OPTIMIZATION MODEL OF EXTERNAL RESOURCE ALLOCATION FOR RESOURCE-CONSTRAINED PROJECT SCHEDULING PROBLEMS

Kuo-Chuan Shih
Ph.D. Student, Graduate School of Engineering Science and Technology
National Yunlin University of Science and Technology,
Touliu, Taiwan, 640, ROC

Shu-Shun Liu
Assistant Professor, Department of Construction Engineering
National Yunlin University of Science and Technology
Touliu, Taiwan, 640, ROC
liuss@yuntech.edu.tw

Abstract: Construction project scheduling is crucial to project success. From the perspective of contractors, a practical schedule based on engineering experience not only improves the accuracy of project duration and cost estimation during the bidding process, but also facilitates the operation during project execution. This study employs Constraint Programming (CP) techniques to resolve resource-constrained project scheduling issues. A new scheduling model aiming for the minimization of total project cost, including resource usage and idle cost, is proposed in this paper. Most importantly, this paper introduces a new idea in resource-constrained project scheduling, namely the concept of external resources to enhance model feasibility for construction scheduling problems practice. A scheduling optimization engine coded in C++ is then developed to validate model feasibility and accuracy. The research results demonstrate the importance of external resources through case studies. Furthermore, the significance of critical resources is evaluated and discussed in this paper.

Keywords: Project scheduling, Resource-constrained scheduling, External resources, Constraint programming

1. INTRODUCTION

The Critical Path Method (CPM) has been widely accepted and used for construction scheduling problems over the recent decades. However, as for the management goal of the effective use of resources in construction projects, traditional CPM applications are difficult to implement since the CPM concept was originally devised to focus on project completion efficiency. Therefore, supported by the rapid development of computer techniques, further studies have been performed for solving the complexity of construction scheduling problems by using different techniques. The techniques adopted can generally be grouped into two categories (Moselhi and Lorterapong, 1993): optimization-based and heuristic-based. Optimization techniques such as mathematical programming and generic algorithm aim to produce optimal solutions. However, these techniques require strong assumptions regarding problem formulation and extensive computational efforts for real-life construction projects that generally include hundreds of activities. Heuristic models are based on decision rules for assigning priority with regard to resource allocation among various activities. Those heuristic models have been demonstrated to perform well over various problems, and are widely used in actual practice owing to their simplicity and efficiency in application. However, they cannot guarantee to find the optimal solution. (Chan et al., 1996).

In order to ensure project success, resource planning is a key topic in effective construction project scheduling. Generally, issues related to resource planning can be classified into the following categories, which sometimes are conceptually interrelated:

1.1 The Time-Cost Trade-off Problem.

This form of analysis focuses on the idea that the duration of certain critical activities can be reduced through the addition of more costly resources, and overall project duration can be improved (Liu and Yang, 1995; Li and Love, 1997; Feng et al., 1997).

1.2 The Resource-Constrained Scheduling Problem. (Resource Allocation)

This form of analysis aims to minimize either project duration or total cost, while assuming an upper limit on resource availability. Due to the possibility of project duration being extended owing to resource constraints, the time-cost trade-off problems represented by different resource combinations in this study were discussed by previous works (Hegazy, 1999; Leu and Yang, 1999).

1.3 The resource Leveling Problem.

This analysis reduces peak resource requirements and smoothens out period-to-period assignments within the required project duration. The original idea of the resource leveling approach is based on the premise of unlimited resource availability. However, this concept has been integrated with resource-constrained scheduling problems by performing two-stage optimization processes as follows: (1) solving project schedules under the scope of resource-constrained scheduling problems; (2) executing resource leveling tasks within the project duration obtained from the first optimization stage (Hegazy, 1999; Leu and Yang, 1999).

Considering the above resource planning problems, this study proposes a new optimization model for solving construction resource-constrained scheduling problems, by adopting Constraint Programming (CP) techniques, which are being developed rapidly through recent decades. The optimized schedule aiming to minimize project total cost under resource constraints is then obtained through this model. Furthermore, in construction scheduling practice, not only must contractors make a resource plan for each resource type through the whole project, but they must also consider the option of procuring temporary-based resources. Those resources are defined as external resources in the proposed model, particularly during the period of peak resource consumption, for fulfilling project completion requirements. The concept of external resource is implemented in this optimization model to help planners make the decisions, such as the timing of external resources are needed, and how many of those resources are needed. Additionally, case studies are used to identify and analyze the influence of the addition of external resources on project objectives.

