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Review

Metaheuristics for the tabu clustered traveling salesman problem

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ABSTRACT

This paper considers a new variant of traveling salesman problem (TSP), called tabu clustered TSP (TCTSP). The nodes in TCTSP are partitioned into two kinds of subsets: clusters and tabu node sets, then the salesman has to visit exactly one node for each tabu node set and ensures that the nodes within a same cluster are visited consecutively, and the problem calls for a minimum cost cycle. The TCTSP can be used to model a class of telemetry tracking and command (TT&C) resources scheduling problem (TTCRSP), the goal of which is to efficiently schedule the TT&C resources in order to enable the satellites to be operated normally in their designed orbits. To solve it, two metaheuristics combined with path relinking are proposed. The one is Ant Colony Optimization (ACO) and the other is Greedy Randomized Adaptive Search Procedure (GRASP). The proposed algorithms are tested on the benchmark instances and real-life instances of the TTCRSP. The computational results show that the hybrid ACO with two path relinking strategies works the best among the studied metaheuristics in terms of solution quality within the same computational time.

1. Introduction

The Traveling Salesman Problem (TSP) is one of the most studied combinatorial optimization problems. It aims at finding the shortest tour that visits the nodes in a given weighted complete graph exactly once and returns to the origin node. A widely studied variant of the TSP is the Clustered TSP (CTSP) (Gutin and Punnen, 2002), which was firstly studied in Chisman (1975). In the CTSP, cities within the same cluster must be visited consecutively. The CTSP can be used to model a broad range of real-life applications, such as vehicle routing (Laporte et al., 2002), manufacturing (Lokin, 1979), warehousing problem (Chisman, 1975), computer disk defragmentation, production planning and several kinds of scheduling problems (Laporte et al., 2002).

Since the CTSP is an NP-hard problem, exact algorithms can merely find an optimal solution for very limited-size instances due to finite computational resource. Instead, many researchers focused on finding a satisfactory solution within reasonable time. Jongens and Volgenant (1985) proposed a Lagrangean relaxation algorithm to obtain lower bounds of the optimal tour lengths for a set of CTSP test instances with the number of vertices varying from 80 to 150 and different sizes of clusters. Gendreau et al. (1994) first transformed the CTSP into a TSP and then applied the GENIUS heuristic procedure. Laporte et al. (1997) proposed a tabu search heuristic to solve the CTSP with a prespecified order of visiting the clusters. In Potvin and Guertin (1996), 1998), genetic algorithm (GA) was applied on the CTSP. Compared with the GENIUS heuristic (Gendreau et al., 1994) and the lower bounds obtained in Jongens and Volgenant (1985), GA can obtain results within 5.5% of the lower bound. Mestria et al. (2013) employed the Greedy Randomized Adaptive Search Procedure (GRASP) metaheuristic.

In this paper, a new variant of the CTSP, motivated by a real-life application of China Satellite Control Center (CSCC), arises when imposing the additional constraint that a feasible tour is allowed to visit only a subset of the nodes. Every day, CSCC has to coordinate communications between satellites and ground stations so as to keep the orbiting satellites working effectively. Each satellite needs services in a specific time window among possible alternative slots and generally asks for 4–6 times one day. The problem of scheduling all the services is referred as the TT&C resources scheduling problem (TTCRSP) (Zhang et al., 2014), which aims to allocate resources (i.e., contact opportunity windows) to as many services as possible during scheduling period (Bianchessi et al., 2007; Karapetyan et al., 2015; Marinelli et al., 2011; Wu et al., 2013). Since the number of satellites grows year by year, more services ask for certain resources than can be accommodated. Therefore the TTCRSP is an oversubscribed problem (Barbulescu et al., 2004).

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The TTCRSP is closely related to the CTSP. The satellite contact opportunity window with a scheduling benefit in TTCRSP can be viewed as a node in TSP. When two contact opportunity windows can be assigned to their corresponding services consecutively, there is an edge between them with an associated cost. Under such a situation, satellite control center would like to design a sequence of the chosen contact opportunity windows so as to complete all the services and maximize the total profit. In order to reduce the sensor opening and slewing time for less energy consumption, some services are generally grouped into clusters so that they can be completed together. More specially, each service has a set of alternative contact opportunity windows, but exactly one is chosen according to the domain constraints. The contact opportunity windows belonging to a same service are mutually exclusive, and node sets consisting of mutual exclusive nodes are tabu node sets in which only one node can be visited. Although the CTSP has been generalized in the literature (Gutin and Punnen, 2002) by taking into account some restrictions on the nodes in a cluster, to the best of our knowledge, our problem does not belong to any existing variant of the TSP. Due to the existence of tabu node sets, we named this new variant of the problem Tabu CTSP (TCTSP).

To deal with the TCTSP, a metaheuristic which combines Ant Colony Optimization (ACO) with path relinking is proposed. ACO is a swarm intelligence optimization algorithm which has been successfully used to solve many combinatorial optimization problems, such as TSP (Dorigo et al., 1996; Feo et al., 1994), while path relinking is an effective intensification search mechanism. Furthermore, we also extend the hybrid GRASP in Mestria et al. (2013) to solve the TCTSP.

