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Development of a Descriptive Cost Effectiveness Model for a Subcontractor with Limited Resources

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ABSTRACT: It only takes one failed project to wipe out an entire year's profit, when the projects are not managed efficiently. Additionally, escalating costs of materials and a competitive local construction market make subcontractors a challenge. Subcontractors have finite resources that should be allocated simultaneously across many projects in a dynamic manner. Significant scheduling problems are posed by concurrent multi-projects with limited resources. The objective of this thesis is to identify the effect of productivity changes on the total cost resulting from shifting crews across projects using a descriptive model. To effectively achieve the objective, this study has developed a descriptive cost model for a subcontractor with multi-resources and multi-projects. The model was designed for a subcontractor to use as a decision-making tool for resources allocation and scheduling. The model identified several factors affecting productivity. Moreover, when the model was tested using hypothetical data, it produced some effective combinations of resource allocation with associated total costs. Furthermore, a subcontractor minimizes total costs by balancing overtime costs, tardiness penalties, and incentive bonus, while satisfying available processing time constraints.

KEYWORDS: Cost Model, Subcontractor, Resource Allocation, Scheduling

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1. Introduction

1.1 Research Background

The construction industry in the U.S and abroad has grown tremendously in recent years in response to large increases in the number of new construction and remodeling projects. However, the engineering and construction market is still highly competitive, driving profit margins down as risks increase. It only takes one failed project to wipe out an entire year's profit, when the projects are not managed efficiently. Additionally, escalating costs of materials and a competitive local construction market make subcontractors a challenge.

In the current booming economy, one of the biggest problems for many smaller companies is securing reliable unskilled or semi-skilled help. By its very nature, construction is a "stop-and-go" industry, often with significant gaps between completion of one job and start of the next. Consequently, the level and type of labor demand varies constantly with the volume and type of work at hand. Therefore, it is crucial that subcontractors maintain their resources and effectively allocate them to multiple projects.

1.2 Research Needs and Motivations

Subcontractors have finite resources that should be allocated simultaneously across many projects in a dynamic manner. Significant scheduling problems are posed by concurrent multi-projects with limited resources. Unfortunately, with a lack of appropriate models, subcontractors mostly make decisions based on their previous experiences to allocate their resources to multiple projects. Therefore, the need for a model for resource allocation on multiple projects is still increasing.

Traditional approaches to scheduling and costing generally depend on network techniques such as time-cost-trade-off (TCT) and critical path method (CPM). The logic of the network methods only reflects the sequence of the activities as they must take place, and ignores

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availability of resources (Hinz, 2004). Furthermore, these techniques do not account for the fact that site conditions such as working space, have an impact on labor productivity. Therefore, traditional approaches do not fully reflect the subcontractor's current situation.

As current construction projects become more complex, changes in schedule commonly occur. It is generally known that subcontractors usually use overtime to accelerate the project. When the contractor master schedule is revised, subcontractors frequently employ overtime to keep up with the revised schedule. However, overtime usage sometimes causes cost overrun; in other words, the direct cost will increase, the more overtime a subcontractor uses, assuming the overtime cost is one and a half times as much as the regular time cost.

Despite much research and discussion on resource allocation and cost models, construction research has focused little attention on the individual firm or multi-project perspective when developing models to aid decision makers. Similarly, models used by practitioners (e.g., project costing methods) stem from a single-project perspective and do not directly support subcontractor resource allocation decisions across projects. Such decisions are made heuristically, because we lack formal models to guide practitioners (O'Brien, 2000).

In the current construction industry, it is recognized that a better understanding of the behaviors of the subcontractor between multi-resources and multi-projects is needed for the subcontractor's competitiveness. Since subcontractors maintain limited resource that should be allocated simultaneously across many projects in a dynamic manner (O'Brien and Fischer, 2000).

2. Literature Review

2.1 Review of Related Work

Traditional methods of scheduling in construction projects largely depend on network planning techniques, particularly the critical path method (CPM) which assumes unlimited resources for a project. This assumption is not always valid in the real world, where there are limitations imposed by the availability of resources, particularly when resources are shared by multiple activities or even several concurrent projects (Lu and Li, 2003; Jiang and Shi, 2005).