2. NATURE OF SCHEDULING PROBLEMS

Referring to literature review, previous researches have implemented different methods of finding the optimum solution, rather than discussing the nature of scheduling problems in construction projects. Before proposing the model formulation, it is necessary to note the topics that inspire this study, and to distinguish the proposed model from prior researches.

2.1 Activity Cost Assessment

Based on the assumptions from most of previous researches regarding activity cost, activity cost varies from activity duration given by a certain resource combination. However, in current construction practices, activity cost assessment is based on resource usage, including labor, material, and equipment. Therefore, in the proposed model, direct cost is calculated based on resource usage costs throughout the entire project, rather than by adding up the costs for each activity.

2.2 Resource Limitations – Internal and External Resource

For construction projects, effective resource management is always crucial for planners. Comparing the characteristics of resource management issues in highly-automated manufacturing industry, the complexity of resource management in labor-intense construction projects arises from the diversity of resource acquirement. For example, machine times in production lines are the major resources dominating productivity in the manufacturing industry, and are normally difficult to acquire from other means. That is, the limitation of main resources such as machine times can be considered as a hard constraint in model formulation. On the contrary to such situation in manufacturing industry, the resource issues existing in construction industry are essentially different, and illustrated as follows:

Some general tasks can be executed using resources from different sources. For example, porterage jobs can be performed by any labor available on site, and do not need to be performed by specialized labor. Therefore, in construction practices, it is difficult to set resource limits while establishing a resource plan. Consequently, the flexibility of resource plans needs to be realized in construction project scheduling problems, rather than blindly setting resource limits based on former experience.

Resource outsourcing actions are frequently considered by contractors as a means of maintaining project performance. In practice, contractors commonly purchase the additional quantity of temporary resources to refine resource plans. Owing to the need for more resources, outsourcing actions such as temporary subcontracting are considered and executed to make up for deficiencies in resource plans. For instance, outsourcing actions can be executed by adding crew formations, construction equipment, or labor working hours, during specific project period. The proposed model defines two general types of resources, namely INTERNAL and EXTERNAL resources, depending on procurement behavior and holding period. These two types of resources are defined as follows: internal resources refer to resources that contractors own or hire for the entire project cycle, while external resources refer to temporary resources hired for specific time frame when resource consumption is heavy, and such resources are dismissed upon completion of the designated activities, on a short-term basis.

2.3 External Resource Usage

According to the above statements, one of the main focuses of this study is investigating the significance of external resources and the corresponding influence on project duration and cost, from the optimization perspective. In addition to setting the upper limits of internal resources, contractors have the option of considering external resources for resolving resource deficiency issues, depending on the assessment of their availability throughout the project.

