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A memetic algorithm for the patient transportation problem ☆

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ABSTRACT

This paper addresses a real-life public patient transportation problem derived from the Hong Kong Hospital Authority (HKHA), which provides ambulance transportation services for disabled and elderly patients from one location to another. We model the problem as a multi-trip dial-a-ride problem (MTDARP), which requires designing several routes for each ambulance. A route is a sequence of locations, starting and terminating at the depot (hospital), according to which the ambulance picks up clients at the origins and delivers them to the destinations. A route is feasible only if it satisfies a series of side constraints, such as the pair and precedence constraints, capacity limit, ride time, route duration limit and time windows. Owing to the route duration limit, in particular, every ambulance is scheduled to operate several routes during the working period. To prevent the spread of disease, the interior of the ambulances needs to be disinfected at the depot between two consecutive trips. The primary aim of the problem investigated herein is to service more requests with the given resources, and to minimize the total travel cost for the same number of requests. In this paper, we provide a mathematical formulation for the problem and develop a memetic algorithm with a customized recombination operator. Moreover, the segment-based evaluation method is adapted to examine the moves quickly. The performance of the proposed algorithm is assessed using the real-world data from 2009 and compared with results obtained by solving the mathematical model. In addition, the proposed algorithm is adapted to solve the classic DARP instances, and found to perform well on medium-scale instances.

1. Introduction

In this paper, we investigate the public patient transportation service provided by the Hong Kong Hospital Authority (HKHA). This service transfers patients from one location to another to receive medical services, and requires that certain service requirements are fulfilled. As the services are all non-emergency in nature, they are reserved in advance.

The classic dial-a-ride problem (DARP) [13,12] is a special case of our problem. In DARP, every vehicle follows a route to provide transportation services for passengers. Along a given route, each vehicle picks up or drops off customers at required locations in pre-reserved time windows. In addition, the service level for each passenger, such as ride time and route duration constraints, must be taken into account.

There are three main differences between our problem and the classic DARP. First, each ambulance completes several short routes instead of just one within the working period. A restrictive duration limit ensures that the ambulances are disinfected regularly to prevent the spread of disease. Second, the lunch breaks of drivers and assistants need to be considered in the schedule. Thus, the scheduling of multiple trips and lunch breaks makes the problem complex to solve. Finally, owing to the limited number of vehicles, some clients may not be served. Here, our objective is to design a transportation plan to service as many patients as possible, and then to minimize the total travel cost for serving the same number of patients. The problem is modeled as a multi-trip dial-a-ride problem (MTDARP).

To solve the MTDARP, we have developed a memetic algorithm (MA) with the state-of-the-art framework proposed by Vidal et al. [55]. First, the initial population is filled by a constructive algorithm based on the *reg-k* regret insertion strategy. We apply a customized crossover operator to generate a new chromosome. The offspring chromosome is improved by a local search with different move types, and then placed into the population. When the size of the population exceeds a given threshold, an advanced diversity management scheme is invoked to perform survivor selection. To accelerate the process, the segment-based evaluation method is adapted to examine the temporal solutions, and a mechanism is proposed to avoid the duplicated checks of moves already examined. We evaluate the performance of the proposed

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algorithm based on real-world data collected by the HKHA for 2009 and compare it with results obtained by solving the mathematical model. In addition, the algorithm is adapted to solve the classic DARP instances and compared with recent methods.

This problem is particularly important and interesting. Theoretically, the classic DARP is an NP-hard problem, and thus the MTDARP is also NP-hard but of even greater complexity. In practice, it is becoming more difficult for decision makers to design schedules manually because of the increasing number of requests and non-emergency ambulances. We believe that our proposed algorithm can provide a superior, good-quality solution. Thus, our problem offers good alignment between research and real-life applications.

The remainder of the paper is organized as follows. In Section 2, we describe the relevant literature, including studies on DARP, multi-trip vehicle routing problems (MTVRP), and a state-of-the-art genetic algorithm (GA). We then provide a formal description and the mathematical formulation of the MTDARP in Section 3. In Section 4, we introduce the proposed algorithm in detail. In Section 5, we report a series of experiments to evaluate the performance of the proposed algorithm based on the real-world data and DARP instances. Finally, Section 6 concludes the paper.

2. Related work

To the best of our knowledge, the MTDARP has not previously been studied. However, the problem is related to several variants of the vehicle routing problem, including DARP, the MTVRP and its extension with time windows (MTVRPTW). Pickup and delivery (PD) as well as time windows (TW) are common characteristics in real applications [23,5,29]. Recently, the healthcare problems attract increasing interest from the researchers [36,27,26,51].