Moreover, fundamental approaches to costing, the time-cost-trade-off (TCT) in particular, do not explicitly account for the capacity costs and constraints of subcontractors. Furthermore, they do not represent the effects of site conditions on productivity (O'Brien and Fischer, 2000). It is noted that site conditions such as working space have an effect on labor productivity. For example, if workers are added to accelerate the project, the potential for productivity will be negatively affected by overcrowding (O'Brien, 2000; RS Means, 2004). Accordingly, these network techniques such as the critical path method (CPM), are difficult to apply to scheduling of repetitive projects or concurrent multiple projects (Reda, 1990; Suhail and Neale, 1994; Hegazy and Wassef, 2001).

To minimize project direct cost, several models have been developed for cost optimization of repetitive projects. Reda (1990) minimized project direct cost assuming linear time-cost relationships. Moselhi and El-Rayes (1993) presented a dynamic programming model that determines optimum crew formation to minimize project direct cost. Additionally, Hegazy and Wassef (2001) developed a practical model for scheduling and cost optimization of repetitive projects. They tried to minimize total construction cost that is affected by several factors: direct cost, indirect cost, daily-liquidated damages, incentive for early completion, or delay penalties.

In spite of these models, existing methods do not fully represent subcontractors' situations. Additionally they do not account for the costs of capacity constraints or site conditions when schedule and/or scope change. More broadly, construction costing and control methods do not take these influences into account.

Currently, sub-contractors with limited resources perform several projects at the same time. According to Nkasu and Leung(1997), with no regard for limitations imposed by resources, most activities will be performed as scheduled. In practice this is not typically the case. However, significant scheduling problems are posed by concurrent multi-projects with limited resources. To illustrate, for subcontractors with unlimited resources, all projects would be performed simultaneously without any need for their prioritization, each being completed in accordance with its own respective schedule. Simultaneously, it is found that subcontractors allocate their finite resources to multiple projects in a dynamic manner and have difficulty in adjusting to changes and uncertainty in schedule (O'Brien and Fischer, 2000).

To resolve this problem, overtime is a commonly used strategy to stretch subcontractors' limited resources. Yang et al. (2004) have studied the algorithm for determining the optimal usage of regular time and overtime for any sequence of jobs to minimize the sum of weighted overtime cost and tardiness cost for any fixed sequence of jobs. Furthermore, significant research advancements have been made in the area of sub-contractors' constraint and optimizing construction resource utilization. Thabet and Beliveau (1994) and O'Brien and Fischer (2000) have identified that limited work area and site conditions negatively affect subcontractors' productivity. Moreover, O'Brien (2000) subsequently developed a parametric model that represents the relationship between productivity, site conditions, and resource allocation.

Based on the aforementioned research, Song (2005) developed a construction cost model for a subcontractor. He not only identified some factors influencing productivity, but he also discussed the effects of multi-resource allocation with a mathematical model. Accordingly, the model reveals the extent to which shifting resources between sites impacts cost. Song did not consider project deadline and overtime usages, though both these factors have critical impact on the total construction costs. Consequently, despite these contributions to establishing a conceptual cost model, a practical cost model that can be applied to multi-projects by a subcontractor are not available.

2.1 Resource Allocation Problems

In the field of subcontractor management, it is recognized that a better understanding of the behaviors of subcontractor between multi-resources and multi- projects is needed, since subcontractors have limited resources that should be allocated to multiple projects in a dynamic manner. To illustrate, when they perform a single project, it is not a big problem to allocate their limited resources, however, with regard to multi-projects, the subcontractors should take into consideration many things to minimize their cost. Sometimes they loan a workers and use overtime to follow up their delayed schedule.

It is significant to note that subcontractors frequently reallocate their resources in response to schedule changes and site conditions (O'Brien and Fischer, 2000; O'Brien, 2000). In response to schedule changes or project demand, these factors should be taken into account before reallocating resources: site conditions, completion dates, overtime usage, productivity, and complementarity. Considering current subcontractors situations, it is necessary for subcontractors to develop a parametric model of total cost minimizing their construction cost.