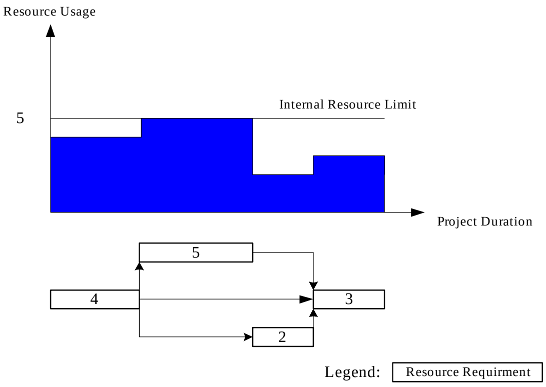

Fig. 1 Planed Schedule Constrained by Internal Resource

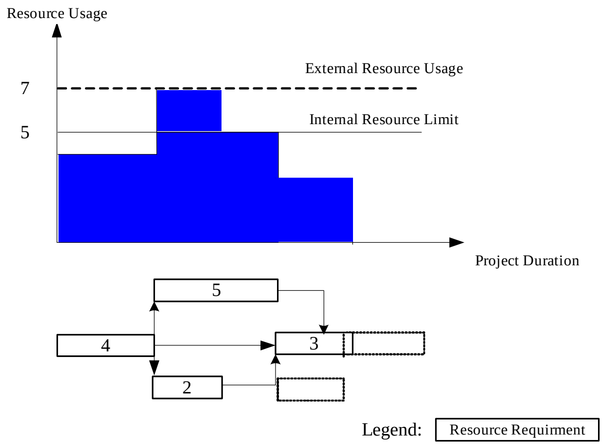

Fig. 2 Modified Schedule by Adding External Resource

Fig. 1 and Fig. 2 illustrate a sketch map of the upper limits of internal and external resources, and the effect on project duration by outsourcing external resource is presented. Fig. 1 shows information of resource usage and project duration without considering external resources. Nevertheless, by adding external resources, the project duration can be reduced as Fig. 2 because of the more resources available for activity execution. Form the viewpoint of solving resource bottleneck, the concept of external resource provides a feasible alternative, in resource-constrained environment.

However, another issue involving the consideration of external resources is that it is sometimes difficult to determine the exact quantity of external resources purchased, due to various complicated reasons such as the corresponding influences on project duration and cost. Therefore, this study presents a scheduling optimization mechanism for providing information on making outsourcing decisions.

Moreover, external resources are usually used for "critical" activities constrained to resource limitation, in order to boost project performance. Generally, the key issue for contractors is how to allocate these external resources to applicable activities and how many of those resources should be acquired during resource allocation. Therefore, the proposed model implements the concept of external resources via a set of decision variables for each activity to determine the timing of external resource assignation and the quantity of such resources to be assigned.

2.4 Resource Idleness

Resource leveling problems in the project scheduling domain involve the attempt to bring daily resource usage to a desired target level, given a fixed project duration. This operation can minimize the fluctuation in daily resource usage. However, compared to resource-constrained issues, resource usage fluctuation is a minor issue since all project resources are limited in practical situations.

Therefore, in resource-constrained environment, the key focus for planners is resource idleness. Minimizing resource idleness is a more important management goal in current construction practices than resource leveling. This goal can be achieved by allowing daily resource usage to approach the limits of available resources, and then minimizing resource idle costs.

However, setting suitable internal resource limits is tough, since high limits lead to resource idleness and low limits create a risk of extended project duration. Therefore, it is crucial for planners to carefully determine suitable internal resource limits to avoid such situations. Through the consideration of external resources as proposed in this study, the limits for all kinds of internal resources can be systematically evaluated, instead of using rough estimates based on the experience of planners. While additional resources are required during the peak period of construction operations, external resources may get involved to make up for resource shortages. Therefore, planners can simultaneously benefit by both lowering internal resource holding level and reducing resource idleness.

To realize the consideration of resource idleness, resource idle cost are implemented in the proposed model. Resource idle cost can refer to resource holding or maintenance fee. For example, as for labor, resource idle cost is equal to the holding fee, regardless of whether the resources are idle or not; as for equipment, maintenance cost are considered as idle cost.

Thus, by integrating resource idleness to meet construction practices, and setting values of idle costs for different kinds of resources, planers can observe resource usage and corresponding variation of the expenses Moreover, goals of optimizing project total cost and resource leveling can be achieved with such consideration.

3. MODEL FORMULATION

This study attempts to identify the optimum solution with respect to the objective of minimizing project total cost in resource-constrained environment. The objective function is shown as Eqn. (1), and comprises four parts: direct cost, indirect cost, bonus, and extension penalty. The components of project total cost are also shown as Eqns. (2) to (5).

3.1 Objective Function

In this study, project total cost includes direct cost, indirect cost, and penalty or bonus, and minimizing total cost is regard as objective function of the proposed model. Eqn. (1) shows the components of project total cost.

Minimize $TC = DC + IC + P - B$ (1)

Where TC is project total cost, consisting of direct cost (DC), indirect cost (IC), and penalty (P) or bonus (B), depending on project duration is longer or shorter than contract duration.

