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Multi-directional local search for a bi-objective dial-a-ride problem in patient transportation

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ABSTRACT

This paper considers a generalization of a bi-objective dial-a-ride problem, incorporating real-life characteristics of patient transportation. It studies the impact of combination restrictions, preventing particular user combinations and limiting the set of drivers to which particular users can be assigned. The academic literature currently lacks insights into the effect of these restrictions on the cost structure of a service provider. A multi-directional local search algorithm is developed to solve this problem, taking into account the fundamental tradeoff between operational efficiency and service quality. Local search is integrated into a variable neighborhood descent framework that applies an intelligent candidate list principle to reduce computation time. Moreover, a new scheduling procedure is proposed, constructing time schedules that minimize total user ride time. It proves to be faster and more efficient than existing scheduling procedures. Overall, computational experiments on existing benchmark data extended with combination restrictions reveal a general pattern in the effect of the combination restrictions. Such insights are essential for service providers in order to support policy choices, e.g. related to service quality or medical education of drivers.

1. Introduction

A dial-a-ride system is an application of demand-responsive, collective people transportation [7]. Each user requests a trip between an origin and a destination of choice, to which a number of service level requirements are linked. The service provider attempts to develop efficient routes and schedules, respecting these service level requirements and all technical constraints of a pickup and delivery problem [18]. Balancing the human and economic perspectives involved in solving such a dial-a-ride problem (DARP) is essential for organizing quality-oriented, yet efficient transportation for users having special needs.

The specific problem context treated in this paper is based on a real-life application in patient transportation. It is characterized by combination restrictions, which prevent some users from being transported together and limit the set of drivers to which users may be assigned. Since the standard problem of Laporte [6] cannot cover these restrictions, the present paper introduces a more general model. In addition, a bi-objective approach is adopted. Contrary to single-objective methods, which usually minimize operational costs subject to full demand satisfaction and service level requirements, the fundamental nature of the problem is emphasized through a simultaneous minimization of operational costs and user inconvenience. To this end, a multi-directional local search (MDLS) algorithm [28] is developed, embedding a variable neighborhood descent (VND) framework [9].

The contribution of this paper is fourfold. First, the standard problem characteristics of the DARP are extended with real-life constraints in patient transportation. Their impact on the cost structure of the service provider is analyzed. Second, this paper presents a successful implementation of an MDLS strategy to a bi/multi-objective DARP. Third, a new efficient scheduling heuristic is developed to determine the start of service at each location in a route. It is structurally designed to minimize total user ride time, is faster than existing procedures and delivers fewer incorrect infeasibility declarations. Fourth, an intelligent candidate list is proposed to guide the VND operators, improving the ratio between solution quality and computation time.

The remainder of this work is organized as follows. Section 2 describes the real-life context this paper is based on. The problem is modeled as a bi-objective DARP with combination restrictions. Section 3 reviews related literature. Section 4 explains the general MDLS strategy and the specific implementation developed. Section

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5 is devoted to the new scheduling heuristic, which is compared with existing techniques. Section 6 discusses the impact of the combination restrictions and explains how service providers may use this information to support policy choices. Conclusions and opportunities for future research are identified in Section 7.

2. Problem description

The problem context addressed in this paper is based on a real-life application of patient transportation in Belgium. It concerns a service provider who specializes in organizing demand-responsive transportation for the purpose of hospital consultations, medical treatments, daycare activities or rehabilitation therapies. Drivers receive regular training in order to offer a high-quality service tailored to the users' specific needs. On a daily basis, a total number of approximately 1300 requests are processed in five branches across the country. Requests originate from both institutions and individuals. The operational challenge of composing vehicle routes and time schedules can be modeled as a DARP with additional real-life characteristics.

Cordeau and Laporte [6] defined a standard version of the DARP. It consists of designing several minimum-cost vehicle routes in a complete graph of nodes and arcs. Nodes correspond to pickup and delivery locations of users, supplemented with the vehicle depot. Each directed link between two nodes is an arc, characterized by a travel time and an associated cost which is incurred if the arc is part of the solution. Each route should start and end at the depot within fixed time intervals and respect a maximum route duration. The service at each location in between must start within a time window. A maximum user ride time cannot be exceeded and a vehicle's load cannot exceed its capacity. To ensure a correct physical route construction, precedence and pairing of a user's origin and destination must be respected by visiting them in the right order, using the same vehicle. A service duration may indicate the time needed for loading and unloading users. Mathematical formulations of the standard problem as an arc-based (mixed) binary program are proposed by Cordeau [5] and Røpke et al. [23].

