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Resource-based Optimization Model for Dynamic Project Planning and Cost Management

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Abstract: A global trend in adopting projects as production functions is prevalent in many industries. Project management professionals have become an important domain and many operational research models were developed for supporting project planning work such as project scheduling and budgeting. In practices, however, frequent work disruptions in the course of project execution can significantly induce waste in resources and relevant costs. The situation becomes one of the most difficult for production economics and few models have been specifically developed to support project cost management under disrupted work conditions. To encompass green and commercial objectives, this research proposes a genetic algorithm model to optimize resource allocation and project schedule for the lowest cost during the project execution stage. Furthermore, the proposed model enables the dynamic impact analysis of work delays on project cost and completion time, which can contribute significant cost savings. A case study demonstrates the applicability of the proposed model, which enables project managers to handle work disruptions by developing an after-impact schedule with optimal resource reallocation in a timely manner. With the support of the proposed model, resource waste can be reduced and in the demonstrative case there was a realistic extra savings for total project cost.

Keywords: Project Management, Evolutionary Computations, Decision Support, Resource Allocation, Budgeting

1 Introduction

There is a global trend in initiating various projects for important business operations and many project-based organizations are prevalent in the modern marketplace [1]. Except for the private sector, in many cases, even public fund-raising projects have been regarded as an important production function for firms and industrial developments [2,3]. Numerous projects can be observed in various industries such as construction, manufacturing and processing, information technology, computers and electronics, communications, energy and transport infrastructures, aerospace, defense, healthcare, services, financial and leisure [3,4,5]. Thus, project management has become a professional domain receiving growing attention in the past decades and many useful models were developed to support project planning work, such as project scheduling and budgeting. In addition, many operational research (OR) techniques have been adopted to support project management tasks [6]. The resource-constrained project scheduling problem (RCPSP) has been proposed as a standard OR applications in project management [7]. However, the RCPSP focuses on minimizing the completion time of the project with resources constraints while the considerations of project cost as well as the production economics are not sufficiently addressed.

The economic theory of production concerns the optimal utilization of inputs so that the output can be maximized and the maximum profit can be obtained. A production process is considered efficient if the resulting quantity of output reaches the highest level. Since a project generally comprises a fixed budget and tasks to be done, an efficient production process is considered as the optimal resource allocation and the minimum production cost. The optimal resource allocation increases a firm?s profit potential from a business perspective, reduces waste and provides a response to energy conservation objectives. Relative to the aforementioned concept of production economics, the resource availability cost problem (RACP) has been proposed for minimizing the cost of the resources required to complete the project on time [8,9]. Although many models for RACP are more focused on cost aspects, applicable models solving the

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limitations and needs of project cost management in practice are still in urgent demand.

Construction projects have been regarded as one of the most complex types of projects and they are representative for studies of production economics. In practice, construction projects are typically undertaken in dynamic business environments and are executed under invariably uncertain work conditions. Disruptions and delays are encountered on most construction projects and are the most common cause of construction claims [10]. If the work disruptions and changes occur along the critical path, contractors can easily claim for the time delay and a monetary adjustment for the damage. On the contrary, if disruptions and changes are not on the critical path and will not cause a project delay, it would be difficult for contractors to claim for a price adjustment due to the lack of a baseline for identifying the damages.

The critical path method (CPM) and program evaluation and review technique (PERT) have proven as effective network scheduling techniques under flexible project time and resources conditions [11]. Although the CPM and PERT can introduce the early start S-curve and the late start S-curve, the conventional methods are limited to be considered as a baseline for implementation or claim. Among previous studies, less single method has been established and broadly recognized as capable of identifying an optimal schedule.

Heuristic optimization methods for solving the resource allocation problem can be traced back to the 1960s [12]. Numerous studies and applications have been made regarding the construction resource allocation, resource leveling, and time-cost trade-off by various techniques such as linear and dynamic programming, expert systems, neural networks, and genetic algorithms [13,14,15,16,17,18,19,20,21,23]. However, the costs for resource substitution, resource mobilization/demobilization, and idle cost have drawn little attention from previous studies.

The objective of this research is to propose a resource-based optimization model for dynamic project planning and cost management. The model can optimize the allocation of resources along with the project schedule and analyze the extra costs for resource reallocation caused by the disruptions. The proposed model is capable of assisting project managers to minimize waste in resources and to reduce project costs.