The rest of this paper is organized as follows. Section 2 describes the formulation of the TCTSP. Section 3 presents the ACO heuristics proposed for the TCTSP. Section 4 gives simulation experiments and performance analysis. Section 5 studies a real-life case of the TCTSP. Finally, Section 6 concludes the main results.

2. A description of the TCTSP

The TCTSP is defined on a complete (loop - free) undirected graph $G=(V,E)$, where $V=\{v_1,v_2,\cdots,v_n\}$ is the set of nodes and $E=\{(v_i,v_j)|v_i,v_j\in V, i\neq j\}$ is the set of edges. In this work, the Euclidean distance c_{ij} between v_i and v_j is set as the cost of each edge $(v_i, v_j)\in E$ and the edge costs satisfy the triangle inequality. In addition, the nodes are properly partitioned into two kinds of subsets : *clusters* $V_1, \cdots, V_l$ and *tabu node sets* $T_1, \cdots, T_m$. A cycle is called *feasible* if it visits the nodes in each cluster consecutively and contains exactly one node from each tabu set. TCTSP then consists of finding a feasible cycle $T\subset E$ whose cost $\sum_{(v_i,v_j)\in T} c_{ij}$ is minimized. When there is only one cluster and each tabu node set contains only one node, TCTSP is reduced to TSP. The problem involves two related decisions:

- choose a node subset $S\subseteq V$, such that $|S\cap V_h|=1$ for all $h=1,\cdots,l$;
- find a minimum cost Hamiltonian cycle in the subgraph of G introduced by S.

Fig. 1 shows a feasible solution to an instance of the TCTSP that has three clusters and ten tabu node sets. The solution is a Hamiltonian tour such that the nodes of each cluster are visited consecutively and exactly one node in each tabu node set is visited. The nodes 1,4,11 and 19 in a tabu set may belong to different clusters, the dotted-line edges (10,11),(2,13) and (14,17) show the inter-cluster connections and the full line ones are the intra-cluster connections.

The binary decision variable $x_{ij}=1$ if and only if the salesman proceeds from city v_i to city v_j. The formulation of the TCTSP can be described as follows:

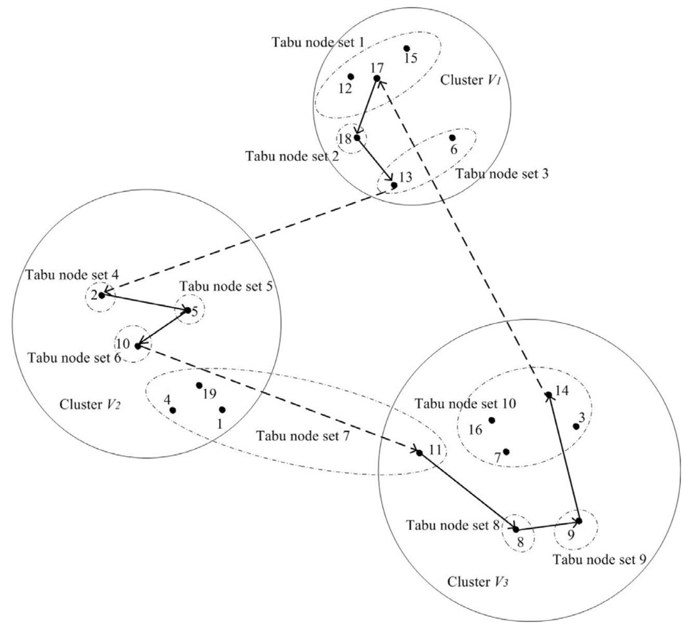

Fig. 1. A feasible solution to an instance of the TCTSP.

$$\min \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ij} \tag{1}$$

$$\text{s.t.} \sum_{j=1}^{n} x_{ij} \le 1, \forall i\in V \tag{2}$$

$$\sum_{i=1}^{n} x_{ij} \le 1, \forall j\in V \tag{3}$$

$$\sum_{i=1}^{n}\sum_{j\in T_k} x_{ij} = 1, \forall T_k\subset V, |T_k|\ge 1, k=1,\cdots,m, \forall i\in V \tag{4}$$

$$\sum_{i\in T_k}\sum_{j=1}^{n} x_{ij} = 1, \forall T_k\subset V, |T_k|\ge 1, k=1,\cdots,m, \forall j\in V \tag{5}$$

$$\sum_{i\notin V_k}\sum_{j\in V_k} x_{ij} = 1, \forall V_k\subset V, |V_k|\ge 1, k=1,\cdots,l \tag{6}$$

$$\sum_{i\in V_k}\sum_{j\notin V_k} x_{ij} = 1, \forall V_k\subset V, |V_k|\ge 1, k=1,\cdots,l \tag{7}$$

$$x_{ij}\in\{0,1\}, \forall i,j\in V \tag{8}$$

The goal is to minimize the total distance traveled by the salesman. Constraints (2) and (3) mean that each city can be visited at most once. Constraints (4) and (5) state that exactly one city of each tabu node set can be visited. Constraints (6) and (7) ensure that cities within the same cluster must be visited consecutively. Constraint (8) defines the domain of every decision variable.

3. The proposed ACO heuristics for the TCTSP

ACO is a metaheuristic framework for solving discrete combinatorial optimization problems. It takes inspiration from the foraging behavior of ant species (Dorigo and Birattari, 2010). ACO represents