Depending on the practical context, the applicability of a solution technique needs to be ensured by including additional real-life problem characteristics. Recent surveys on service quality (e.g. [15,14]) conclude that most solution techniques do not meet the expectations of service providers and users in daily practice. Relevant constraints and objectives need to be identified through contacts with stakeholders. The present paper takes into account various extensions to the standard problem, as discussed below.

In the standard problem, all users can be combined with any other user(s) and be assigned to any driver/vehicle, provided that time and capacity restrictions are respected. Contrastingly, the given problem context includes two types of combination restrictions. The first type prohibits the combination of specific pairs of users in the same vehicle at the same time. This may be due to medical causes (e.g. contamination risk, radiation therapy, mental health) or financial agreements between the service provider and a particular institution to keep a vehicle exclusively available for its patients. The second type of combination restrictions is caused by the medical needs of certain users. Drivers must be qualified to service users who suffer from a disease which requires special treatment (e.g. behavioral disorder, mental impairment). The impact of both additional restrictions on the cost structure of a service provider will be analyzed.

Another extension to the standard problem relates to the objective function. Given that the cost incurred on a certain arc is proportional to its length, the standard problem minimizes total distance traveled, which is an operational objective. Such a problem definition assumes that user quality is sufficient as soon as all service level requirements are respected, but does not provide any further incentive to optimize the service level. This paper emphasizes the fundamental nature of the DARP by taking into account the conflicting interests of service providers and users in the objective function. Therefore, an additional quality-related objective is added. This second objective minimizes total user ride time, being the total time users spend aboard the vehicles. All other problem characteristics, including the maximum user ride time constraint, remain unchanged. Since assigning a priori weights on the importance of both objectives is difficult, an MDLS algorithm is developed to approximate the Pareto frontier, which is the optimal set of uncomparable solutions. Even though only one solution is executed in practice, this approach provides useful insights into the tradeoff between operational costs and service quality. The operational effect of implementing a particular service level (and vice versa) can be analyzed, which ultimately allows a service provider to reflect on its service policy and to define well-considered quality guidelines.

3. Literature review

Although patient transportation has been a common application of the DARP, the trend of including associated real-life characteristics into models is rather recent. Little attention has been paid to combination restrictions. Beaudry et al. [2] consider dynamic patient transportation between different hospital campuses. They take into account emergency requests, isolated transportation and restrictions in vehicle assignments due to the presence of specialized equipment. Applying tabu search, they minimize a weighted sum of an operational objective and a service-related objective, being total vehicle travel time and lateness/earliness, respectively. Xiang et al. [29] impose driver qualifications based on the equipment in the vehicles and the users' disabilities. Their local search approach alternatively optimizes a primary and secondary objective, consisting of various components. A driver's wage is correlated with his qualifications, whereas the cost of a vehicle depends on its equipment. However, neither Beaudry et al. [2] nor Xiang et al. [29] analyze the *effect* of these real-life characteristics on the cost structure of the service provider.

Apart from combination restrictions, models in patient transportation may focus on heterogeneous users with respect to their transportation needs. For example, Parragh [17] observes that certain users travel in a wheelchair or on a stretcher. Vehicle capacity is divided into different resource types, among which upgrading conditions may apply. Qu and Bard [22] assume adjustable resource configuration in vehicles. Other contributions respond to the high degree of uncertainty. Schilde et al. [26] consider the unpredictable duration of hospital visits, making it difficult for users to specify a return time. Rather than considering such inbound trips as dynamic requests, possible inbound trips at various times are anticipated by a statistical distribution. Coppi et al. [4] integrate scheduling of health care services and vehicle routing.

Despite its inherent bi-objective nature, most heuristics approach the DARP as a single-objective minimization of total distance traveled, taking into account service level requirements. Early research mainly focused on insertion heuristics [11] and cluster-first route-second approaches [10]. Since Cordeau and Laporte [6] presented their efficient implementation of tabu search, numerous metaheuristics were designed to improve solutions. Particularly frameworks based on local search, such as variable neighborhood search [19] or deterministic annealing [3], obtained outstanding results within realistic computation times. A recent shift of attention is the application of matheuristics [21],