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# GA Optimization Model for Time/cost Trade-off Problem in Repetitive Projects Considering Resource Continuity

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**Abstract:** Discrete time/cost trade-off problem (DTCTP) is very common in project scheduling. In repetitive projects, some activities are required to maintain resource continuity. This paper proposes an optimization model based on the genetic algorithm for DTCTP in repetitive projects considering different requirements for resource continuity of activities. First, two kinds of resource continuity are defined, namely, the constraint of work continuity and resource consistency. Impact of resource continuity on the time and cost is analyzed. Then the model including its five modules is described in detail. The model can provide a set of Pareto near optimal solutions representing the time/cost trade-off in repetitive projects. It can also deal with all kinds of situations where the resource continuity of activities is differently required. A project from the pertinent literature has demonstrated its capabilities.

**Keywords:** genetic algorithm, time/cost trade-off, repetitive project, resource continuity, work continuity, resource consistency

## 1. Introduction

Repetitive construction projects are commonly found in highways, housing project, high-rise buildings, tunnels and pipeline networks. They are characterized by repeating activities performed from unit to unit [1]. The traditional network scheduling methods are criticized in the literature for their inabilities while modeling the repetitive projects, and a series of methods have been proposed for repetitive projects [4], such as the "Repetitive Scheduling Method (RSM)", "Line of Balance", and "Linear Scheduling Methods". In this paper, the term of RSM is adopted. Disadvantages of using network model for repetitive projects include the followings: 1) The network models are unable to provide resource continuity; 2) The network model cannot display the progress in the space as RSM does [2, 3]. In repetitive projects, there is always a possibility that two set of equipments and crews will conflict in the same space and disturb each other. If this occurs, the projects will be delayed. Furthermore, the RSM provides a location for the work crew to move to. 3) The network is difficult to update. Usually, a RSM with many units corresponds to a largescale network. It is much more difficult to update. Different from network models that use only one variable, RSM uses two variables - time and distance, and thus RSM is more representative and accurate for repetitive projects. It is very convenient for project managers to use RSM while scheduling and controlling the repetitive projects.

The discrete time/cost trade-off problems (DTCTP) are of great importance in project scheduling. It assumes a single nonrenewable resource, which is usually the cost. The duration of an activity is assumed to be a discrete, non-increasing function of the cost. An activity assumes different execution modes according to the possible resource allocations. Three possible objective functions have been studied for DTCTP. For the first objective function, referred to as the deadline problem, there is a limit on the project duration and we try to minimize the cost. For the second objective function, referred to as the budget problem, a limit is specified on the total availability of the cost and one tries to minimize the duration of the project. For the third objective function, referred to as the time/cost curve problem, the complete time/cost trade-off function for the total project is to be computed, that is, all the efficient points $(T,C)$ such that with a cost limit $C$ a project duration $T$ can be obtained and such that no other point

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$(T',C')$ exists for which both $T'$ and $C'$ are smaller than or equal to $T$ and $C$. Many algorithms have been developed for DTCTP in these decades. Exact algorithms include the branch and bound algorithms [5], dynamic programming algorithms, and enumeration algorithms. But as DTCTP is strongly NP-hard for general networks, many heuristic algorithms have been designed [6,7].

But all the former mentioned algorithms are for DTCTP in network models, and they cannot be used for the repetitive projects without the ability to maintain the resource continuity. Hyari et al [8]. developed a bi-objective optimization model based on the genetic algorithm which can provide a set of Pareto near optimal solutions that represent the time/cost trade-off in repetitive construction projects. All the repetitive activities in the model were assumed to have no requirement for resource continuity, i.e., the model did not take resource continuity into consideration. Long and Ohsato [9] presented a method for time/cost tradeoff considering the constraint of work continuity. In their methods, some activities allowed interruptions, and some did not. For each activity, the same production rate was assumed throughout all units.

In this paper, an optimization model based on the genetic algorithm for DTCTP in repetitive projects considering resource continuity is proposed. The trade-off can be made according to the practical requirements for resource continuity of each activity. The rest of the paper is organized as follows. In section 2, the constraint of resource continuity and its impact on the time and cost are analyzed. Two kinds of constraint are defined, namely, the work continuity constraint and the resource consistency constraint. In section 3, the model is presented, with four modules included. For validation of the proposed model, a concrete bridge project in pertinent literature is analyzed in section 4. In section 5, the conclusion is made.

