instances, significant construction resources are required to move forward toward strategic objectives. In these instances, the subcontractor must set priorities and balance available resources (Chinowsky and Meredith, 2000). For example, if a subcontractor finds two projects are scrambling for the same kinds of limited resources, then a decision must be made as to which of these gaps requires the greater attention at the current time.

Each subcontractor impossibly supplies unconditional resources to their projects. Normally they strive to grab sufficient projects so as to ensure a ready supply of available work. In addition they must tend to make the most of limited resources when they perform work on multiple projects simultaneously. From the subcontractor’s point of view, the focus is not on any one specific project, but on multiple projects. Each

construction project manager, on the other hand, is highly focused on the project for which they are responsible, so that they would rather utilize resources as much as they possibly can. However, rather than advancing an individual area, the subcontractor must retain an overall perspective acknowledging that each of the projects and each of the resources are equally important to achieving a long-term vision. Moreover, the mutual influence caused by multi-resource allocation must be taken into consideration. Will the subcontractor suffer losing interest in any other projects if the amount of one kind of resource goes down on a project? What is the optimal point of resources arrangement to guarantee a company's profit? Similar to the balancing of resources on a project, the balancing of resources at a subcontractor's organization level is required to keep him on a continued path of advancement. This thesis proposes to attempt to understand the behavior of subcontractors in resources allocation on multiple projects that requires looking beyond the boundaries of a single resource/project and taking the subcontractor's multi-resource/multi-project viewpoint.

Significance of Independence Subset in Multi-Resource Allocation

Different from the single-resource allocation elaborated in chapter 3, various resources are in use on a subcontractor's projects. Those resources are applied to each project in accordance with the construction processing sequence. And the same project utilizes different resources in different periods, including materials, labor, equipment, working areas, etc. Normally the subcontractor takes care of every resource at the same time. How to help coincide the usage of resources to offset the possible shortage or excess, avoid the possible conflicts and wastage between resources, and finally obtain the maximum financial return is the only problem the subcontractor cares about. Figure 4-1 imitates the situation of multi-resource allocation.

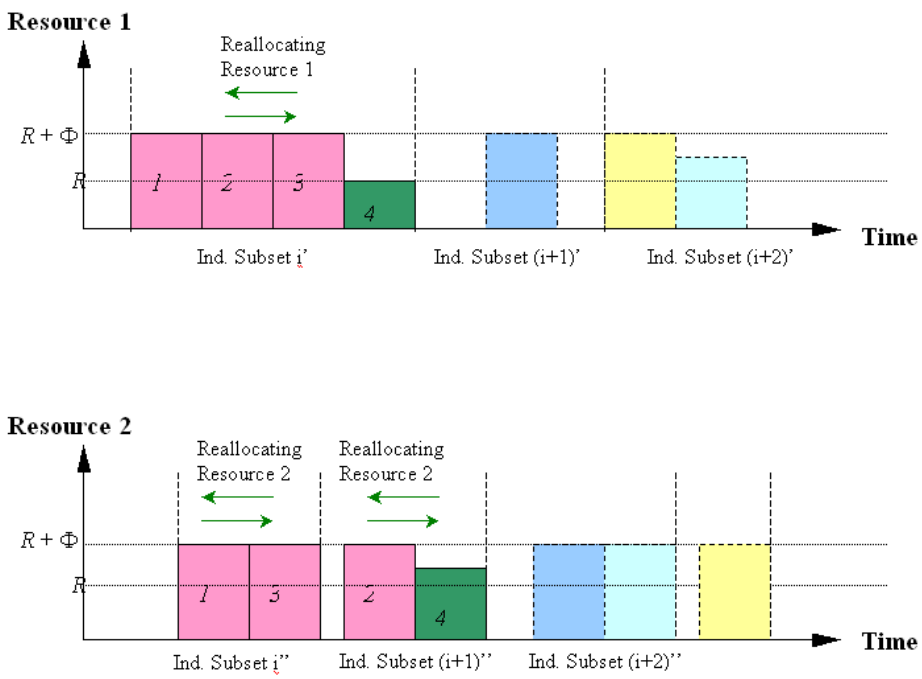

Figure 4-1. Illustration of multi-resource allocation across projects

A simple multi-resource allocation sketch is shown in Fig. 4-1. It consists of only resource 1 and resource 2. The subcontractor's projects are arranged along the time horizon, represented by blocks with different colors. It can be seen that these projects are processed in different periods with different resources and different regular time *R* and overtime Φ. Also due to the different processing time, those projects are merged into or divided into different independent subsets. As shown in Fig. 4-1, resource 1 is applied to project 1, 2, 3 and 4 at the same time. So project 1, 2, 3, and 4 are integrated into one independent subset. The next project using resource 1, leading the next independent subset, has a time gap with its predecessor. For the application of resource 2, project 1 and 3 are dealt with firstly as an independent subset. Project 2 and 4 do not start immediately after the completion of the first independent subset that is composed of project 1 and 3. So project 2 and 4 form a new separate independent subset. In the

following independent subsets, the construction sequence for other projects might differ from that in the construction with resource 1.