2 The Proposed Model

2.1 Genetic Algorithms

By mimicking the principles of natural selection, genetic algorithms (GA) consisting reproduction, crossover, and mutation operations have emerged as a promising optimization tool in construction management applications [24,25]. GA is especially the more effective techniques for determining optimal solutions when the combinations of feasible solutions are rather large. In conventional practices, a construction project consists of numerous activities and each activity comprises several tasks. Particular resources are required for the execution of each task. If a project contains $1\dots i$ activities, each activity requires $1\dots j$ task, and each task can be supported by $1\dots n$ types of resources, the possible combinations for resource allocation alternatives (n^{j*i}) would be enormous.

2.2 The Chromosome

The proposed chromosome is based on the project activities planned in the network schedule. As shown in Fig. 1, each activity is designed to have an individual chromosome that consists of task and optimal schedule sections. In the task section, the gene value r_{ij} represents the quantity of each type of resource and the cell value is presented between 0 and 1. The second section of the chromosome is the optimal schedule for the activity. The "tf" is used to determine the optimal schedule, which is expressed as Eqn. (1):

$$tf = \frac{\text{optimal start time} - \text{the earliest start time}}{\text{total float}} \tag{1}$$

2.3 Resource Substitution and Loss of Productivity

There are many substitutable resources in a construction project and an appropriate arrangement of resource substitution could improve the efficiency of total resource utilization and reduce the cost induced by mobilization and demobilization.

Assume that R_j is the most efficient and economical resource for task i when i = j, although it also can be performed by other types of resources with a certain loss of productivity. The initial gene value r_{ij} is 1 when i = j, and r_{ij} is 0 when $i \neq j$. If some resources are idle, substitution between resources may help to minimize the idle cost. The gene value represents the quantity of each type of resource for the activity. For example, if a task can be supported by three types of resources and the ideal resource is R1, R2 and/or R3 may be used to replace certain amount of R1 for the overall resource cost reduction. The amount of resource R_j required to complete the task can be represented by Eqn. (2):

$$R_j = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}} \times R_{i0} \times \frac{1}{PL_{ij}} \tag{2}$$

Task1			Task2			...	Task$_i$			Optimal Schedule
r11	r12	...	r21	r22	...	...	r$_i$1	r$_i$2	...	tf

Fig. 1. The proposed chromosome

where R_i represents the ideal resource for task i and R_{i0} represents the required quantity of R_i for task i. PL_{ij} represents the discounted rate of productivity while resource R_j is used to replace R_i. The value of PL_{ij} is presented between 0 and 1 and PL_{ij} equals 1 while i = j.

2.4 Demobilization and Idle Cost

In this study, idle resources will be used to replace substitutable resources if the mobilization/demobilization costs are higher than the cost of productivity loss. However, if there is an idle resource not appropriate for substitution, the cost of demobilization/mobilization and the idle cost should be compared to decide the need of demobilizing the idle resource. If the idle cost is greater than the cost of demobilization/mobilization, the idle resource should be demobilized.

2.5 Objective Function

Since the GA optimization process is a heuristic searching process for better solutions, an objective function will help to eliminate inferior chromosomes through competition until the optimization process cannot evolve a better solution and converge to a stable condition. The objective function is as Eqn. (3):

$$Min\left\{\frac{TC_o}{TC_e}\right\} \tag{3}$$

where TC_e is the project total cost based on the early start schedule and TC_o is the total cost after GA optimization.

3 Applications and Numerical Analysis

3.1 The Example Project

In this section, a 20 activities example project is adopted for the applications of the proposed resource-based optimization model. The time constraint and the resources required for each activity are shown in Table 1.

For the example project, each activity consists of four tasks, and four different types of resources, R1, R2, R3, R4, are required for supporting the tasks, while R1, R2, R3 are considered substitutable resources with certain productivity loss and the discounted productivity rate. In other words, R1, R2, and R3 can apply to all the tasks of all activities, while R4 is a non-substitutable resource for task 4. Based on the general chromosome model as described in Fig. 1, each activity requires 11 genes to form the chromosome as shown below in Fig. 2. Since task 4 can only be supported by R4, the value of r44 equals 1.