## 2. Resource Continuity and the impact on time/cost

Resource continuity means uninterrupted and unchanged usage of resources for the same activity from one unit to another. In this paper, we define the uninterrupted usage of resources as the work continuity constraint as the pertinent literature has done, and the unchanged usage of resources as the resource consistency constraint. Both the work continuity constraint and resource consistency constraint have impact on the duration and cost of a repetitive project.

### 2.1. Work continuity constraint

Work continuity constraints have been defined by El-Rayes and Moselhi [12] in which repetitive units must be scheduled in such a way as to enable timely movement of crews from one unit to the next, avoiding crew idle time. The importance of this feature has also been emphasized by De Boer for spatial resources, Gong for time dependent cost and Goto et al. for time dependent cost resources.

Work continuity brings many benefits to the project managers. Not only does it result in the maximization of the benefits from the learning curve effect for each crew, but also the minimization of the off-on movement of crews on a repetitive project [13,14]. Moreover, work interruption leads to an increased direct cost because of the idle crew time. However, violation of the work continuity constraint by allowing work interruption may result in a reduction in the overall project duration. Consequently, it leads to a reduction of the corresponding indirect costs, and a possible increase (reduction) in rewards (punishment) for shorter duration. Therefore, a careful tradeoff should be made between these two extremes.

### 2.2. Resource consistency constraint

The resource consistency constraint means only one execution mode is chosen for each repetitive activity, and it is not allowed to change the amount and combination of resources once the activity has begun. The advantages of ensure the resource consistency constraint are as follows. First, it maximizes the benefits of learning effect as the work continuity constraint does. [10,11] Second, it leads to the minimization of extra hiring and firing which may bring much more difficulties to the managers.

However, violation of the resource consistency constraint may lead to a reduction in the project duration. When there is a backward controlling segment, its succeeding controlling activity can start earlier by changing production rates without violating the precedence constraint. Consequently, the project duration is shortened [15,17], which leads to a reduction of the costs, and a possible increase (reduction) in rewards (punishment) for shorter duration. If the labor and equipments are easily available, a tradeoff is worth trying between these two extremes.

## 3. The optimization model

The optimization model for DTCTP in repetitive projects incorporates five modules: (1) input module; (2) scheduling module; (3) total cost module; (4) time/cost trade-off module based on genetic algorithm; and (5) output module. The model is shown in Fig.1. The particular describes of these modules are as follows.

### 3.1. Input module

All the required data can be divided into two parts: project basic information and activities basic information. Project basic information includes (1) number of activities and repetitive units; (2) quantities of work of each activity in all units; (3) types of precedence relations in between activities; and (4) the project indirect cost rate. Activities basic

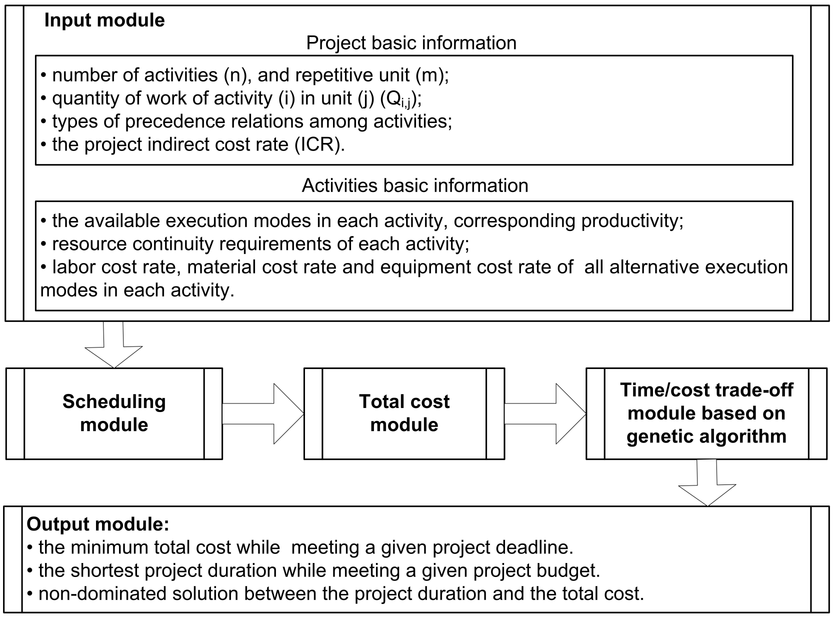


**Figure 1** Optimization model.

information includes (1) alternative execution modes and corresponding productivities, cost rates of each activity; and (2) resource continuity requirements of each activity.