1) Direct Cost

Three parts comprise total direct cost, including internal resource cost, external resource cost, and resource idle cost. Eqn. (2) calculates total amount of internal and external resource utilized by each activity in a project, and sums up resource usage cost and idle costs through the whole project. In Eqn. (2), parameters for resource usage limit, unit cost, and idle costs can be determined by users' assessments.

$$DC = \sum_{j=1}^{r}[(\sum_{i=1}^{n} IRU_{ij} \times d_i) \times IRC_j] + \sum_{j=1}^{r}[(\sum_{i=1}^{E} ERU_{i,j} \times d_i) \times ERC_j]$$
$$+ \sum_{j=1}^{r}[(IRL_j \times T - \sum_{i=1}^{n} IRU_{i,j} \times d_i) \times RIP \qquad (2)$$

$IRU_{i,j}$ is the amount of internal resource type j utilized for activity i; IRC_j is unit cost per day of internal resource type j; d_i is duration of activity i; $ERU_{i,j}$ is total amount of external resource type j utilized for activity i; ERC_j is unit cost of external resource type j; IRL_j is limit of internal resource type j per day; T is project duration, calculated during program runtime; RIP_j is daily idle cost for internal resource type j per unit; r is total number of resource types; n is total number of activities; and E is set of activities which require external resources during program runtime.

2) Indirect Cost

The proposed model computes total indirect cost by summing up daily indirect cost, and sets up daily indirect cost as a constant. Eqn. (3) shows the definition of indirect direct cost.

$$IC = T \times IDC \qquad (3)$$

Where IDC is daily indirect cost.

3) Extension Penalty and Bonus

Penalty and bonus are calculated based on the deviation of optimized project duration and contract duration, and are shown as Eqns. (4) and (5). Clearly, the values of both variables cannot exist simultaneously, and thus must be positive values. The logical constraints then for calculating penalty and bonus are presented in Eqns. (6a) and (6b).

$$P = (T - CD) \times PPD \qquad (4)$$
$$B = (CD - T) \times BPD \qquad (5)$$
$$if \quad T \ge CD \quad then \quad B = 0 \qquad (6a)$$
$$if \quad T \le CD \quad then \quad P = 0 \qquad (6b)$$

Where CD is contract duration and PPD is penalty per day, if project duration is longer than contract duration; and BPD is bonus per day if project duration is shorter than contract date.

3.2 Constraints

The constraints in constraint programming formulation are described in two groups, including activity relationship and resource constraints, displayed as Eqns. (7) to (10).

1) Activity Relationship Constraints

Project scheduling problems involve four typical activity relationships, but only the FS (Finish to Start) relationship is used in the proposed model for illustrating the solution solving procedure of the following case study. Besides, in the proposed model, activity duration (d_i) comes from a set of durations (D_i), and is assigned depending on resource requirement combination of the activity.

$$S_j - S_i \ge d_i \qquad i = 1, 2, \ldots\ldots, m;$$
$$\text{all } (i, j) \in A; \ \forall\, d_i \in D_i \qquad (7)$$

Where S_i is start time of activity i; m is last activity in project network; A is set of pairs of activities with precedence relationships; and D_i is set of possible durations of activity i.

2) Resource Constraints

The concept involving resource usage, such as internal and external resource, is introduced in this study, and the following Eqns. illustrate constraints for resource issues. Eqn. (8) constrains daily limits of all resource types, and resource limit consists of daily internal resource limit and external resource limit, which are constants assigned by planners. Resource total amount for each type, including internal and external resource, employed by activities can not exceed resource limit as shown in Eqn. (9). Referring to Eqn. (9), it restricts daily resource usage for all activities that must be less than resource availability, and daily resource usage comprises of internal resource usage, and if necessary, external resource. Then it also indicates resources utilized by all in-progress activities on day k must be smaller than or equal to resource limits. As for Eqns. (10a) and (10b), both illustrate the components of resource usage for activities in varied situations, depending on external resource usage, where activity j belongs to set E or set $\overline{E}$.

$$RL_j = IRL_j + ERL_j \qquad j = 1, 2, \ldots\ldots, r \qquad (8)$$
$$RL_j \ge \sum_{i=1}^{S_k} RUd_{i,j} \qquad \forall\ i \in S_k;\ k = 1, 2, \ldots\ldots, T \qquad (9)$$
$$\forall i \in E \qquad RUd_{i,j} = IRU_{i,j} + ERU_{i,j}$$
$$j = 1, 2, \ldots\ldots, r \qquad (10a)$$
$$\forall i \in \overline{E} \qquad RUd_{i,j} = IRU_{i,j}$$
$$j = 1, 2, \ldots\ldots, r;\ \text{all} \quad i \in \{\, E \cup \overline{E} \,\} \qquad (10b)$$

Where is RL_j is daily limit of resource type j per day, including internal and external resources; ERL_j is limit of external resource type j per day; RUd_i j is daily resource usage of resource type j for activity i at duration d; S_k is set of in-progress activities on day k; and E is set of activities which require external resources during program runtime.