Although some of the resources are substitutable, there are different costs for different resources. Assume that the unit cost of R1 accounts for the most efficient expense. The unit cost of R2, R3, and R4 accounts for 120%, 130%, and 125% of R1's unit cost respectively. In addition, the mobilization cost equals the demobilization costs and is 150% of the resource's unit cost. Whenever the demobilization and mobilization costs are higher than the cost of productivity loss arising from the resource substitution, resource substitution occurs. The CPM helps to identify the activities on critical path and the total floats of each non-critical path activities. The GA optimization process starts from the early start schedule and then shifts the non-critical activities within the time span of the total float by allowing the gene values to change randomly. Since the objective function helps to minimize cost, the values of the chromosomes are calculated and the best fitness solutions can be determined.

Task 1			Task 2			Task 3			Task 4	OS
r11	r12	r13	r21	r22	r23	r31	r32	r33	r44	tf

Fig. 2. The chromosome in the case study

3.2 The Optimal Schedule

Based on the proposed model, the optimal schedule can be established after the GA optimization process. Since the optimal schedule incorporates the concept of resource substitution and the relevant costs of resource mobilization/demobilization, we found that the total cost can be reduced based on the optimal schedule (4.37% less than the cost of the early start schedule and 4.25% less than late start schedule). In addition, Table 2 compares the variation of resource utilization in the early schedule and the optimal schedule.

The up and down of resource utilization indicates the mobilization and demobilization of resources, while it occurs three times in the optimal schedule and six times in the early start schedule. The results suggest that the optimal schedule can improves the allocation of resources and relevant costs by reducing the times of mobilization and demobilization. In addition, the smoother resource utilization plan is more feasible to be implemented for the real world projects.

3.3 Dynamic Planning and Cost Analysis

Under uncertain work conditions and a project environment, the ability to plan dynamically and execute a cost analysis during the project execution stage is a

Table 1: Project data

Project activity	Dura -tion (days)	Succe -ssors	Total float (days)	Required resource quantity for the activity			
				R1	R2	R3	R4
A_1	6	A_3	0	60	30	18	72
A_2	2	A_5	9	26	42	18	18
A_3	4	A_6	0	32	64	64	48
A_4	6	A_7	23	180	144	108	72
A_5	8	A_8	9	128	240	96	120
A_6	10	A_{10}	0	120	60	90	110
A_7	3	A_{12}	23	15	6	18	36
A_8	2	A_9	9	20	20	16	14
A_9	2	A_{11}	9	12	8	16	24
A_{10}	7	A_{16}	0	105	210	147	84
A_{11}	1	A_{13}	9	10	10	15	13
A_{12}	2	A_{14}	23	24	16	16	24
A_{13}	5	A_{15}	9	35	35	35	55
A_{14}	2	A_{18}	23	14	16	16	24
A_{15}	3	A_{17}	9	45	45	36	36
A_{16}	5	A_{19}	0	75	50	75	35
A_{17}	6	A_{20}	9	180	240	252	66
A_{18}	2	A_{20}	23	20	12	12	20
A_{19}	6	A_{20}	0	72	144	216	66
A_{20}	2		0	4	24	8	20
Total resource required				1,177	1,416	1,272	957

critical success factor. Various delay analysis techniques such as the "what-if" method, the "but-for" method, and the contemporaneous period analysis (CPA) method are widely used to analyze the effects of work disruption and each has its own theoretical support.

This study adopts the "what-if" method and uses the optimal schedule before the impact as the baseline schedule. Subsequently, by adding the delay caused by the disruption of work into the schedule and then re-scheduling the uncompleted activities through the optimization of project resources, an after-impact schedule is developed. The impact on project duration and cost can be determined by comparing the before and after-impact schedule.

Assume that a disruption of work causes the delay of the start day of activity A_4 to day 16. The optimization results show that the total cost of this delay is 1.8% more than the cost of original optimal schedule. In addition, activity A_4 has 10 days float in the optimal schedule and thus, any delay within the time span will not cause changes in project cost. However, once the delay lasts beyond day 10, the original optimal schedule becomes infeasible and an after-impact optimal schedule has to be developed as a new execution plan for the project.