Within the independent subset, every activity or project is allowed to adjust the usage of resource. Similar to the single-resource allocation, this kind of resource allocation probably is beneficial to related projects; meanwhile the different resources collaborate or influence each other. Usually the allocation of one kind of resource will result in the ripple effect on other resources. The subcontractor needs to take into consideration all relevant impacts so as to maximize the profits.

Efficient allocation of resources for construction activities or projects requires that the determination of resource requirements should be undertaken on a return-adding and cost-effective basis. Too little resource allocation effort possibly results in implementation failures, delays, mediocrity, and inefficiency. Consequently there is a high probability that the project will exceed the subcontractor's existing budget. When the correct amount of resource allocation effort is invested, the project implementation time is optimized, the construction costs are decreased, and there is a high probability that the project will save much money for the subcontractor. But additional resource allocation effort beyond the optimal level is essentially wasteful, probably even projects will achieve intended objective, because of the implementation delays that inevitably arise due to the additional time required to complete the allocation and the increasing costs of associated work such as the resource shifting expenses.

Since it is hard to work out how much effort should be invested, and it is not possible to readily identify from so many multi-resource allocation options, which projects to assign higher priorities to, and which projects to improve the subcontractor's

financial status, a simple repetitive calculation procedure may be used. It is possible, therefore, to introduce a scheduling software system into resource allocation scheduling and consequently monitor the impact on the total yield results. Each project within the independent subset is selected in turn, given the highest priority over all of the others, and the consequent project duration and corresponding construction costs are monitored. Repeat this procedure to figure out costs of all resource-allocation combining possibilities, then the optimal one will be obtained through the comparison of results. The procedure is demonstrated in a case study in the following section.

Multi-Resource Allocation Parametric Model

On the basis of the productivity function formula discussed in single-resource allocation analysis, a parametric model is presented here to promote the understanding of multi-resource allocation concept by attempting to explain the basic tenet of this concept in the context of the subcontracted construction environment. The basic tenet begins with a statement of the ultimate goal from the subcontractor's point of view—to maximize his profit over considered projects.

In the single-resource analysis in chapter 3, the overtime cost or tardiness cost are involved in total cost calculation. For the sake of simplicity, both overtime and tardiness cost will be ignored. Assuming that the subcontractor is remunerated only according to quantity of work performed in each project, this model can be stated as follows:

$$I = \sum_{j=1}^{n} (A_j D_j - C_T) \qquad \text{Equation 4-1}$$

where

I – subcontractor's net income over project 1 through project j

A_j – total work amount of project j (j = 1, 2, 3…n)

D_j – unit price for the work on project j (j = 1, 2, 3…n)

C_T – total construction cost

As discussed in the previous chapters, total construction cost is composed of direct cost C_d that is obtained by multiplying the total quantity of resources on project j with the unit cost of resources, and indirect cost C_{ind}. Using the definitions in chapter 3, the subcontractor's net income is:

$$I = \sum_{j=1}^{n} (A_jD_j - C_{ind} - C_d) = \sum_{j=1}^{n} (A_jD_j - C_{ind} - q_jS_j) \qquad \text{Equation 4-2}$$

C_{ind} – subcontractor's overall indirect construction cost

q_j – total quantity of resources on project j (j = 1, 2, 3…n)

S_j – unit cost of resources on project j (j = 1, 2, 3…n)

Because the cost of resources can be separated into material part and labor part, and the material cost may be expressed as the product of actual performed work multiplied with the unit price of the material for the work. In this thesis, the focus is on the subcontractor's strategy in allocating resources; the material waste will be omitted. Then assuming the actually performed work is equal to the demanded work that is represented by A_j, So Equation 4-2 will be deduced to as follows:

$$I = \sum_{i=1,\, j=1}^{m,n} (A_jD_j - C_{ind} - A_jM_j - T_{ij}L_{ij}y_{ij}) = \sum_{i=1,\, j=1}^{m,n} [A_j(D_j - M_j) - C_{ind} - T_{ij}L_{ij}y_{ij}]$$

