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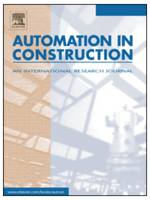

Ant colony optimization-based multi-mode scheduling under renewable and nonrenewable resource constraints

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ABSTRACT

An ant colony optimization (ACO)-based methodology for solving the multi-mode resource-constrained project scheduling problem (MRCPSP) considering both renewable and nonrenewable resources is presented. With regard to the MRCPSP solution consisting of activity sequencing and mode selection, two levels of pheromones are proposed to guide search in the ACO algorithm. Correspondingly, two types of heuristic information and probabilities as well as related calculation algorithms are introduced. Nonrenewable resource-constraint and elitist-rank strategy are taken into account in updating the pheromones. The flowchart of the proposed ACO algorithm is described, where a serial schedule generation scheme is incorporated to transform an ACO solution into a feasible schedule. The parameter-selection and the resultant performance of the proposed ACO methodology are investigated through a series of computational experiments. It is expected to provide an effective alternative methodology for solving the MRCPSP by utilizing the ACO theory.

1. Introduction

In a construction process, available amounts of renewable and nonrenewable resources may be limited due to cost or other factors. Therefore the resource-constrained project scheduling problem (RCPSP) that has been intensively addressed in the manufacturing field has also been studied in the construction field. In the classical RCPSP, each activity has a single execution mode, that is, the resource requirements and associated duration for an activity are fixed. However, in the practical circumstance when limited resources are shared by multiple activities and the real-time amounts of available resources are thus flexible, some activities may have multiple execution modes to be selected, each mode having different resource amounts corresponding to different durations for each activity. Multiple selections of execution modes are considered to reduce delay of activities and idle times of resources in consideration of real-time amounts of resources. It is shown that the study on the multi-mode resource-constrained project scheduling problem (MRCPSP) is important and has been gradually paid attention in the construction field.

The methodologies that have been developed for solving the MRCPSP include the exact and heuristic or meta-heuristic approaches. The exact methods include the exact enumeration schemes [29], a depth-first branch and bound procedure [31], as well as the dynamic programming approaches [27]. In addition, the enumeration scheme [12] for the single-mode was extended to the multi-mode case [32]. Finally, a branch-and-bound algorithm [33] was developed based on the exact procedure [19]. Sprecher and Drexl [33] suggested to use their branch and bound algorithms as heuristic procedures by imposing a time limit. Other heuristic methods for solving the MRCPSP include the biased random sampling approach [15], the single-pass and a multi-pass approach [37], the local search procedure [24], the one based on total floats [5], and the branch-and-cut procedure [36]. The meta-heuristic methods for solving the MRCPSP include the simulated annealing schemes [7], the genetic algorithm (GA) methods [2,20,30] and the particle swarm optimization methods [21,35].

In this study an ant colony optimization (ACO) algorithm, another meta-heuristic method, is proposed to solve the MRCPSP with the renewable and nonrenewable resources. Based on the theory of ACO and the feature of the MRCPSP, the mechanism of the ACO algorithm is proposed. Two types of pheromones with regard to sequence and mode selection of activities are proposed. Similarly, two types of heuristics and probabilities as well as their computation algorithms for each type of pheromone are respectively introduced. Each ant-constructed solution should be checked against the nonrenewable resource infeasibility and will be handled by adjusting the mode-combination. Then the flowchart of the ACO algorithm for solving the MRCPSP is presented. A series of computational experiments are carried out to investigate the performance of the ACO-based methodology for solving the MRCPSP.

2. MRCPSP description

Resources involved in a construction project can be renewable (i.e., recoverable after serving an activity, such as equipment or crews) or nonrenewable (i.e., limited in amount over project process

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and not recoverable, such as budget or materials). In a construction process, some activities such as "concreting" cannot be interrupted once started, while others such as "frame-forming" may be interrupted and resumed later and the required resources can be allocated again when resumed. The ACO-based methodology presented here assumes that the activities cannot be interrupted once started so as to ignore the issue of reallocation of the resources when restarted. Further studies on the MRCPSP will address interruption of activities.

Like the classical RCPSP, the MRCPSP also consists of a set of activities ($j = 1, \ldots, N$) that have to be scheduled under precedence and resource constraints. The precedence constraints mean that no activity can be started before all its predecessors are finished. When multiple execution modes are considered, each activity j ($j = 1, \ldots, N$) can be executed in one of M_j modes. The resource constraints here mean that the available amount (NR_k) for every renewable resource k ($k = 1, \ldots, NR$) is limited per period of time for every resource and the amount (NN_l) of each nonrenewable resource $l = 1, \ldots, NN$) is limited for the entire project duration. Each activity j ($j = 1, \ldots, N$) executed in mode m ($m = 1, \ldots, M_j$) has duration d_{jm} and requires r_{jmk} units of renewable resource k ($k = 1, \ldots, NR$) and n_{jml} units of nonrenewable resource l ($l = 1, \ldots, NN$). Minimization of project duration is generally considered as the objective for the MRCPSP. Therefore, the goal of solving the MRCPSP is to find sequence and mode selection for each activity as well as the resultant schedule (including start times and resource allocation policies for all activities) that leads to minimal project duration.