4. COMPUTATIONAL EXPERIMENTS

Data from Table 1 is adapted for examining the proposed model, and the representation of activity costs is modified based on resource usage. In following experiments, direct cost for each activity is generated through calculating resource costs, such as costs of internal and external resources. Besides, several parameters are designated and added into the proposed model to fulfill scheduling practice requirements, including indirect cost, bonus, penalty, and other resource information. Table 2 lists all specific parameter values:

Table 1 Example Project Information (Leu and Yang, 1999)

Activity	**Duration**	**Cost**	**Resource type I**	**Resource type II**	**Resource type III**	**Succeeding activities**
A	5	480	5	4	5	B, D, F
	6	300	3	4	5	
B	9	450	4	5	2	C
C	12	850	4	6	6	H
	13	600	3	6	5	
D	15	420	5	2	4	C, E
E	12	1860	1	5	6	H, I
	13	1450	1	5	4	
	14	1050	1	5	2	
F	16	3860	6	4	4	E, G
	17	3220	5	3	3	
	18	2600	4	2	2	
	19	2000	3	1	1	
G	13	1900	3	3	6	I
	14	1200	3	2	5	
H	7	950	6	4	3	I
	8	640	6	3	2	
I	9	560	5	5	5	--

Table 2 Model Parameter Setting

Parameters	**Values**
IDC	2,000 ($ /per day)
CD	80 (days)
BPD	80 ($ /per day)
PPD	50 ($ /per day)
IRC_j (j=1)	500 ($ / per unit, per day)
$RIPj$ (j=1)	100 ($ / per unit, per day)
ERC_j (j=1)	700 ($ / per unit, per day)
IRC_j (j=2)	400 ($ / per unit, per day)
$RIPj$ (j=2)	80 ($ / per unit, per day)
ERC_j (j=2)	600 ($ / per unit, per day)
IRC_j (j=3)	300 ($ / per unit, per day)
RIP_j (j=3)	60 ($ / per unit, per day)
ERC_j (j=3)	500($ / per unit, per day)
RL_j (j=1)	10 in case 1 and 2; 7 in case 3; 8 to 10 in case 4a to 4c respectively
RL_j (j=2)	10
RL_j (j=3)	10

4.1 Case Description

After setting the above parameters, several case studies are performed to clarify the influence on project schedule by engaging different model parameters. The same objective function in each case is shown below:

Table 3 present the optimization results, and visualization comparisons on project duration and total cost are shown as Fig. 3 and Fig. 4. Furthermore, Fig. 5 illustrates the resource idle costs for case 2 to case 4.

1) Case 1: Base Total Cost

Minimize total cost of example project, and refer the results as a comparison of resource idleness in case 2. Based on example project, case 1 implements resource usage cost as activity direct cost for minimizing project total cost. Additionally, project total cost also includes indirect cost and bonus / penalty (contract duration is 80 days). This case is used as a comparison basis for the subsequent cases. Thus, the influence of parameters such as resource idle costs and external resource usage in the following cases for resource-constrained project scheduling problems can be observed and analyzed.

2) Case 2: Add Resource Idle Cost

Consider resource idle costs, and observe cost and resource schemes after optimization process. Resource idle costs are added to the model in Case 2, and the results relating to cost and resource schemes are observed. Naturally, direct cost increases with the involvement of resource idle costs; however, considering this parameter can increase overall resource utilization and possibly shorten project duration.

From Tables 5 and 6, applying resource idle cost to the proposed model in case 2 results in varied project duration, total cost ,and resource scheme compared with the solution in case 1. Planners can enhance resource utilization by considering resource idle costs owing to the goal of minimizing total cost, but have to pay more direct cost than when no such concept is involved.

Examining the solution in case 2, project duration is shortened by one day (from 63 days to 62 days; Referring to Fig. 3), and the total cost is increased (form $562,640 to $625,520; Referring to Fig. 4) compared with case 1. However, shorter project duration is not guaranteed for all projects because of different project circumstances.