$$= \sum_{i=1,\, j=1}^{m,n} [A_j(D_j - M_j) - C_{ind} - (Q_{ij}/P_{ij})L_{ij}y_{ij}]$$

$$= \sum_{i=1,\, j=1}^{m,n} \{A_j(D_j - M_j) - C_{ind} - [Q_{ij}/(a_{ij}y_{ij}C_{ij}W_{ij})]L_{ij}y_{ij}\}$$

$$= \sum_{i=1,\, j=1}^{m,n} \{A_j(D_j - M_j) - C_{ind} - [Q_{ij}/(a_{ij}C_{ij}W_{ij})]L_{ij}\} \qquad \text{Equation 4-3}$$

where

M_j – average unit cost of material on project j

T_{ij} – work time of resource i on project j

L_{ij} – cost of unit time for one unit of resource i (other than material) allocated by the subcontractor to project j over period T

Q_{ij} – amount of work with resource i on project j

P_{ij} – productivity with resource i on project j

a_{ij} – full productivity with resource i on project j

y_{ij} – units of resource i on project j

C_{ij} – complementarity productivity modifier of resource i on project j

W_{ij} – work area productivity modifier of resource i on project j

(i = 1, 2, 3…m; j=1, 2, 3…n)

The parameters for productivity P are quoted from Equation 3-1 in chapter 3. The parameter on the left side of equation 10 represents the subcontractor's profit. The terms on the right hand side of the equation represent income for work performed deducted by cost of materials, indirect cost, and cost of resources except that of materials.

For the sake of simplicity, it is assumed that the existing work amount is fixed; material cost and indirect cost are both assumed constant over time period T as well as amount of each resource and cost of unit time for unit resource. Under these assumptions, it can be seen from the equation that the subcontractor's challenge in any period T is to set resource units y_{ij} that determines complementarity productivity modifier C_{ij}, and work area productivity modifier W_{ij} for each resource on each project to maximize productivity P_{ij}.

The subcontractor will set the quantity of resources applied to each project at each distinct time period. Determination of the correct resource level must take into account not only the expected amount of work that will be made available during the different period and total construction term or schedule, but also the available fixed machine, work area provided by the general contractor, and mutual effects on productivity of resources due to resources allocation to each other.

As can be seen, the subcontractor's profitability is extremely sensitive to the ratio of the quantity of work that can be performed during the specific period, to the productivity in that period. The subcontractor can reduce this sensitivity by increasing the average productivity across all projects. Sometimes even when some projects are assigned appropriate resources, resource availability on other projects will be diminished by these assignments, so does the productivity. For the subcontractor, the goal is the aggregate benefit with multi-resource across multiple activities in separate projects.

From the established model, it is possible to explore the factors that motivate a subcontractor in assigning resources to the various projects. When will a subcontractor increase, decrease, or withdraw resources from any particular project? How do the working conditions influence the behavior of the subcontractor in assigning resources? How does market force affect the ability of a subcontractor to commit appropriate resources to projects? And so on. However, the immediate goal of this thesis should not be able to answer these questions directly. Rather its goal should be to establish an economic and behavioral model of subcontractor decision-making that would enable prediction of the range of decisions that may be made.

Multi-Resource Allocation Case Study

Assuming a roofing subcontractor has two projects to build at the same time, one is 6,000 square feet, and the other one's size is 7,500 square feet. Our study focuses on two sorts of crews, membrane crew and insulation crew, working on two projects. The cost for each membrane crew per day is $200, and that for each insulation crew per day is $300. So in this case, membrane crew and insulation crew are two resources needed to reallocate between these two projects. Only one membrane crew and one insulation crew are assigned to Project 1, two membrane crews and 3 insulation crews are assigned to Project 2. As the schedule changes, one membrane crew is shifted from Project 2 to Project 1, and one insulation crew is also moved to Project 1 from Project 2. Due to the interactive affects on construction complementarity and working area on both projects caused by multi-resource reallocation, the change of comprehensive construction costs can be obviously observed.

Ignoring the time gap between the two resources applications, both projects are presumed to utilize two different kinds of resources contemporarily. So the multi-resource on these two projects can be described with independent subsets as follows.

The resource assignment information is given as follows:

- Project 1: 6,000 sf to work; 4,000 sf working space; one fixed membrane application machine; one fixed insulation application machine; one membrane crew with an ideal productivity of 1,200 sf/day; one insulation crew with an ideal productivity of 800 sf/day.
- Project 2: 7,500 sf to work; 5,000 sf working space; one fixed membrane application machine; one fixed insulation application machine; two membrane crews, each of them has an ideal productivity of 1,200sf/day; three insulation crews, each of which has an ideal productivity of 800sf/day.
- Allocation: respectively moving 1 membrane crew and 1 insulation crew from Project 2 to Project 1.

