

# Resource Allocation for Repetitive Construction Schedules: An Ant Colony Optimization Approach

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Project scheduling is one of the most important topics in construction management. Many construction projects, such as highway construction, pipelines, tunnels, and high-rise buildings, typically contain activities that are repeated continuously at different locations. Research has shown that many widely used scheduling techniques are not efficient enough in scheduling linear construction projects with repetitive activities. An Ant Colony Optimization (ACO) approach is proposed, evolutionary methods based on the foraging behavior of ants, to resource allocation in repetitive construction schedules constrained by the activity precedence and multiple resource limitations. The algorithm is used to optimally assign resources to repetitive project activities in order to minimize the overall project duration as well as the number of interruption days. A sample case study is utilized to illustrate the application of the model.

**Keywords:** Construction scheduling, Resource Allocation, Ant Colony Optimization

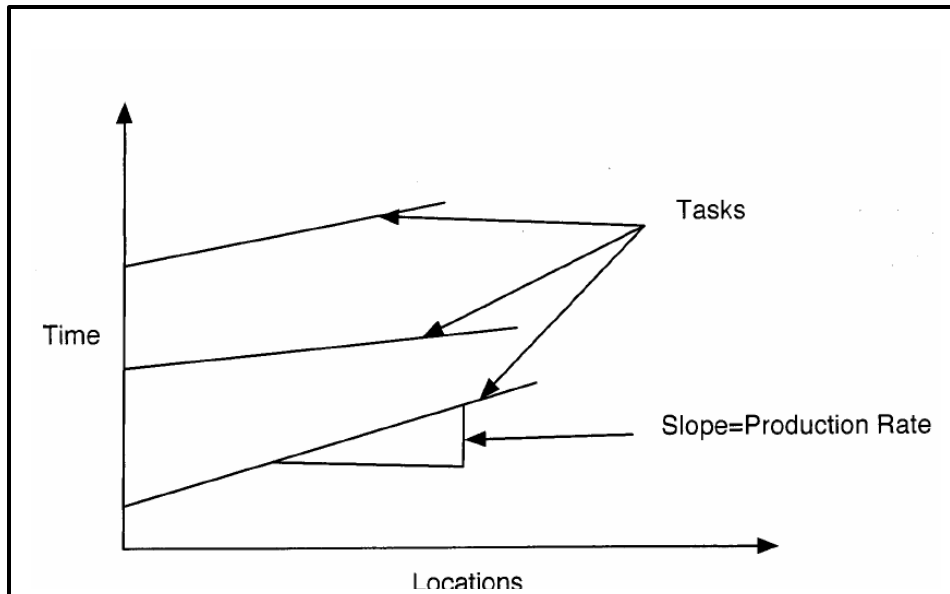
## Introduction

Project scheduling is one of the most important topics in construction management. Many scheduling techniques have been developed and are widely used for construction projects. A bar chart is one of the simplest scheduling techniques but it does not clearly show the dependency among activities. The Critical Path Method (CPM) is another popular scheduling technique used in project scheduling. Due to its network presentation capability and ease of use, 93% of the Engineering News Record's top 400 contractors use it as their main scheduling tool (Tavakoli and Riachi, 1990).

Many construction projects, such as highway construction, pipelines, tunnels, and high-rise buildings, typically contain activities repeated continuously at different locations. Research has shown that CPM lacks efficiency in scheduling linear construction projects with repetitive activities (Rahbar and Rowings, 1992). According to Harris (1996), CPM is unable to provide work continuity for crews or resources to plan the large number of activities necessary to represent a repetitive or linear project, to indicate rate of progress, to accommodate changes in the sequence of work between units, and to accurately reflect actual conditions.

Johnston (1981) introduced the Linear Scheduling Method (LSM) in a highway construction project. A typical Linear Scheduling Method Diagram (Figure 1) is a time- versus -distance or -location diagram. Activities are presented as line segments, blocks, or bars in the diagram. The slope of the segments represents the production rate of the corresponding activities. A LSM diagram, which provides a visual presentation of an activity, can clearly show the scheduled progress status of any activity at any given time, as well as identify conflicts between activities. Few of the previous LSM researchers have studied the impact of project duration with resource limitation constraints. Harmelink (1995) implants the concept of CPM

into LSM by defining a controlling activity path, which is similar to a critical path on the CPM method. He established a heuristic algorithm to determine the controlling activities path but with no resource limitation considered. Mattila (1997) proposed a model of a highway construction project with the consideration of resource leveling. The proposed model was solved by mixed integer programming. Liu (1999) proposed another resource allocation model with the consideration of a single resource. He also developed a heuristic solution procedure using the Tabu Search Algorithm.