DARP can be seen as a variant of the pickup and delivery problem with time windows (PDPTW) which usually focuses on goods transportation. For more information on the widely used benchmark, the state-of-the-art meta-heuristic and exact algorithms of PDPTW, readers are referred to Li and Lim [25], Ropke and Pisinger [47], Baldacci et al. [4]. DARP addresses passenger transportation, and thus service quality must be taken into account. DARP usually arises in contexts in which passengers cannot easily use the regular public transportation system, e.g., rural areas [54,15], airports [43], and the health-care context [44,31,19,7]. Most of the DARP literature is derived from real-world applications, and accordingly the problem definitions usually differ slightly. The proposed algorithms for these problems include exact algorithms, constructive heuristics, and meta-heuristics. The exact algorithm can solve only small- or medium-scale instances to optimality, such as branch-and-cut [12] and branch-and-price-and-cut [17], whereas the aim of constructive methods is to generate a feasible solution quickly. Diana and Dessouky [15] proposed a regret insertion method in which the spatial and temporal aspects are considered simultaneously in selecting the seed customer for each route. Wolfler Calvo and Colorni [58] first solved the assignment problem on an auxiliary graph to create clusters of customers, and then designed the routes using those clusters. Cordeau and Laporte [13] developed a tabu search (TS) in which the infeasible solutions are allowed to enlarge the search space and an eight-step evaluation scheme is used to solve the maximum ride time constraint optimally. This eight-step scheme was often employed in subsequent studies. Recently, Kirchler and Wolfler Calvo [24] proposed a granular tabu search in which the assignment problem is solved to define the closeness of two customers. The variable neighborhood search (VNS) was addressed by Parragh et al. [38], who designed several novel neighborhood structures. Moreover, Jain and Hentenryck [21] developed the large neighborhood search (LNS), in which a tree search is used to complete the partial solutions. Guerriero et al. [18] presented the greedy randomized adaptive search programming (GRASP) to solve DARP with heterogeneous vehicles. A GA was also attempted by Jorgensen et al. [22] and Rekiek et al. [44]. In their studies, the chromosomes only record information on the clusters of customers, and the corresponding routes are constructed by an insertion method. Furthermore, Braekers et al. [8] proposed an exact branch-and-cut algorithm and a deterministic annealing (DA) meta-heuristic to extensively solve the homogeneous and the heterogeneous single depot DARP instances and the multi-depot heterogeneous DARP problem. Several authors have recently tried to design hybrid methods to exploit the advantages of both exact algorithms and meta-heuristics. For example, Parragh and Schmid [39] developed a hybrid column generation and large neighbourhood search method in which a new solution is obtained via column generation and improved by LNS. For a more detailed review of DARP, readers are referred to the survey of Cordeau and Laporte [14].

The multi-trip concept is actually very common in practice. A multi-trip arrangement usually results from the limits on route duration. The MTVRP was first proposed by Fleischmann [16], who proposed a route-first pack-second strategy. The author first constructed the routes via saving-based heuristics, and then assigned them to working shifts through a bin-packing algorithm. A number of other interesting algorithms were later developed, such as a constructive method [40], tabu search [9,10,1], adaptive memory programming [53,35], a genetic algorithm [48], and a memetic algorithm [11]. Furthermore, a detailed review has been carried out by Sen and Bülbül [50]. To date, the only exact algorithm is proposed by Mingozzi et al. [32].

A recently proposed extension of the MTVRP is the imposition of the MTVRPTW. The scheduling of routes is more difficult in the MTVRPTW. Thus, Azi et al. [2] developed a two-phase exact algorithm for the MTVRPTW with a single vehicle in which all non-dominated feasible routes are enumerated in the first phase, and some routes are then selected and scheduled to form a solution. A number of authors recently extended the framework to the problem with multiple vehicles [3,30,20]. For meta-heuristics, however, only Battarra et al. [6] have presented an adaptive guidance approach for solving the problem with the objective of minimizing the number of required vehicles.

In the proposed MTDARP model, assistant requirements and lunch breaks are taken into consideration. These constraints have been examined in ambulance routing problems [36,26]. For example, Parragh et al. [37] proposed a heterogeneous DARP that considers the requirements of assistants (referred to as attendants in their paper) and lunch break constraints. They implemented a branch-and-price algorithm to solve the problem. However, in their problem, a lunch break can be held in any vertex, whereas in the proposed model, staff have to return to the depot to have lunch. A similar lunch break constraint was investigated by Sze et al. [52]. In their work, a two-stage scheduling heuristic is implemented to solve the problem arising in in-flight food loading operations. Lim et al. [26] considered a problem where the time windows of lunch breaks for assistants are heterogeneous.

Memetic algorithms (MAs), which are also called hybrid genetic algorithms (hybrid GAs), are optimization techniques based on the synergistic combination of ideas taken from different algorithmic solvers, such as population-based searches (as in evolutionary techniques) and local searches (as in gradient-ascent techniques) [33]. These algorithms have been effectively applied to solve the vehicle routing problem (VRP) and its variants. For more detailed information, we refer readers to the recent survey by Potvin [41]. Less work has been reported on the PDPTW and its variants. Nagata and Kobayashi [34] stated that the main reason for this gap is the difficulty of designing an effective crossover operator for the problem with time windows, because of the fairly constrained search space. Recently, Vidal et al. [55] proposed a framework with advanced diversity management for the genetic algorithm, and demonstrated its effectiveness on a series of VRP variants [56,57].