Case 2 involves using resource idle cost to minimize project total cost, and relationship between project duration and resource idle costs are explained as follows: the quantity and cost of internal resources are arranged depending on fixed project work once the contract is awarded, and thus longer project duration is avoided to reduce the total resource idle costs.

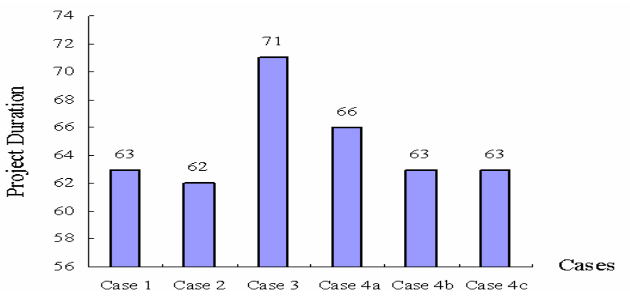

Fig. 3 Project Duration for Each Case

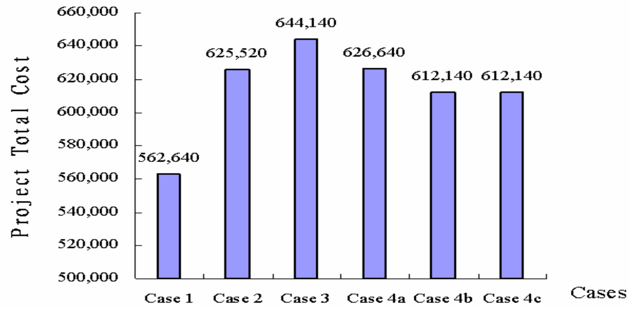

Fig. 4 Project Total Cost for Each Case

Table 3 Cost and Resource Information after Calculation

Case	Cost information ($)				Project Duration	Resource information							Case information
	Direct cost	Indirect cost	Bonus	Total cost		Internal resource type I	External resource type I	Internal resource type II	External resource type II	Internal resource type III	External resource type III	Resource idle cost	
Case 1	438,000	126,000	1,360	562,640	63	375	0	363	0	351	0	---	Base case
Case 2 (100,80,60)	502,960	124,000	1,440	625,520	62	374	0	358	0	375	0	60,260	Consider resource idle cost
Case 3	502,860	142,000	720	644,140	71	384	0	357	0	358	0	60,660	Limit of resource type I =7
Case 4a	495,760	132,000	1,120	626,640	66	359	15	358	0	375	0	51,560	One unit external resource type I available
Case 4b	487,500	126,000	1,360	612,140	63	351	24	363	0	351	0	47,100	Two unit external resource type I available
Case 4c	487,500	126,000	1,360	612,140	63	351	24	363	0	351	0	47,100	Three unit external resource type I available

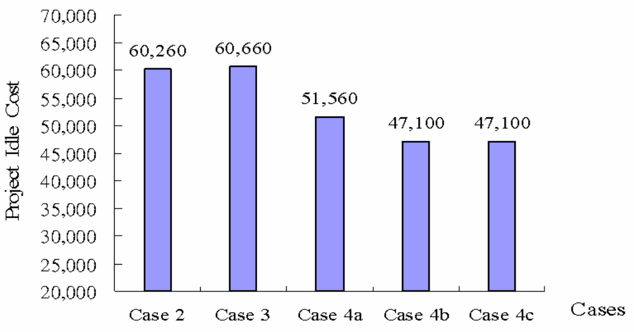

Fig. 5 Project Idle Cost from Case 2 to 4c

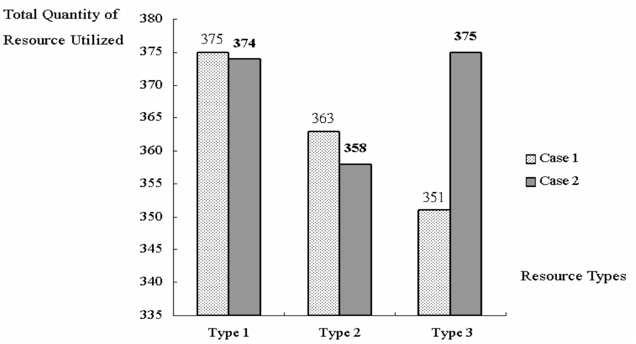

Fig. 6 Resource Usage Histogram for Case 1 and Case 2

Fig. 6 compares total usage of three types of internal resources in cases 1 and 2. For example, the amount of internal resource type III (375) utilized in case 2 is significantly higher than that (351) in case 1, and the amounts of internal resource type I and II are both decreased slightly in case 2 for achieving the goal of minimizing project total cost while resource idle costs are involved. It implies that implementing resource idle cost into project cost increases overall resource utilization while minimizing total cost.