Let $w_i$ be a 0-1 variable which is 1 if activity $(i)$ must meet the work continuity constraint and 0 otherwise, and $m_{i,j}$ be an integer variable which is $k$ when activity $(i)$ in unit $(j)$ is performed by execution mode $k(k = 1,,K_i)$. Decision variables will be determined by resource continuity requirements of each activity, and the specific processes are shown in Fig.2.

```
Decision_variable= ϕ
FOR i=1 to n THEN
  IF activity (i) have the requirement of work continuity THEN
    Decision_variable= Decision_variable
  ELSE
    Decision_variable= Decision_variable ∪ w_i
  END
  IF activity (i) have the requirement of resource consistency
  THEN
    Decision_variable= Decision_variable ∪ m_{i,1}
  ELSE
    Decision_variable= Decision_variable ∪ (m_{i,1},...,m_{i,n})
  END
END
```

**Figure 2** Determination of decision variables.

## *3.2. Scheduling module*

For any given decision variables, the objective of this module is to generate a feasible schedule S that not only complies with precedence relations, work continuity constraint and resource consistency constraint, but also minimize the project duration and the total cost. The steps are as follows.

**Step1.** Calculate the duration of activity $(i)$ in unit $(j)$, $d_{i,j}$ , by

$$d_{i,j} = \frac{Q_{i,j}}{P_{i,j}}. \qquad (1)$$

Where $P_{i,j}$ denotes the productivity of activity $(i)$ in unit $(j)$, which is determined by the selected execution mode in this sub-activity.

**Step2.** Calculate the start time and the finish time of activity $(i)$ in unit $(j)$, which are denoted by $S_{i,j}$ and $F_{i,j}$ , respectively. The essential way of this step is to starting all activities as early as possible in all units. Taking the precedence relation of finish-to-start as an example, this step is implemented by the following algorithm.

IF $w_i = 1$ THEN

$$Delta = \max_{j=1,\ldots,m}\left(0, F_{i-1,j} + l_{i-1,i} - \sum_{k=1}^{j-1} d_{i,k}\right)$$

$$S_{i,j} = \sum_{k=1}^{j-1} d_{i,k} + Delta,\ F_{i,j} = \sum_{k=1}^{j} d_{i,k} + Delta$$

ELSE

$S_{i,1} = F_{i-1,1}, F_{i,1} = S_{i,1} + d_{i,1}$

FOR $j = 2$ TO $m$ THEN

$S_{i,j} = \max\left(F_{i-1,j}, F_{i,j-1}\right),\ F_{i,j} = S_{i,j} + d_{i,j}$

END

END

Where $l_{i-1,i}$ denotes the lag-time between activity $(i)$ and activity $(i-1)$. Repeats the above procedure from activity (1) to activity $(n)$ order, and then the project duration, denoted by $TD$, can be determined by the finish time of the last activity in the last unit.

**Step3.** Minimize the total interruption duration in each activity. The essential way of this step is to fix the start time of activity $(i)$ in unit $(m)$, and then start the remaining sub-activities as late as possible (from unit $(m-1)$ to unit (1)). Similarly, taking the precedence relation of finish-to-start as an example, this step is implemented by the following algorithm.

IF $w_i = 0$ THEN
 FOR $j = m-1$ TO 1 THEN
  $F_{i,j} = \min\left(S_{i+1,j} - l_{i-1,i}, S_{i,j+1}\right)$
  $S_{i,j} = F_{i,j} - d_{i,j}$
 END
END

### 3.3. Total cost module

For any given feasible schedule $S$, this module aims to calculate the financial expenses, which include the labor cost, material cost, equipment cost, indirect cost and cost for idle resources. The detailed processes are shown as the following steps.

**Step1.** Calculate the labor cost of activity $(i)$ in unit $(j)$, denoted as $LC_{i,j}$, by

$$LC_{i,j} = d_{i,j} \times LCR_{i,j,k}. \quad (2)$$

Where $LCR_{i,j,k}$ denotes the labor cost rate of the execution mode $k$ of activity $(i)$ in unit $(j)$.