**Figure 1** : Typical Linear Scheduling Method Diagram

The previous research projects initiated the study of Linear Scheduling with resource constraints. However, in real world practice, resources are usually limited. In many cases there may be more than one critical resource that is limited and may affect the project duration. Therefore, it is important to study project scheduling with the constraints of multiple resource limitations. Optimizing resource usage under multiple resource limitation profiles is the primary consideration, but minimizing the resource usage fluctuation is also important. Levelling the resource usage will minimize the amount of idle resources and, therefore, reduce the total cost.

Resource levelling and resource allocation problems usually can not be formulated as a linear programming problem without adding assumptions to simplify the problem. This type of problem usually requires a great deal of computing time to identify the global optimum (Clough and Sears, 1991; Ahuja, et al., 1994). Therefore, heuristic algorithms are often utilized to efficiently find a reasonable solution for such problems. Several heuristics searching techniques such as Genetic Algorithm (GA), Tabu Search, and Simulated Annealing have been developed in the past (Liu 1999; Leu & Hwang, 2001; El-Rayes, 2001) and are widely used in finding acceptable solutions for combinatorial problems.

In this paper, the authors propose an Ant Colony Optimization (ACO) approach to resource allocation in repetitive construction schedules constrained by the activity precedence and multiple resource limitations. The ACO approach has recently been applied to scheduling problems, as Job-shop, Flow-Shop, and Single Machine Tradiness problems (Bauer et al, 1999; Den Besten et al., 1999; Colorni et al., 1994; Merkle and Middendorf, 2000, Stutzle,

1998; Vander Zawaan and Marques, 1999). In ACO several generations of artificial ants search for good solutions. Every ant of a generation builds up a solution step by step, going through several probabilistic decisions. In general, ants that found a good solution mark their paths through the decision space by putting some amount of pheromone on the edges of the path. The following ants of the next generation are attracted by the pheromone so that they will search in the solution space near good solutions. In addition to the pheromone values, the ants will usually be guided by some problem-specific heuristic for evaluating the possible decisions.

### Problem Description

The resource constraint project scheduling problem is normally characterized by objective functions, features of resources, and pre-emptive conditions (Lee and Kim, 1996). Minimizing of project duration is often used as an objective function, while other objectives such as minimization of total project cost and levelling of resource usage are also considered. This paper will assume a construction project containing repetitive activities (N) that are repeated at different locations (M). Different critical resources (I) will affect the project schedule. The problem is to determine the resource assignments of all resources for all activities at all locations. The goal of this problem is to find a best - resource assignment combination and a project schedule to optimize the following two objectives: (1) to minimize the total project duration, and (2) to maintain the fluctuation of resource usage. The resource assignments also need to satisfy the resource limitation constraint, while the project schedule needs to follow the activities precedence relationships. The model will be based on the following assumptions:

- a) A resource can not be split
- b) A task can not be split
- c) Resources are limited
- d) The amount of resources assigned to a task at a certain location will remain constant until the activity at that location is finished. However, the amount of resources assigned to a task can vary from location to location.
- e) Resources are assumed to maintain a constant productivity level within a certain range of assignments.

Based on the assumptions described above, the formulation of a repetitive project scheduling problem with multiple resource constraints can be presented mathematically as:

### OBJECTIVES

#### Minimize:

$$\text{Max } \{ f(n, m) \mid n = 1..N; m = 1..M$$

$$\sum_{t=1}^{T-1} \sum_{i=1}^I w_I (dp_{t,i} + dm_{t,i})$$

**CONSTRAINTS**

1. Activities Precedence Relationships

$$s(n, m + 1) \geq f(n, m) \dots \dots \dots \forall n = 1, Nm = 1, m$$

$$s(n, m) \geq f(p, m) + L(n, p) \dots \dots \dots \forall m = 1..M, \forall p \in P$$

2. Resource Availability

$$\sum_{m=1}^M \sum_{n=1}^N r_i(n, m, t) \leq RA_i(t) \dots \dots \dots \forall t = 1, T \quad i = 1, I$$

3. Activities Completion

$$\sum_{t=1}^T r_i(n, m, t) \geq TR_i(n, m) \dots \dots \dots \forall n = 1, N; m = 1, M; i = 1, I$$

4. Resource Usage Deviation

$$\sum \sum [r_i(n, m, t + 1) - r_i(n, m, t)] - dp_{t,i} + dm_{t,i} = 0 \dots \dots \dots \forall t = 1, T - 1; i = 1, I$$

There are two objective functions for this model. The first one is to minimize the project duration. Since the largest finish time among all activities is equal to the project duration, it can achieve the purpose of minimizing the project duration. The second objective function is to minimize the total sum of the absolute resource usage fluctuation, which can be achieved by minimizing the total sum of the absolute resource usage change at any two consecutive days for the entire project time span. Because resources may have different critical levels, a weighting factor  $w_i$  is used and multiplied to its respective resource fluctuation.