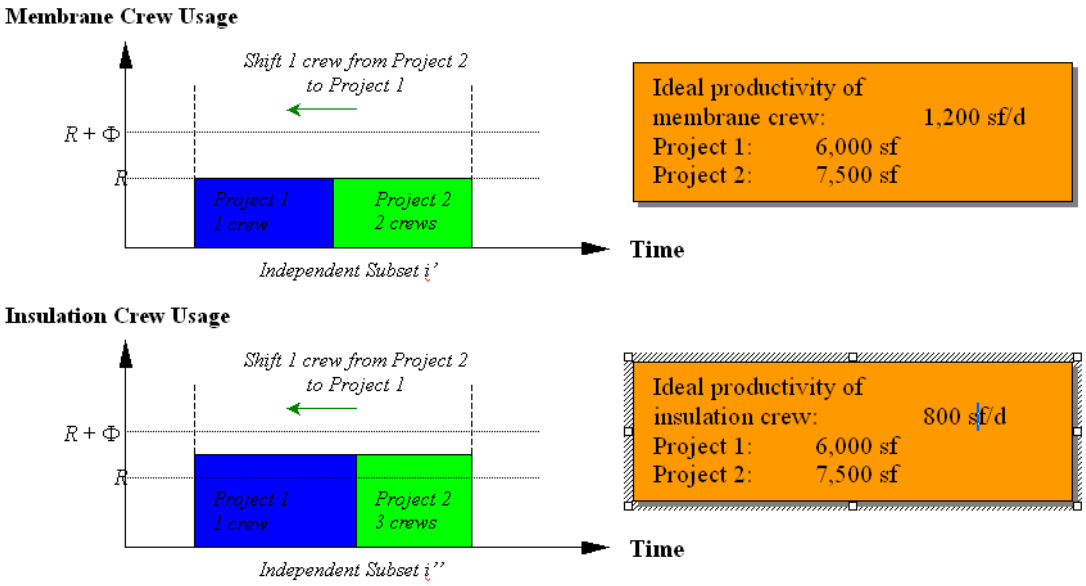

Figure 4-2. Two resources applications on two projects

Meanwhile, influence parameters described in Equation 3-1, i.e., the complementarity modifier and the working space modifier, comply with the following figures. Furthermore, another prerequisite is the ideal unit productivity, for both membrane crew and insulation crew, does not change although crews are reallocated from Project 2 to Project 1.

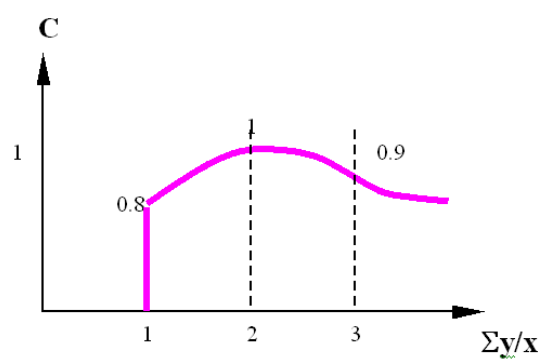

Figure 4-3. Complementarity modifier C in multi-resource allocation case study

Before reallocation, the calculation is as follows:

For membrane crews:

$$a_m C_{1m} W_{1m} = 1200x0.8x0.8 = 768 \text{ sf/d.each}$$

$a_m C_{2m} W_{2m}$ = 1200x1x0.4 = 480 sf/d.each

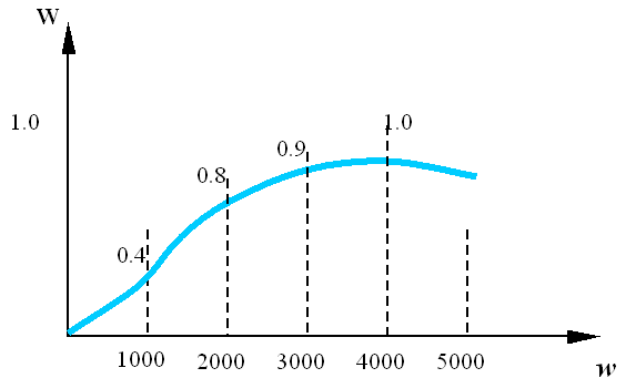

Figure 4-4. Working area productivity modifier W in multi-resource allocation case study

For insulation crews:

$a_i C_{1i} W_{1i}$ = 800x0.8x0.8 = 512 sf/d.each

$a_i C_{2i} W_{2i}$ = 800x0.9x0.4 = 288 sf/d.each

a_m/a_i – ideal productivity of each membrane crew/insulation crew.