**Step2.** Calculate the material cost of activity $(i)$ in unit $(j)$, $MC_{i,j}$, by

$$MC_{i,j} = Q_{i,j} \times MCR_i. \quad (3)$$

Where $MCR_i$ denotes the material cost rate of activity $(i)$.

**Step3.** Calculate the equipment cost of activity $(i)$ in unit $(j)$, denoted by $E_{i,j}$, as follows:

$$EC_{i,j} = d_{i,j} \times ECR_{i,j,k}. \quad (4)$$

Where $ECR_{i,j,k}$ denotes the equipment cost rates of the execution mode $k$ of activity $(i)$ in unit $(j)$.

**Step4.** Calculate the indirect cost, denoted by $IC$, as follows:

$$EC = TD \times ICR. \quad (5)$$

Where $ICR$ denotes the indirect cost rate.

**Step5.** Calculate the cost of idle resources of all activities, denoted by $IRC$. It can be described as follows:

$$IRC = \sum_{i=2}^{n}\sum_{j=2}^{m}\left(S_{i,j} - F_{i,j-1}\right) \times LC_{i,j,k}. \quad (6)$$

**Step6.** Calculate the project direct cost, denoted by $DC$, as follows:

$$DC = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(MC_{i,j} + LC_{i,j} + EC_{i,j}\right) + IRC. \quad (7)$$

**Step7.** Calculate the project total cost, denoted by $TC$, as follows:

$$TC = DC + IC. \quad (8)$$

### 3.4. time/cost trade-off module based on genetic algorithm

This module is designed to have the ability to obtain the optimal scheduling for different sub-problems of DTCTP in repetitive projects. This module is implemented by the following procedure which is shown in Fig.3.

**Step1.** Initialize population. According to the determination of decision variables in Fig.1, this paper employ decimal coding to generate the initial population $POP$, whose size is denoted by $N_p$.

**Step2.** Evaluate the fitness value of each individual. For different sub-problems of DTCTP in repetitive projects, the evaluating strategies for corresponding fitness values are introduced as follows.

**Sub-problem[1]:** The deadline problem is to minimize the total cost of the project while meeting a given project deadline.

In this sub-problem, the fitness value of the individual $i$ , denoted by $fit_i$, is evaluated according to the difference between the project duration corresponding to it and the given project deadline, shown as follows:

$$fit_i = \begin{cases} \frac{1}{TC^i} & TD^\Delta - TD^i \geq 0 \\ \frac{1}{TC^i \times \alpha \times \left(1 + TD^\Delta - TD^i\right)} & TD^\Delta - TD^i < 0 \end{cases} \quad (9)$$

Where $TD^i$ and $TC^i$ denote the project duration and the project total cost corresponding to the individual $i$, respectively, and $TD^\Delta$ represents the given project deadline, and $\alpha$ is a constant which is employed to adjust the fitness value of individual $i$.

**Sub-problem[2]:** The budget problem is to minimize the project duration without exceeding a given project budget.

In this sub-problem, the fitness value of the individual $i$ is evaluated according to the difference between the project total cost corresponding to it and the given project budget, shown as follows:

$$fit_i = \begin{cases} \frac{1}{TD^i} & TC^\Delta - TC^i \geq 0 \\ \frac{1}{TD^i \times \beta \times \left(TC^\Delta - TC^i\right)} & TC^\Delta - TC^i < 0 \end{cases} \quad (10)$$

Where $TC^\Delta$ denotes the given project budget, and $\beta$ is also a constant employed to adjust the fitness value of the individual $i$.