3. A Descriptive Cost Model

3.1 Model Formulation

This approach has been taken by O'Brien (2000) in a model of production rate on a work area as well as Yang et al. (2004) in an approach for minimizing weighted tardiness and overtime costs.

It is well known that adding workers to the site may not always improve productivity. If additional workers are added to accelerate the project or to perform changes while maintaining the schedule, the potential for productivity will decrease. Some of the factors that cause this productivity loss are overcrowding (producing restrictive conditions in the working space) and possibly a shortage of special tools and equipment required. Such factors affect not only the crew working on the elements directly involved in the change order, but also other crews whose movement may also be hampered.

The relation between productivity and site conditions has been well developed by O'Brien (2000) as follows:

$$Pi = (aj^{T} y)CW \quad \text{Eq. 3-1}$$

where, Pi: actual productivity rate in the work area for all resources applied, aj: ideal productivity rate per unit of flexible resource for construction method j, y: units of flexible resources applied, C: complementarity productivity modifier, W: work area productivity modifier

When calculating total cost of resource allocation, some extra cost must be considered: Switching costs for moving resources between sites, where each resource will have different transportation costs, training cost for new added unskilled laborers, and rewards for early completion and penalties for tardiness, specified in the contract. In this thesis, we only consider the bonus and penalties and ignore the shifting costs and training costs. Total cost is largely the sum of direct cost and indirect cost.

Total Cost = Indirect Cost + Direct Cost
= Indirect Cost + Duration × Unit cost of flexible resource × units of flexible resource
= Indirect Cost + (Quantity of Work/ Productivity) × Unit cost of flexible resource * units of flexible resource
= Indirect Cost + [Quantity of Work/ (a × y ×C × W)] × Unit cost of flexible resource × units of flexible resource(y) ―――――― Eq. 3-2

Direct cost generally means a cost directly attributable to the construction activity. It includes material cost, equipment expense, and labor cost. In this thesis, however, only labor cost will be considered as direct cost for the sake of simplicity. Moreover, overtime cost will be assumed one and a half times as much as regular time cost. Indirect cost includes the overhead and project management expense; furthermore, it is a linear relationship along the activity construction time. Therefore, direct cost and indirect costs are calculated as follows:

Direct cost = unit cost of flexible resource × units of flexible resource × work hours ―――――― Eq. 3-3

Indirect cost = m × Duration (m>0) ――――― Eq. 3-4

Considering that, generally, each project provide a bonus for earlier completion and imposes penalties for tardiness, the subcontractor's total cost can be expressed as:

Σ {Cind + Cd − B + T} ――――――――――― Eq. 3-5

Where, Cind: indirect cost, Cd: direct cost, B: bonus, T: penalty for tardiness.

Assuming that the policy of overtime is 0 or 4-hours per day, overtime will be expressed "0" or half the amount of regular time. Additionally, direct cost includes overtime cost and regular time cost. Consequently, Equation 4-5 will be represented by Equation 4-6 and Equation 4-7.

Σ{(Cind + Crij + Coij − Bij + Tij) ―――――― Eq. 3-6

From Co = 1.5 Cr and Φij = 0.5R, Equation 3-6 will be deduced to as follows:

Σ{(Cind + yijMijRij + 1.5×yijMijΦij−Bij+Tij) ― Eq. 3-7

After applying Equation 4-1 and Equation 4-2 to Equation 4-7, we can get a multi-resources and multi-projects cost model for a subcontractor as shown in Equation 4-8.