C_{1m}/C_{1i} – complementarity modifiers of membrane crew/insulation crew on Project 1. It is 0.8 for both membrane crew and insulation crew (respectively 1 crew for the machine) before reallocation.

C_{2m}/C_{2i} – complementarity modifiers of membrane crew/insulation crew on Project 2. It is 1 for membrane crew (2 crews for the machine) and 0.9 for insulation crew (3 crews for the machine) before reallocation.

W_{1m}/W_{1i} – working space modifiers of membrane crew/insulation crew on Project 1. It is 0.8 for both membrane crew and insulation crew (respectively 2000 sf space every crew with total 2 crews) before reallocation.

W_{2m}/ W_{2i} – working space modifiers of membrane crew/insulation crew on Project 2. It is 0.4 for both membrane crew and insulation crew (respectively 1000 sf space every crew with total 5 crews) before reallocation.

So the subcontractor's net income before allocation will be:

$$I_{before} = \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [Q_{i,j}/(a_{i,j}C_{i,j}W_{i,j})]L_{ij}\}$$

$$= \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [(6000/768 + 7500/480) \text{ x } 200 + (6000/512 + 7500/288) \text{ x } 300]\}$$

$$= \sum_{i=1,\, j=1}^{2,2} [A_j(D_j - M_j) - C_{ind} - 16200]$$

After reallocation:

For membrane crews:

$a_m C_{1m} W_{1m}$ = 1200x1x0.4 = 480 sf/d.each

$a_m C_{2m} W_{2m}$ = 1200x0.8x0.75 = 720 sf/d.each

For insulation crews:

$a_i C_{1i} W_{1i}$ = 800x1x0.4 = 320 sf/d.each

$a_i C_{2i} W_{2i}$ = 800x1x0.75 = 600 sf/d.each

C_{1m}/C_{1i} – complementarity modifiers of membrane crew/insulation crew on Project 1. It is changed to 1.0 for both membrane crew and insulation crew (respectively 2 crews for the machine) after reallocation.

C_{2m}/C_{2i} – complementarity modifiers of membrane crew/insulation crew on Project 2. It is changed to 0.8 for membrane crew (1 crew for the machine) and 1.0 for insulation crew (2 crews for the machine) after reallocation.

W_{1m}/W_{1i} – working space modifiers of membrane crew/insulation crew on Project 1. It is changed to 0.4 for both membrane crew and insulation crew (respectively 1000 sf space every crew with total 4 crews) after reallocation.

W_{2m}/ W_{2i} – working space modifiers of membrane crew/insulation crew on Project 2. It is changed to 0.75 for both membrane crew and insulation crew (respectively 1667 sf space every crew with total 3 crews) after reallocation.

So the subcontractor's net income after allocation will be:

$$I_{after} = \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [Q_{i,j}/(a_{i,j}C_{i,j}W_{i,j})]L_{ij}\}$$

$$= \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [(6000/480 + 7500/720) \text{ x } 200 + (6000/320 + 7500/600) \text{ x } 300]\}$$

$$= \sum_{i=1,\, j=1}^{2,2} [A_j(D_j - M_j) - C_{ind} - 14200]$$

The subcontractor's income from all projects' contracts, material cost, and indirect cost are assumed constant no matter which resource allocation way they adopt. Then by comparing net income after reallocation I_{after} with net income before reallocation I_{before},

obviously the fact is the subcontractor will gain more net income than that before reallocation.

$$I_{after} - I_{before} = \sum_{i=1,\, j=1}^{2,2} [A_j(D_j - M_j) - C_{ind} - 14200]$$

$$- \sum_{i=1,\, j=1}^{2,2} [A_j(D_j - M_j) - C_{ind} - 16200] = 2000$$

It can be seen that the membrane crew cost on these two projects is $4,600 before crew reallocation. Even after the crew reallocation, the final cost of membrane crews remains at $4,600. The allocation process does not profit the subcontractor on membrane crew cost. However, after crew reallocation, the insulation crew cost on two projects goes up to $11,400 from $9,600. During the two resources allocation, the shift of membrane crew and the insulation crew from Project 2 to Project 1 cuts down the cost of membrane crews, but it indeed lessens the insulation crews' competition of utilizing working spaces, and urges them to make the most of construction equipment, and finally shortens the total construction period on these two projects, making further profit for the subcontractor. This impact resulted not only from the allocation of one sort of crew, but also from multi-resource allocation between two projects.