**Sub-problem[3]:** The time-cost curve problem is to construct the complete and efficient time/cost non-dominated

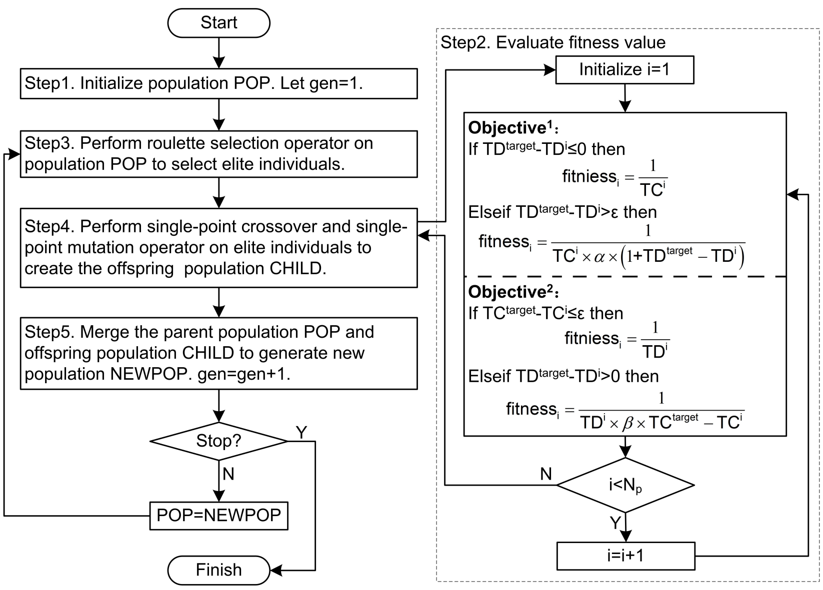


**Figure 3** Time/cost trade-off module based on genetic algorithm.

solutions over the set of feasible project durations. These complete non-dominated solutions can be found by means of a horizon-varying approach, which involves the iterative solution of the deadline problem over the feasible project durations.

**Step3.** Perform roulette selection operator on population *POP* in order to decide which elite individuals are selected for mating the next generation.

**Step4.** Perform single-point crossover and single-point mutation operator on elite individuals to create offspring population *CHILD*.

**Step5.** Merge the parent population *POP* and offspring population *CHILD* to generate new population *NEWPOP* according to fitness values.

Repeating the above-mentioned steps until the termination criterion is met, and the optimal scheduling is obtained.

## 4. An illustrative example

For validation of the proposed method, a concrete bridge project example which was first introduced in Selinger (1980) is analyzed. This project consists of five activities: excavation, foundation, columns, beams and slabs that repeat in four units. The precedence relations in between these five activities are finish to start with lag-time equal to zero. Information of the project is shown in Table 1. The project indirect cost rate is 2500 dollars per day.

We will discuss the non-dominated solutions in different cases where resource continuity of the activities is differently required.

**Case1.** All the activities are required to maintain the resource consistency, but not required to maintain the work continuity.

This is the case that Hyari and El-Rayes [8] have discussed. In the study by Hyari and El-Rayes [8], the decision variables are the interrupted days in each activity between adjacent units and the execution mode in each activity, and the number of decision variables is $n(m+1)$, where n and m denote the number of the activities and units respectively. In the current model, however, the number of decision variables is $2n$ according to Fig.2. The comparison of non-dominated solutions between these two methods is shown in Fig.4. When the project duration is large than 117 days, the non-dominated solutions between the project duration and the project direct cost obtained by the current study are as good as those by Hyari and El-Rayes [8]. However, when the project duration is less than 117 days, the non-dominated solutions by this paper are obviously better than those by Hyari and El-Rayes [8].

**Case2.** All the activities are not required to maintain the work continuity and resource consistency.

In this case, the non-dominated solutions are shown in Fig.5. The project gets its least total cost of \$ 1,654,032 when the project duration is 123 days.

The model can be used to deal with all kinds of situations where the resource continuity of activities is differently required. We will not discuss it for lack of space.

## 5. Conclusion

DTCTP is very common in repetitive projects. This paper has proposed a optimization model based on the ge-