Σ{(Cind + yijMij(Qij−Qpij − 0.5PijΦij)/ Pij + 1.5yij MijΦij − Bij + Tij)}
= Σ{(Cind+yijMij(Qij−Qpij −0.5aijyijCijWij Φij)/ aijyijCijWij +1.5yijMijΦij−Bij+Tij)} ――――― Eq. 3-8

Where, Cind –subcontractor's overall indirect construction cost, Cd – subcontractor's overall direct construction cost, Bij – bonus, Tij – tardiness cost, Crij – total Cost for regular time, Coij – total Cost for overtime, yij – units of resource on project j, Cij – complementarity productivity modifier, Wij – work area productivity modifier, Mi – cost of unit time for one unit of resource (other than material), Rij – duration for regular time, Qij – total work amount of project j, Qpij –quantity of work performed, Φij – duration for overtime, Pij – productivity for resource I, aij – ideal productivity rate per unit of flexible resource (i = 1,2,3⋯m; j = 1, 2, 3 ⋯n)

Therefore, we can apply Equation 3-8 to the compact and relax phases of the algorithms introduced by Yang et al. (2004). In this thesis, we assumed that independent subsets consist of a single job in a single project.

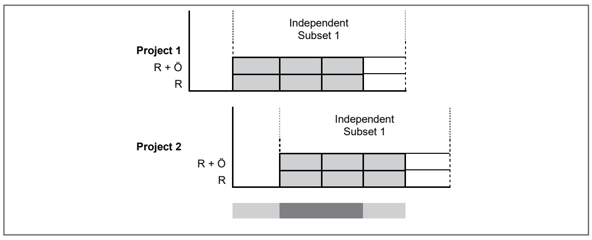

Figure 1. The schedules of two concurrent projects

Figure 1 represents two concurrent projects, project 1 and project 2, performed by a subcontractor with limited resources. Before considering multiple projects, it is important to determine the optimal combination of overtime and penalty for tardiness in a single project. Therefore, applying Equation 4-6 to analyze project 1, decrease the amount of overtime scheduled for each job by an amount that provides the greatest cost reduction as compared to the current schedule. Beginning with the last job, we apply Equation 4-6 to a reverse order. Thereby, we can obtain the optimal combination of overtime and penalty for tardiness in a single project.

With the optimal combinations of resources for each project, we proceed to multiple projects. If there were unlimited resources, both projects could of course be performed simultaneously without any need for their prioritization, each being completed in accordance with its own respective schedules. However, when resources constraints are imposed, resource prioritization and reallocation must be considered.

As shown in Figure 2, Part A and B are applied to the same methodology of single project, while Part C resources are affected by each project. Therefore, before allocating resources, a subcontractor must identify the option that will yield maximum profits.

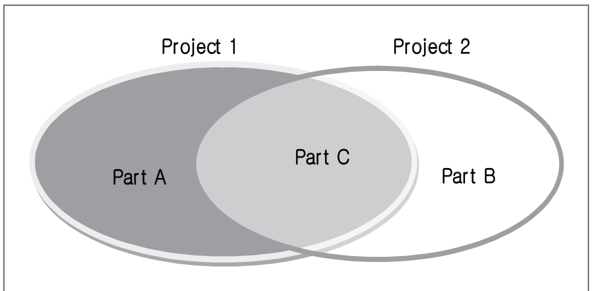

Figure 2. Diagram of schedule overlapped with two concurrent projects

4. Case Study

4.1 Multi-resources and multi-projects allocation

Assuming a roofing subcontractor has two projects to build at the same time with limited resources (two membrane crews and two insulation crews), one is 6,000 square feet, and the other one's size is 7,500 square feet. Our study focuses on two kinds 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. 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:

o Project 1: 6,000sf to work; 4,000sf 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.

o Project 2: 7,500sf to work; 6,000sf working space; one fixed membrane application machine; one fixed insulation application machine; one membrane crew with an ideal productivity of 1,200sf/day; one insulation crew with an ideal productivity of 800sf/day.

Several assumptions were made as follows:

- A subcontractor has limited resource with two membrane crews and two insulation crews
- Overtime cost is 1.5 × regular time cost
- Overtime is limited 4hours per day.
- In overtime, Membrane costs $ 150 / day and Insulation worker costs $225 per day.
- Bonus is $ 300 / day and tardiness cost is $ 500 / day.
- Resource 1 and resource 2 do not affect each other to perform their jobs. They affect only working area modifier, not a precedence of work.
- When using overtime, the productivity is identical with that of regular time.