Case Study on Multi-Resource Allocation

Introduction

The multi-resource allocation case study questionnaire was sent out to subcontractors with different disciplines and located in different places. Then the analysis focused on feedback information from those subcontractors that devoted exactly multiple resources to multi different projects. The ultimate target of collecting information from those subcontractors is to see if they adopted multi-resource allocation measures across

their multi-projects, then to evaluate their allocating policies from the subcontractor's standpoint if they really adopted some measures on projects. Finally a better allocation method may be found in light of the analysis results.

Taken out from feedback information from those subcontractors, two subcontractors are presented here for analysis. One is a painting subcontractor, and the other one is a mechanical subcontractor. The multi-resource allocation case study questionnaire had 3 parts, Part 1 Background Information, Part 2 Questions on Productivity, and Part 3 Evaluation of Resource Allocation.

Part 1 asked the recipient to provide background information on its company name, project and resource information, and respective quantities of work with different resources on different projects. Part 2 asked the participant some questions regarding construction productivity. Ten questions were asked for a descriptive response to the possible influence on productivity due to either assigned fixed machine or available working area. This part tried to find affecting factors in the parametric model of resource allocation. Part 3 asked detailed questions about resource allocating criteria, direct cost, and workers shifting information. This part was designed to confirm if the subcontractor's actual thinking about the resource allocation complies with the theoretical model discussed in the last two chapters.

B&G Painting, Inc.

B&G Painting, Inc. was performing painting and wall-covering work on two projects during the same period. It performed 350,000 square feet painting and 7,000 square feet wall covering on project 1; 175,000 square feet painting and 5,000 square feet wall covering on project 2. With sufficient applying of machines and working areas, two kinds of workers might respectively reach the full productivities of 300 square feet per

hour and 15 linear yards per hour, wherever the project is. The painter was paid $40 per hour, and the wall-covering worker could earn $20 per hour.

No fixed machine was required to do the painting work, but wall covering workers need pasting machine in the construction process. Each project was provided with a pasting machine. One worker can operate the machine alone, but the productivity would be doubled with two workers. At most four workers could be assigned to use one machine together when the productivity reached the maximum.

Each painter needs 10,000 square feet of working space to achieve the full productivity, which would be declined to two-thirds of full productivity with the minimum working space of 1,000 sf. The ideal working space for wall-covering worker is 1,000 sf when they may construct at the fastest speed. At least 500 square feet space is required for each wall-covering worker, but the productivity was only half of full productivity. There were 30,000 sf and 9,000 sf respectively provided for project 1 and 2. The subcontractor does not think too large a work area would de-motivate workers and make them less productive because the company set up daily goals on what should be achieved.

In accordance with the situation supplied above, the complementarity figure for the wall covering can be shown:

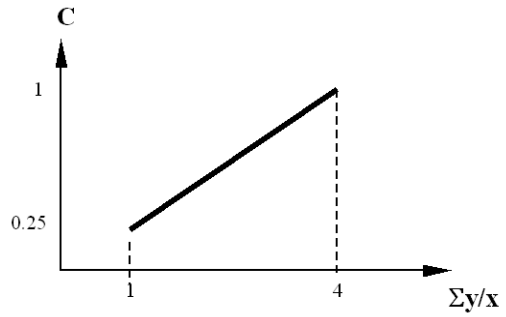

Figure 4-5. Complementarity modifier C for wall covering

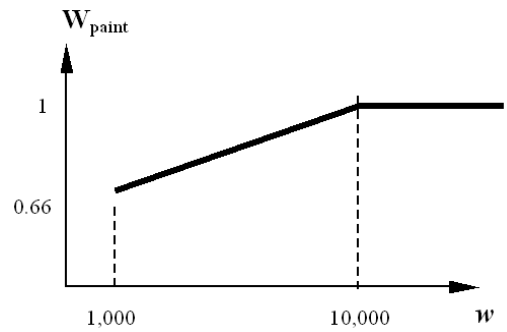

Figure 4-6. Working area productivity modifier W for painting

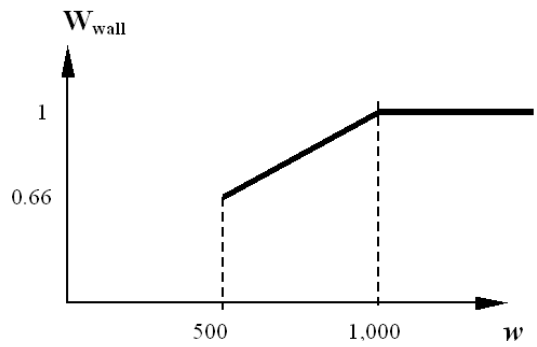

Figure 4-7. Working area productivity modifier W for wall covering

From the very beginning, B&G Painting, Inc. allocated 5 painters and 3 wall-covering workers on project 1; 3 painters and 2 wall-covering workers on project 2. They did not shift any workers across projects till the completion of both projects. So a total of 8 workers were working on project 1 and 5 workers on project 2. Then the working space for each worker would be 3,750 sf (30,000/8=3,750) on project 1 and 1,800 sf (9,000/5=1,800) on project 2. So the working space modifier W of painting would be deduced to 0.76 and 0.69 for project 1 and project 2 on the basis of Figure 4-7. Every wall-covering worker's working area was bigger than 1,000 sf so that the working space modifier of wall covering is 1 for both projects. Because the painter did not need any fixed machine, so the complementarity modifier C for painting is also 1. But it would be 0.75 for wall covering on project 1 with 3 workers and 0.5 on project 2 with 2 wall covering workers. The subcontractor's income may be worked out as follow:

For painting:

$$a_pC_{1p}W_{1p} = 300x1x0.76 = 228 \text{ sf/hr.each}$$

$$a_pC_{2p}W_{2p} = 300x1x0.69 = 207 \text{ sf/hr.each}$$

For wall covering:

$$a_wC_{1w}W_{1w} = 15x0.75x1 = 11.25 \text{ ly/hr.each}$$

$$a_wC_{2w}W_{2w} = 15x0.5x1 = 7.5 \text{ ly/hr.each}$$

$$I = \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [Q_{ij}/(a_{ij}C_{ij}W_{ij})]L_{ij}\}$$

$$= \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [(350000/228 + 17500/207) \text{ x } 40 + (7000/11.25 + 5000/7.5) \text{ x } 20]\}$$

$$= \sum_{i=1,\, j=1}^{2,2} [A_j(D_j - M_j) - C_{ind} - 120998]$$

The subcontractor did not reallocate workers between these two projects, so they did not know if their policy of spending $120,998 on labor cost was the best choice or not. Although project 1 was larger than project 2, dense workers on project 1 affected worker's productivity. Assuming anther situation—reallocate one painter from project 2, also one wall covering worker from project 1 to project 2. Therefore, there would be 4 painters and 2 wall-covering workers on project 1, 4 painters and 3 wall-covering workers on project 2. Correspondingly, the working area modifier W for painting would be changed to 0.81 on project 1 and 0.67 on project 2. Meanwhile, the complementarity modifier C for wall covering also reversed, then there would be 0.5 on project 1 and 0.75 on project 2. What would have happened?

For painting:

$a_pC_{1p}W_{1p}$ = 300x1x0.81 = 243 sf/hr.each

$a_pC_{2p}W_{2p}$ = 300x1x0.67 = 201 sf/hr.each

For wall covering:

$a_wC_{1w}W_{1w}$ = 15x0.5x1 = 7.5 ly/hr.each

$a_wC_{2w}W_{2w}$ = 15x0.75x1 = 11.25 ly/hr.each

$$I = \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [Q_{ij}/(a_{ij}C_{ij}W_{ij})]L_{ij}\}$$

$$= \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [(350000/243 + 17500/201) \text{ x } 40 + (7000/7.25 + 5000/11.25) \text{ x } 20]\}$$

$$= \sum_{i=1,\, j=1}^{2,2} [A_j(D_j - M_j) - C_{ind} - 119995]$$

Comparing two results, it is obvious that the new allocation suggestion would save $1,003 for the subcontractor. With recommended allocating measure, the cost on project 2 would be increased a little. But as the whole plan, the final cost of both projects would be less. Maybe this amount is not a big money resource for the subcontractor in this case, but it might result in a huge loss on the big scale project. With the parametric model as the guideline, allocating 1 painter and 1 wall-covering worker from project 1 to project 2 seems more profitable to the subcontractor.

BCH Mechanical Inc.

BCH Mechanical Inc. has performed 22,000 linear feet and 34,000 linear feet of pipefitting and plumbing for project 1 and project 2. Both the pipefitting and the plumbing crew need to be equipped with the same welding device to carry out the work. Every set of welding devices can meet the requirements for two crews, either pipefitting

or plumbing. Each worker requires 4000 square feet working space to maximize the productivity, and at least 1500 square feet working space with half of full productivity. The full productivity of the pipefitting crew is 200 linear feet per day, and the plumbing crew can finish at most 100 linear feet per day. These ideal productivities keep same at different projects. Project 1 provided 10,000 sf working area for crews; project 2 provided 20,000 sf. Hourly salaries of crews are $70 for pipe fitters and $50 for plumbers.