**Ant Colony Optimization**

The first ACO meta-heuristic (Figure 2), called ant system (Colormi et al., 1991; Dorigo, 1992), was inspired by studies of the behaviour of ants (Deneubourg et al., 1983; Deneubourg and Goss, 1989; Goss et al., 1990). Ants communicate among themselves through pheromones, a substance they deposit on the ground in variable amounts as they move about. It has been observed that the more ants use a particular path, the more pheromone is deposited on that path and the more it becomes attractive to other ants seeking food. If an obstacle is suddenly placed on an established path leading to a food source, ants will initially go right or left in a seemingly random manner, but those choosing the side that is, in fact, shorter will reach the food more quickly and will make the return journey more often. The pheromones on the shorter path will therefore be more strongly reinforced and will eventually become the preferred route for the stream of ants.

The works of Colorni et al. (1991), Dorigo et al. (1991), Dorigo et al. (1996), Dorigo and Gambardella (1997), Dorigo and Di caro (1999) offer detailed information on the workings of the algorithm and the choice of the values of the various parameters.

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/* Initialization*/
For each edge  $(i, j)$  do
    Set an initial value  $\tau_{ij}(0) = \tau_0$ 
End for
Let  $T_+$  be the shortest tour found from beginning and  $L_+$  its length

/* Main loop*/
For  $t = 1$  to  $t_{\max}$  do
    /*Starting node*/
    For  $k = 1$  to  $m$  do
        Place ant  $k$  on a randomly chosen node
        Store this information in  $tabu_k$ 
    End for

    /* Build a tour for each ant*/
    For  $k = 1$  to  $m$  do
        Build a tour  $T_k(t)$  by applying  $n-1$  times the following steps:
        Choose the next node  $j$  with the probability given by the equation (1)
        Store this information in  $tabu_k$ 

        Compute the length  $L_k(t)$  of the tour  $T_k(t)$  produce by ant  $k$ 
        If an improved tour is found then
            Update  $T_+$  and  $L_+$ 
        End if
    End for

    /* Update pheromone trails*/
    For each edge  $(i, j)$  do
        Update pheromone trails according to equation  $\tau_{ij}(t+1) = r * \tau_{ij}(t) + \sum_{k=1}^m \Delta \tau_{ij}^k(t)$ 

        Where  $\Delta \tau_{ij}^k(t) = \begin{cases} Q / L_k(t) & \text{if } (i, j) \in T_k(t) \\ 0 & \text{otherwise} \end{cases}$ 
    End for

    Empty all  $tabu_k$ 
End for
Print the shortest  $T_+$  and its length  $L_+$ 

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**Figure 2** : Ant System (Colorni et al., 1991).

An ACO meta-heuristic was used to treat the complex problem that has been described. The formula is based on the well-known Quadratic Assignment Problem (QAP). Each node will be processed to represent each activity location and will be treated as an empty site in the QAP network. In a single objective QAP network, a matrix  $D$  shows the relative importance between each facility (resource) and the empty site. In our optimization problem, each  $(d_{ij})$

represents a set of conditions required to allocate resources for activity j if it is preceded by activity i.

When the ant moves from node I to node j, it will leave a trail analogous to the pheromone on the edge (ij). The trail records information related to the previous use of the edge (ij) and the more intense this use has been, the greater the probability of choosing it once again.

At time t, an ant k at node I chose the next node j to visit based on the probabilistic rule  $p_{ij}^k(t)$  as calculated in the following equation:

$$p_{ij}^k(t) = \begin{cases} \frac{[\tau_{ij}(t)]^a \cdot [h_{ij}]^b}{\sum_{l \notin tabu_k} [\tau_{il}(t)]^a \cdot [h_{ij}]^b} & \text{if } j \notin tabu_k \\ 0 & \text{if } j \in tabu_k \end{cases}$$

In this equation, the visibility ( $h_{ij}$ ), defined as being  $1/d_{ij}$ , favors the closer nodes. The choice probability is also affected by  $\tau_{ij}(t)$ , which is the intensity of the pheromone trail on edge (ij). At initialization of the algorithm, the trail on each edge is set at an arbitrary but small positive level,  $\tau_0$ . Parameters  $a$  and  $b$  are used to vary the relative importance of the visibility and the trail intensity. To ensure the production of a feasible assignment, nodes that have already been visited on the current assignment are excluded from the choice through the use of a taboo list. Each ant will have its own tab list,  $tabu_k$  recording the ordered list of nodes already visited.