Table 2: Analysis of resource utilization

Dura -tion	Variation of resource utilization in the early schedule ◎: Turning point		Variation of resource utilization in the optimal schedule ◎: Turning point	
1	41.2%		-35.0%	
2	41.2%		-35.0%	
3	48.4%		-18.9%	
4	48.4%		-18.9%	
5	48.4%		-18.9%	
6	48.4%	◎	-18.9%	
7	18.5%		4.3%	
8	18.5%		4.3%	
9	18.5%		4.3%	
10	24.7%	◎	4.3%	
11	-16.5%		28.4%	
12	-17.5%		28.4%	
13	-35.1%		28.4%	
14	-35.1%		28.4%	
15	-54.7%		42.9%	◎
16	-54.7%		27.6%	
17	-54.7%		-19.7%	
18	-54.7%		-19.7%	
19	-54.7%	◎	-19.7%	
20	6.2%		58.9%	◎
21	6.2%		-3.7%	
22	6.2%		-3.7%	
23	85.5%		-3.7%	
24	85.5%		11.6%	
25	85.5%		11.6%	
26	85.5%	◎	11.6%	
27	60.8%		42.1%	
28	60.8%		42.1%	
29	-58.8%		42.1%	
30	-58.8%		42.1%	
31	-58.8%	◎	42.1%	◎
32	-20.6%		-4.5%	
33	-20.6%		-4.5%	
34	-20.6%		-35.0%	
35	-20.6%		-35.0%	
36	-20.6%		-35.0%	
37	-20.6%	◎	-35.0%	
38	-80.4%		-70.3%	
39	-80.4%		-70.3%	
Sum -mary	Average Variation: 43.0%	6 times up and down	Average Variation: 25.9%	3 times up and down

Table 3: Variance between optimal and after-impact schedule

Activity	Optimal Schedule		After-impact Schedule		Time Variance
	Start	Finish	Start	Finish	
A_1	1	6	1	6	0
A_2	1	2	1	2	0
A_3	7	10	7	10	0
A_4	11	16	21	26	10
A_5	3	10	3	10	0
A_6	11	20	11	20	0
A_7	17	19	28	30	11
A_8	11	12	11	12	0
A_9	13	14	13	14	0
A_{10}	21	27	21	27	0
A_{11}	15	15	15	15	0
A_{12}	20	21	33	34	13
A_{13}	16	20	16	20	0
A_{14}	22	23	35	36	13
A_{15}	24	26	24	26	0
A_{16}	28	32	28	32	0
A_{17}	27	32	27	32	0
A_{18}	33	34	37	38	4
A_{19}	33	38	33	38	0
A_{20}	39	40	39	40	0

As shown in Table 3, if the original optimal start date is interrupted, the after-impact optimal start date for activity A_4 is day 21 instead of day 11. The updated after-impact optimal schedule with its revised start and finish dates for each activity can be conveniently identified through the optimization process. Furthermore, if the total float of activity A_4 is completely consumed, the project cost increased after the GA optimization procedure is 3.99% as shown in Table 4. In this case, even the cost of the after-impact optimal schedule is still lower than the cost for both the early and late start in day 40. The results of analysis suggest the importance and effectiveness of establishing a resource-based optimal schedule for project execution. Once the activity is interrupted to disrupt the optimal schedule, the project cost will increase, and the amount of cost increase is highly associated with float loss as well as the loss of flexibility for resources utilization.

Table 4: Float loss of activity A_4 and project cost

Float loss (FL) (Total float = 23)	Optimal start date	Increased cost compared with the optimal schedule
FL = 0	11	0%
$11 \leq FL \leq 20$	21	1.81%
$21 \leq FL \leq 22$	22	3.67%
FL = 23	23	3.99%

4 Conclusions

Efficient resource allocation and project management can effectively reduce waste and project costs. Green and business objectives can be simultaneously considered by the same effort. Thus, a sound project schedule and optimal resource allocation can facilitate successful completion and increase the profit potential of a project. This research successfully proposes a resource-based optimization model, which can be used to identify an optimal schedule with the optimal quantities for each resource and the specific timing required to perform each activity to obtain the lowest overall project cost. The research results show that whenever there is a work disruption during the project execution stage, an after-impact optimal schedule can be built timely and the extra cost caused by the disruption of works can be conveniently identified. For practical implications, the study demonstrates that project cost is highly associated with the float loss. Thus, if the project resource allocator has less and less room to modify the resource utilization plan, the project costs increase drastically. While work disruptions and project changes become parts of project management tasks, the proposed model would help project managers to handle the challenges of dynamic planning and cost management. By building an optimal schedule with the proposed model, project managers are able to be aware of the potential consequences of every incident during the project execution stage. Timely solutions to the encountered problems then can be engineered systematically.

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