- Regular time is defined as 8hour per day.
- Machine cost is excluded for the direct cost in convenience.
- Indirect cost is $ 150 / day in regular time, $ 75 / day in overtime.
- Membrane worker is $ 200/ day and Insulation worker is $ 300 / day
- Each project has 7 days for its construction duration, if they would not finish by completion date, tardiness cost will be fined.

The information of the projects and related modifiers are summarized as shown in Table 1, 2 and 3.

Table 1. Ideal productivity of each crew

project #	working space	Ideal productivity	
		membrane	insulation
Project 1	4,000sf	1,200 sf/day	800 sf/day
Project 2	6,000sf	1,200 sf/day	800 sf/day

Table 2. Complementarity modifier C

Σy/x	1	2	3	4
C	0.8	1	0.9	0.85

Table 3. Work area productivity modifier W

Work Area	1,000	2,000	3,000	4,000	5,000	6,000
W	0.4	0.8	0.9	1	0.95	0.9

Using Equation 3–1, we can calculate each combination's labor productivity for its respective project as shown in Table 4 and Table 5. These results shows us adding workers to the site may not always improve productivity linearly.

4.2 Two single projects

As shown in Table 6 the best option that has the least total cost is the combination of one membrane crew and one insulation crew. Although this combination does not complete project 1 beyond completion duration, 7days, it has the least total cost. Therefore, we can select this combination of one membrane crew and 1 insulation crew with a total cost of $7,500 for project 1.

For the project 2, the best optimal combination of resources is two membrane crews and 2 insulation crews with a total cost of $ 7,175 as shown in Table 7.

Table 4. Each labor productivity for project 1

# of m crews	# of i crews	total # of crews	am	ai	Cm	Ci	W	Pm	Pi
0	1	1	1,200	800	0	0.8	1	0	640
1	0	1	1,200	800	0.8	0	1	960	0
1	1	2	1,200	800	0.8	0.8	0.8	768	512
1	2	3	1,200	800	0.8	1.0	0.53	512	853
2	1	3	1,200	800	1.0	0.8	0.53	1,280	341
2	2	4	1,200	800	1.0	1.0	0.40	960	640

Table 5. Each labor productivity for project 2

# of m crews	# of i crews	total # of crews	am	ai	Cm	Ci	W	Pm	Pi
0	1	1	1,200	800	0	0.8	0.9	0	576
1	0	1	1,200	800	0.9	0	0.9	972	0
1	1	2	1,200	800	0.8	0.8	0.9	864	576
1	2	3	1,200	800	0.8	1.0	0.8	768	1,280
2	1	3	1,200	800	1.0	0.8	0.8	1,920	512
2	2	4	1,200	800	1.0	1.0	0.6	1,440	960

Table 6. The result of the applied model for project 1

# of m crews	# of i crews	duration(m)-day		duration(i)-day		direct cost	indirect cost	bonus bonus	tardiness cost	total cost
		regular	overtime	regular	overtime					
ym	yi	R	Φ	R	Φ	Cd	Cind	B	T	C
2	0	3	2	0	0	1800	900	N/A	N/A	2700
1	0	5	3	0	0	1450	1875	N/A	N/A	3325
0	1	0	0	8	3	3075	1200	N/A	N/A	4275
0	2	0	0	4	3	3750	600	N/A	N/A	4350
1	1	8	0	8	8	5800	1200	0	500	7500
1	2	12	0	7	1	7050	1800	0	2500	11350
2	1	5	0	12	12	8300	1800	0	2500	12600
2	2	6	1	7	6	9600	1575	0	0	11175