At any given time, more than one ant seeks a feasible tour. A cycle is completed when each of the m ants have completed a tour of the n nodes. At the end of each cycle, the pheromone trail intensity will be updated according to the evaluation of solutions found in this cycle.

### Numerical Example and Results

The numerical example used in this study illustrates the application of the model. The example considers an artificial housing project. Assume the project consists of four activities: foundation, ground-floor walls, walls floor slab, and finishing. A total of five housing units will be constructed in this project and all activities are identical for each unit. The following table lists the activity ID, the duration, the precedent relationship with other activities, and the required resources for each activity. The five units are planned to be built in order, from unit 1 to unit 5. Two different labor resources were assumed to be required in the housing project. The activity priority shows the importance in which it will be used in the resource allocation procedure. Labor resource 1 supply was limited to eight (units /day), while labor resource 2 has a limit of nine (units/day).

**Table 1:** An Artificial Housing Project Example (Durations, Relationships, and Resource requirements)

Activity ID (Description)	Dur. (days)	Predecessor (Lead Time)	Labor 1 (men/day)	Labor 2 (men/day)	Activity Priority
A/Foundation	1	--	1	3	1
B/Ground-floor walls	3	A (1)	4	2	2
C/Ground-floor walls	5	B (0)	5	2	3
D/Finishing	3	C (1)	3	4	4

The ACO model was encoded using Matlab. The parameter settings of ACO chosen for the computational experiments ( $a=1$ ,  $b=1$ ,  $r=0.1$ ,  $t_0=0.01$ ,  $n=10$ ) were taken from other applications in which they have proven to be advantageous (Coloni et al., 1991). The only exception is parameter  $q_0$ ; it was increased from 0.9 to 0.99 because lower computational time is desired for the application. An alternative solution is obtained from the model created, with project duration of 37 days, compared to the original project duration of 25 days, and is presented in the following table:

**Table 2:** An Alternative solution obtained from the Ant Colony Optimization Model

Activity	Start	Finish	Duration	L1 assigned	L2 Assigned
A1	0	1	1	2	3
A2	1	2	1	2	3
A3	2	4	2	1	3
A4	4	5	1	2	3
A5	5	7	2	1	3
B1	2	6	4	3	2
B2	6	10	4	3	2
B3	10	14	4	3	2
B4	14	18	4	3	2
B5	18	22	4	3	2
C1	7	12	5	3	2
C2	12	17	5	5	2
C3	17	22	5	5	2
C4	22	27	5	5	2
C5	27	32	5	5	2
D1	22	25	3	3	4
D2	25	28	3	3	4
D3	28	31	3	3	4
D4	31	34	3	3	4
D5	34	37	3	3	4

## Conclusion

An Ant Colony Optimization model has been developed to satisfy practical requirements in repetitive construction schedules to find a best-resource assignment combination and a project schedule to optimize the following two objectives: (1) to minimize the total project duration, and (2) to maintain the fluctuation of resource usage. The ant colony optimization algorithm is very efficient and is able to solve difficult problems, such as the proposed one.

The computational requirements are very nominal. An artificial housing project was utilized to illustrate the application of the model. In real-world practice, resources are usually limited and repetitive project scheduling with resource constraints is always encountered in construction management. The ant colony approach can be included in the list of reliable and useful optimization tools for solving such problems.

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**NOTATIONS**

$s(n,m)$ : Start time of activity  $n$  at location  $m$ .

$f(n,m)$ : Finish time of activity  $n$  at location  $m$ .

$dp_{t,i}$ : Absolute difference plus value of resource  $i$  assignment between day  $t+1$  and day  $t$

$dm_{t,i}$ : Absolute difference minus value of resource  $i$  assignment between day  $t+1$  and day  $t$

$w_i$ : Weighting factor for resource  $i$

$r_i(n,m,t)$ : Resource  $i$  assigned to activity  $n$  at location  $m$  at time  $t$

$RA_i(t)$ : Resource  $i$  availability at time  $t$

$TR_i(n,m)$ : Total amount of resource  $i$  required to complete activity  $n$  at location  $m$