3. Fundamental theory of ACO

Ant colony optimization (ACO) is a population based meta-heuristic method proposed by Dorigo [13]. By imitating the foraging behavior of ant colonies, ACO aims to search for solutions to the combinatorial problems, where a colony of artificial ants combines priori information about the promising solutions with posterior information about the better-found solutions [13]. The solutions are constructed in a probabilistic way by taking into account pheromone trails which change with each cycle and a heuristic information depending on the problem to solve.

In contrast to GA, ACO resembles PSO in that they retain memory of entire colony instead of previous generation only. PSO is based on the choreography of swarm having almost the same natures, instead ACO is based on a population of individuals that has different morphological structures but the common goal. Unlike GA and PSO, ACO also utilizes additional information such as problem-dependent heuristic information in the search course, which may help and speed up finding the optimality.

ACO has been applied to the traveling salesman problem, quadratic assignment problem, production scheduling, time-tabling, vehicle routing, telecommunications routing and investment planning. Recently, ACO has been applied to solve the time–cost tradeoff optimization for construction [1,28]. In addition, the application of ACO to the RCPSP [10,11,25] has been noticed. Blum [3] stated that ACO is one of the successful swarm intelligence meta-heuristic methods for solving the RCPSP and open shop scheduling problem. Chiang et al. [9] have applied ACO to solve the MRCPSP, however, no more applications of ACO to the MRCPSP have been noticed to the best of our knowledge.

4. ACO mechanism for solving MRCPSP

Based on the ACO theory and the characteristic of MRCPSP solution consisting of activity-sequencing and mode selection, the ACO mechanism for solving the MRCPSP is described. In contrast to the work of Chiang et al. [9] that considered one pheromone in terms of two-dimensional matrix respectively for sequence selection and mode selection of the MRCPSP solution, this work considers two levels of pheromones and two types of the corresponding probability and heuristic information respectively in searching for the MRCPSP solution. Elitist-rank strategy and nonrenewable resource-constraint are considered in the pheromone updating procedure, and a serial schedule generation scheme is adopted to transform ACO solutions to feasible schedules.

4.1. Constructing of ACO solutions to MRCPSP

By consulting the mechanism of the ACO algorithm for the traveling salesman problem (TSP) [15], ACO has been applied to solve the RCPSP [25] by determining an optimal activity-list (i.e., sequence of activities) associated with the allocation of resources. In every search cycle, each ant constructs one RCPSP solution by sequentially selecting an activity j at the place i in the activity-list, namely selection (i, j), according to the probabilities of the feasible activities, and then deposit pheromone $\tau_{i,j}$ on the corresponding selection. The probability $p_{i,j}$ on the selection (i, j) indicates how good the activity j is sequenced in the order i, and is calculated based on the pheromone $\tau_{i,j}$ and the heuristic information $\eta_{i,j}$. The pheromone reflects the memory of good-findings of ants, while the heuristic value $\eta_{i,j}$ is obtained by some problem-dependent heuristic information. Deposit of the pheromones on the adopted selections is achieved by increasing the pheromones after each search cycle. Meanwhile, the pheromones should be reduced according to the evaporation rate after each cycle, reflecting decline of the memory of ants over time and also avoiding stagnation in the search process. The above operations are repetitive until the stop criteria are satisfied.

For the MRCPSP, however, the corresponding solution consists of not only sequence but also execution mode of activities. An ant faces two levels of selections in constructing a MRCPSP solution: one is to probabilistically select an activity j at the place i in the activity-list, namely selection (i, j), and the other is to probabilistically select the execution mode k for this activity j, namely selection (i, j, k). Hence, it is herein suggested to use two types of pheromones on each of the two selections, denoted as $\tau_{i,j}$ and $\tau_{i,j,k}$. Similarly, two types of probabilities $p_{i,j}$ and $p_{i,j,k}$ are respectively accounted in face of the two selections (i, j) and (i, j, k). Accordingly, two types of heuristic information, denoted as $\eta_{i,j}$ and $\eta_{i,j,k}$, are proposed to calculate $p_{i,j}$ and $p_{i,j,k}$.

These definitions can be illustrated through Fig. 1, where an example MRCPSP (Fig. 1(a)) needs to be solved using the ACO methodology. The example project consists of six activities and involves one type of renewable resource and one type of nonrenewable resource with the amounts 4 and 15, respectively. Two execution modes for each activity are considered and shown in Table 1.

Fig. 1(b) describes how an ant searches for an ACO solution to the example MRCPSP by sequencing activities (i.e., probabilistically selecting an activity and putting in the activity-list one by one) and probabilistically selecting one execution mode from two modes for each activity. Notice that each selection, whether (i, j) or (i, j, k), corresponds to the probability $p_{i,j}$ or $p_{i,j,k}$, the pheromone $\tau_{i,j}$ or $\tau_{i,j,k}$ and the heuristic information $\eta_{i,j}$ or $\eta_{i,j,k}$, though some of them are not shown in Fig. 1(b) due to the size limitation. The number in the brackets at the corner of an activity symbol indicates the activity index j. The number located at the solid line between two activities means the sequence order i (i.e., the place i in the activity-list) that has been currently selected by an ant. The dotted line in the activity symbol indicates that the mode k has been selected for the current activity j sequenced in the order i, while the dotted line in the activity symbol indicates the other modes that have not been selected. Fig. 1(b) also illustrates the mapping between the search course for a MRCPSP and the ACO solution, such as that constructed by ant l, denoted as $\mathbf{S}^l = (\mathbf{A}^l, \mathbf{M}^l)$, consisting of sequence of activities and the associated execution modes.

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