Table 7. The result of the applied model for project 2

# of m crews	# of i crews	duration(m)-day		duration(i)-day		direct cost	indirect cost	bonus	tardiness cost	total cost
		regular	overtime	regular	overtime					
ym	yi	R	Φ	R	Φ	Cd	Cind	B	T	C
2	0	3	1	0	0	1500	675	N/A	N/A	2175
1	0	8	0	0	0	1600	1200	N/A	N/A	2800
0	1	0	0	9	4	3600	1350	N/A	N/A	4950
0	2	0	0	4	1	2850	600	N/A	N/A	3450
1	1	9	0	9	3	5175	1350	0	1000	7525
1	2	10	0	5	0	5000	1500	0	1500	8000
2	1	4	0	8	8	5800	1200	0	500	7500
2	2	5	1	5	3	6650	1125	600	0	7175

4.3 Concurrent multi-projects

Then, we can apply Equation 3-8 to the compact and relax phase of algorithm that was introduced by Yang et al. (2004). In this study, we assumed that independent subset consist of two concurrent projects as shown in Figure 2.

As reviewed in two single projects, we cannot allocate the optimal combinations to each project because of limited resources. The existing model (Song, 2005) may not introduce appropriate combination of multi-projects.

Only what it can do is to evaluate which combination is better. However, the model developed shows several appropriate combinations to minimize total cost using spreadsheet based on the Equation 3-8.

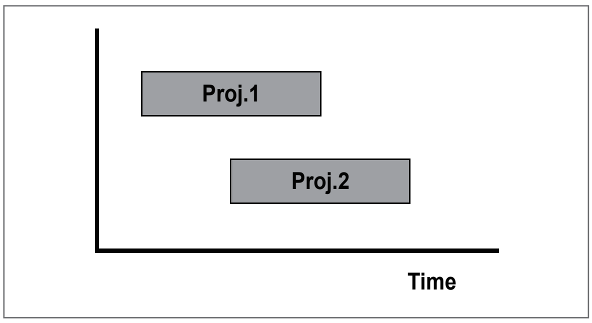

Figure 2. The schedules of two concurrent projects

The following Figure 3 shows several reasonable combinations. Therefore, we can find an appropriate combination for the two concurrent projects. The total cost of combination 2 is $14,575 and this cost is less than the sum of each best option for each project. Table 8 presents the result of each combination by each project and the two concurrent projects. All the combinations produce the same optimal total cost for project 1. For project 2, combination 2 shows the best total cost of $7,075. However, combination 2 shows the best optimal cost when project 1 and project 2 are concurrently performed.

Table 8. The optimal combination for the two concurrent projects

Combinations	Project 1 Total Cost	Project 2 Total Cost	Project 1+2 Total Cost
Combination 1	7,500	7,525	15,025
Combination 2	7,500	7.075	14,575
Combination 3	7,500	7,650	15,150