3) Case 3: Critical Resource

Lowers the limit of internal resource (type I) from ten to seven, and examine the influence of critical resource on project cost and duration. According to example project, the limit for each type of internal resource was originally set to ten. In this case, the limit of internal resource (type I) is lowered from ten to seven. Based on optimization experiments not further described here, the maximum requirement of resource type I per day, is nine. Moreover, through optimization experiments, resource type I is identified as a “critical resource”, which influences project performance, and resource type II and III are less important than type I, regarding of resource requirement. Consequently, case 3 reduces the limit of internal resource (type I) to seven, to observe the influence for project schedule plans and the utilization of internal resources.

Compared with case 2, Figs. 4 and 5 show that both the project duration and total cost are increased by lowering the limit of internal resource in case 3. Referring to Fig. 5, one interesting observation is that resource idle cost of case 3 is also higher than that in case 2. Thus, setting reasonable limits for resources is crucial for project performance and should be the subject of an in-depth discussion, which will be discussed later in case 4.

4) Case 4a to 4c: Influence of Critical Resources

Set different quantity of external resource (type I), and inspect the behavior related to project performance. the purpose of this case is to investigate the influence of critical resources on project schedule. Referring to case 3, critical resource type I is identified as a critical resource for example project. Therefore, this case designs a series of experiments by adding external resource (type I) one at a time until reaching three, and then inspects the influence on the project schedule through experiments.

In this case, external resources are considered, and the unit cost of external resources is set higher than that of internal resources owing to temporary outsourcing behavior in the construction industry. Thus, for the purpose of project cost minimization, the utilization of external resources is avoided if internal resources are available.

However, in the event of internal resources being insufficient, the application of external resources will be considered, depending on the corresponding influence on the variation of project duration and total cost. Supposing the expense of external resources is less than the increment of total cost owing to project duration extension, assuming no external resources involved, then it is worthwhile to acquire those external resources to achieve the objective of simultaneously shortening project duration and reducing total project cost.

For example, one external resource of type I is added to the project in case 4a, and the result is compared with case 3. As shown in Fig. 3 and Fig. 4, the project duration decreases by five days, or around 7.04% (from 71 days to 66 days), and the total cost decreases by $17,500, or approximately 2.79% (from $644,140 to $626,640). Furthermore, the project idle costs observed in Fig. 5 is reduced by $9,100, or approximately 15% (from $60,660 to $51,560) Eventually, the results demonstrated the importance of external resources for project performance.

Fig. 7 shows the utilization of external resource in case 4a. In this case, the limit of internal resource type I is seven, and one external resource is added for model examination. Base on the result, the one external resource is employed for activity D, executed form day 6 to day 20, and so that the project duration is shorten to 66 days. Meanwhile, Fig. 8 illustrates external resource usage in case 4b. Activity B (day 6 to day 14) and activity D (day 6 to day 20) use one external resource, respectively, to decrease the project duration to 63 days since two external resource of type I are involved in case 4b. As a result, adding appropriate amount of critical resource can conduct positive influence for project objectives, especially daily indirect cost and resource idle cost are costly.

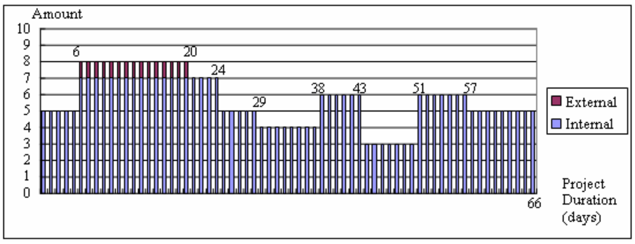

Fig. 7 Usage of Resource Type I in case 4a (One External Resource)