**Table 1** Quantity of work, available execution modes and their associated financial expenses

| Activity $(i)$ | Excavation $(i=1)$ | | | | Foundation $i=2$ | | | | Columns $i=3$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit $(j)$ | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Quantity of work $(Q_{i,j})(m^3)$ | 1147 | 1434 | 994 | 1529 | 1032 | 1077 | 943 | 898 | 104 | 86 | 129 | 100 |
| Execution mode $(k)$ | 1 | | | | 1 | 2 | 3 | | 1 | 2 | 3 | |
| Productivity $(m^3/day)$ | 91.75 | | | | 89.77 | 71.81 | 53.86 | | 5.73 | 6.88 | 8.03 | |
| Labor cost rate $(dollar/day)$ | 340 | | | | 3804 | 2853 | 1902 | | 1875 | 2438 | 3000 | |
| Equipment cost rate $(dollar/day)$ | 566 | | | | 874 | 655 | 436 | | 285 | 371 | 456 | |
| Material cost rate $(dollar/day)$ | 0 | | | | 92 | | | | 479 | | | |
| Activity $(i)$ | Excavation $(i=4)$ | | | | Foundation $(i=5)$ | | | | | | | |
| Unit $(j)$ | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | | | | |
| Quantity of work $(Q_{i,j})(m^3)$ | 85 | 92 | 101 | 80 | 0 | 138 | 114 | 145 | | | | |
| Execution mode $(k)$ | 1 | 2 | 3 | 4 | 1 | 2 | | | | | | |
| Productivity $(m^3/day)$ | 9.9 | 8.49 | 7.07 | 5.66 | 8.73 | 7.76 | | | | | | |
| Labor cost rate $(dollar/day)$ | 3931 | 3238 | 2544 | 1850 | 2230 | 1878 | | | | | | |
| Equipment cost rate $(dollar/day)$ | 315 | 259 | 204 | 148 | 177 | 149 | | | | | | |
| Material cost rate $(dollar/day)$ | 195 | | | | 186 | | | | | | | |

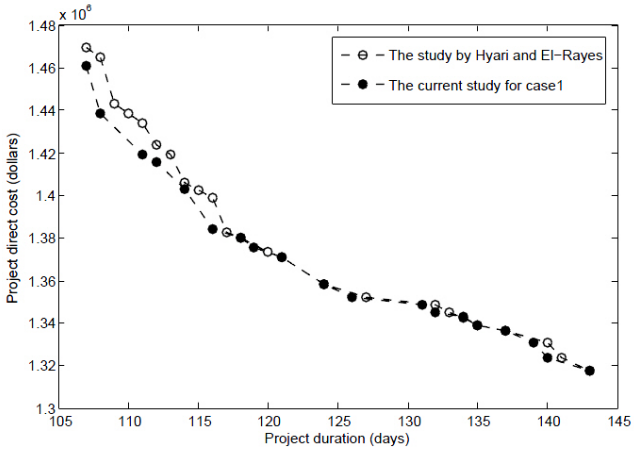


**Figure 4** The comparison of non-dominated solutions between different methods for case1.

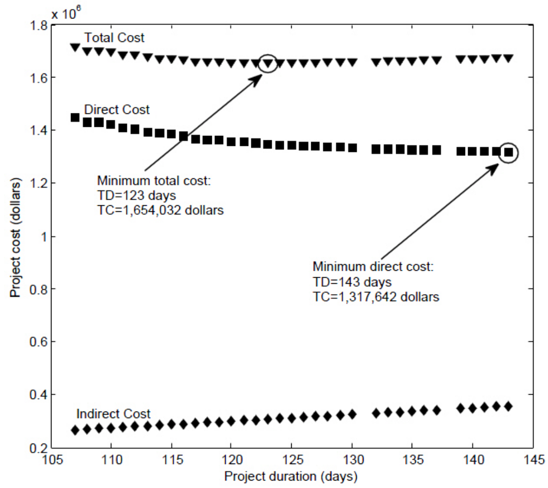


**Figure 5** Total cost, direct cost and indirect of case2.

netic algorithm for DTCTP in repetitive projects considering different requirements for resource continuity of activities. Two kinds of resource continuity are defined and analyzed, namely, the constraint of work continuity and resource consistency. The algorithm includes five modules, which can provide a set of Pareto near optimal solutions representing the time/cost trade-off in repetitive projects. Moreover, it can deal with all kinds of situations where the resource continuity of activities is differently required. A project from the pertinent literature has shown that the algorithm proposed in this paper works better. The model can deal with all kinds of situations where the resource continuity of activities is differently required.

Although the main benefit of resource continuity is that the learning effect can be maximized, the learning-forgetting effect is not considered in the current model. Hence, the learning-forgetting effect should be taken into consideration for future enhancements of the model.

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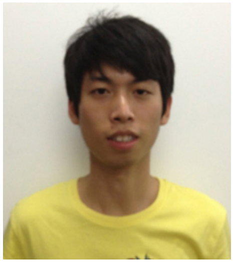

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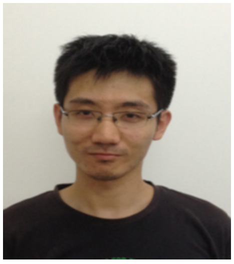

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