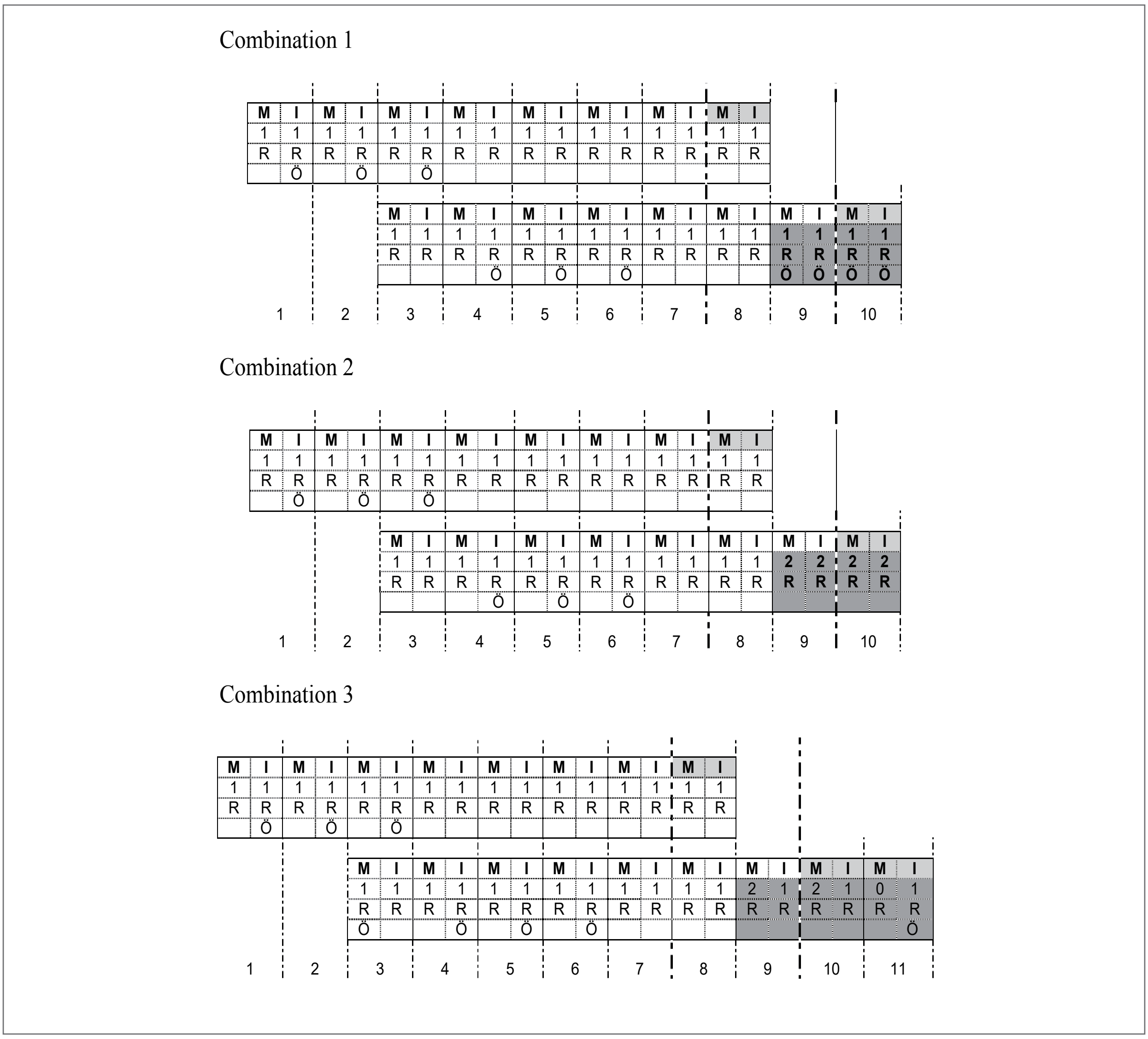

Figure 3. The schedules of two concurrent projects

5. Conclusions

This study has developed a descriptive cost model for a subcontractor with multi–resources and multi–projects. The model was designed for a subcontractor to use as a decision–making tool for resources allocation and scheduling. The model identified several factors affecting productivity. Moreover, when the model was tested using hypothetical data, it produced some effective combinations of resource allocation with associated total costs.

Issues about multi–resources allocation are still being researched. Compared to existing multi–resource allocation tools, this model better accounts for subcontractors' real situation. Therefore, this thesis may contribute to better understanding of subcontractors' behaviors and improve the traditional approaches to scheduling and costing.

Although the applicability of the derived resource allocation model does not take into consideration all of the influencing factors, the analysis has nevertheless demonstrated appropriate resource allocation across several projects from the cost–effective perspective of a subcontractor. With this model, subcontractors can maximize profits by balancing overtime costs and incentive bonus or tardiness penalties.

The study about multi–resources allocation across multi–projects is still under development. Through the course of this study effort, the following recommendations have been identified.

1. It is well known that even though overtime achieves schedule acceleration, labor productivity can be negatively impacted by overtime, causing several problems such as fatigue, safety problems and low morale (Hanna et al., 2004; Horner and Talhouni, 1995). However, the relationship between overtime and productivity is beyond scope of this model. Therefore, future research should be pursued to improve our understanding of this relationship.

2. It is difficult to determine optimal combination of cost factors manually because of the many variables. Therefore, using computer programming may enable us to find the best option for minimizing total cost and maximizing profit.

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