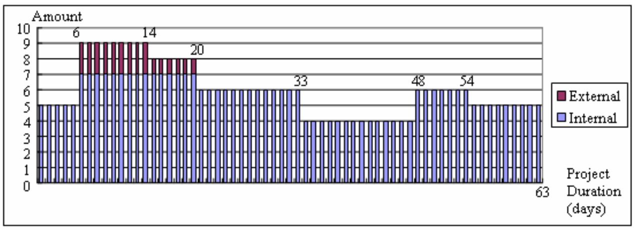

Fig. 8 Usage of Resource Type I in Case 4b (Two External Resources)

5.2 Relationship between Internal and External Resource Limits

Referring to research results, another critical issue for applying external resource is the limits of internal resources. Different limits of internal resources influence not only resource utilization for activities but also resource idle costs. Furthermore, such limits determine the behavior of external resources for total cost minimization. Higher limits of internal resources prevent planners from encountering unforeseen risks during the construction phase, and yield shorter project duration. However, an inappropriately high limit will cause unnecessary resource idleness, and increase resource idle costs.

Nevertheless, because of the higher unit costs of external resources, lesser total cost scheduled by the proposed model is not guaranteed. The benefit of external outsourcing is based on the flexibility aiming to resolve the insufficiency of internal resources, which lead to project duration extension.

Moreover, the idle costs for external resources is zero owing to the temporary outsourcing behavior, which is based on as-needed situation. Fig. 3 (case 4a to 4c) illustrates the relationship between project duration and the cases with different quantities of external resources, and Fig. 4 (case 4a to 4c) displays project total cost for different cases. As a result, both project duration and total cost of those cases can be reduced by acquiring more available external resources into the project. An exception to above statement is case 4c, where the limit of external resources is three, since two of external resources are sufficient to ensure minimal total costs.

Therefore, incurring unnecessary resource idle cost can be avoid since the external resources can be released upon completion of the corresponding activities. Restated, the outsourcing behavior of external resources not only refines the concept of limited resources, but also enhances project performance.

5. CONCLUSIONS AND SUGGESTIONS

This study presents a new optimization model for handling resource-constrained project scheduling problems in construction. According to research results, the proposed model is demonstrated to solve resource-constrained project scheduling problems efficiently and successfully.

The importance of external resources is revealed particularly in the situation where resources are insufficient while several activities are simultaneously being scheduled in resource-constrained environment. The concept of external resources considers outsourcing decisions to deal with the situations mentioned above during planning phase, and creates possibilities to refine resource and schedule plans. Based on the results of case study, by adopting the concept of external resource to the proposed model, the performance in terms of project cost and duration can be improved. Thus, the implementation of external resources provides planners with additional flexibility in arranging schedules, and provides planners with a diversity of resource supply.

This study employs the example from prior research to construct the model formulation, and only one project is involved. However, it is common that contractors are always involved in several projects simultaneously. Therefore, multi-project scheduling issues should be discussed in further studies to align the proposed model with complicated projects, and the applicability of external resource in multi-project environment should be further examined.

Furthermore, there should be in-depth discussion on issues of determining the limit of internal resource to minimize enterprise operational costs. That is, arranging appropriate limits for internal resources can help planers produce practical resource plans, and it should be an important topic for further investigation.

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APPENDIX

The following symbols are used in this paper:

TC: project total cost
DC: project direct cost
IC: project indirect cost
P: penalty
B: bonus
T: project duration, calculated during program runtime
d_i: duration of activity i
r: total number of resource types
n: total number of activities
m: last activity in project network
E: set of activities which require external resources during program runtime
IDC: daily indirect cost
CD: contract duration
PPD: penalty per day if project duration is longer than contract duration
BPD: bonus per day if project duration is shorter than contract date
S_i: start time of activity i
A: set of pairs of activities with precedence relationships
D_i: set of possible durations of activity i
S_k: set of in-progress activities on day k
$IRU_{i,j}$: amount of internal resource type j utilized for activity i
IRC_j: unit cost per day of internal resource type j
$ERU_{i,j}$: total amount of external resource type j utilized for activity i
ERC_j: unit cost of external resource type j
IRL_j: limit of internal resource type j per day
RIP_j: daily idle cost for internal resource type j per unit
RL_j: daily limit of resource type j per day, including internal and external resource
ERL_j: limit of external resource type j per day
$RUd_{i,j}$: daily resource usage of resource type j for activity i at duration d_i