At the beginning, one pipefitting crew and one plumbing crew with one set of welding device were assigned on project 1, but three pipefitting crews and three plumbing crews with three sets of welding devices on project 2. Being aware of too few crews on project 1, there were one pipefitting crew and one plumbing crew reallocated later from project 2 to project 1, with one set of welding device also shift to project 1. Is this reallocation a good decision?

Before allocation: (5000 sf working space for each crew, so the working area modifier is 1 on project 1; 3333 sf working space for each worker on project 2, so the working area modifier W is 0.87.)

For pipefitting:

$$a_{pf}C_{1pf}W_{1pf} = 200x1x1 = 200 \text{ lf/day}$$

$$a_{pf}C_{2pf}W_{2pf} = 200x1x0.87 = 174 \text{ lf/day}$$

For plumbing:

$$a_{pb}C_{1pb}W_{1pb} = 100x1x1 = 100 \text{ lf/day}$$

$$a_{pb}C_{2pb}W_{2pb} = 100x1x0.87 = 87 \text{ lf/day}$$

$$I_{before} = \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [Q_{ij}/(a_{ij}C_{ij}W_{ij})]L_{ij}\}$$

$$= \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [(22000/200 + 34000/174) \times 70 \times 8 +$$

$$(22000/100 + 34000/87) \times 50 \times 8]\}$$

$$= \sum_{i=1,\, j=1}^{2,2} [A_j(D_j - M_j) - C_{ind} - 415344]$$

After allocation: (2500 sf working space for each worker, so the working area modifier is 0.7 on project 1; 5000 sf working space for each worker on project 2, so the working area modifier W is 1.)

For pipefitting:

$$a_{pf}C_{1pf}W_{1pf} = 200x1x0.7 = 140 \text{ lf/day}$$

$$a_{pf}C_{2pf}W_{2pf} = 200x1x1 = 200 \text{ lf/day}$$

For plumbing:

$$a_{pf}C_{2pf}W_{2pf} = 200x1x1 = 200 \text{ lf/day}$$

$$a_{pb}C_{2pb}W_{2pb} = 100x1x1 = 100 \text{ lf/day}$$

$$I_{after} = \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [Q_{ij}/(a_{ij}C_{ij}W_{ij})]L_{ij}\}$$

$$= \sum_{i=1,\, j=1}^{2,2} \{A_j(D_j - M_j) - C_{ind} - [(22000/140 + 34000/200) \times 70 \times 8+$$

$$(22000/70 + 34000/100) \times 50 \times 8]\}$$

$$= \sum_{i=1,\, j=1}^{2,2} [A_j(D_j - M_j) - C_{ind} - 444912]$$

It can be seen that $29,568 more were spent on workers' cost. However, the subcontractor just allocated resources according as the superficies of lacking workers on project 1, they did not realize that they would incur more costs. In case they have a parametric model analysis as the guideline, the subcontractor could avoid this kind of

resource allocation across multi projects that might be harmful to the subcontractor's benefits.

CHAPTER 5
CONCLUSIONS

This thesis has explored the concept of single-resource allocation across projects for the subcontractor, and derived a concept of multi-resource allocation across projects from a parametric model. The study reported in this thesis focuses on the construction of multi-resource allocation undertaken within a subcontract for the purpose of achieving success in project performance. Based on the results obtained from the study, multi-resource allocation can be defined as an effective scheduling optimization measure. Through rational resources allocation across projects, the whole construction cost can be controlled more effectively with timely completion that satisfies customers. Certainly a great deal of calculation in accordance with the thinking described in this thesis is needed to approach a more optimized solution.

Although the applicability of the derived resource allocation model does not take into account all of the influence factors, the analysis has nevertheless demonstrated that appropriately allocating resources across a project increases the probability of perfect project performance and is therefore likely to be cost-effective. This would be of benefit to the top management of subcontracting firms in determining how to achieve cost-effectiveness in resource allocating within the firm.

A subcontractor should not be discouraged if he finds one or more areas have significant weakness associated with resource allocation at the present time. The research about multi-resource allocation is still under development, and further research work is

being undertaken so that it is hoped that the solution of multi-resource allocation rationality will be more easily refined, evaluated, and implanted.

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BIOGRAPHICAL SKETCH

Chuan Song was born in Beijing, China. He graduated from Beijing University of Technology (formerly named Beijing Polytechnic University) with a bachelor's degree in civil engineering. He attended graduate school at the M.E. Rinker, Sr. School of Building Construction at the University of Florida in 2003, graduating with a Master of Science in Building Construction in 2005.