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Discrete Optimization

Hybrid large neighborhood search for the bus rapid transit route design problem

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ABSTRACT

Due to an increasing demand for public transportation and intra-urban mobility, an efficient organization of public transportation has gained significant importance in the last decades. In this paper we present a model formulation for the bus rapid transit route design problem, given a fixed number of routes to be offered. The problem can be tackled using a decomposition strategy, where route design and the determination of frequencies and passenger flows will be dealt with separately. We propose a hybrid metaheuristic based on a combination of Large Neighborhood Search (LNS) and Linear Programming (LP). The algorithm as such is iterative. Decision upon the design of routes will be handled using LNS. The resulting passenger flows and frequencies will be determined by solving a LP. The solution obtained may then be used to guide the exploration of new route designs in the following iterations within LNS. Several problem specific operators are suggested and have been tested. The proposed algorithm compares extremely favorable and is able to obtain high quality solutions within short computational times.

1. Introduction

Due to an increasing demand for public transportation and intra-urban mobility, an efficient organization of public transportation has gained significant importance in the last decades. Cities have continued to grow and hence require more transport capacity and improved access to those. In this paper we will focus on a specific type of public transportation system: the design of routes and their frequencies for bus rapid transit (BRT) systems.

BRT systems enjoy great popularity. Currently more than 168 cities world-wide employ BRT systems, covering a network of 4424 km and providing service to approximately 31 million passengers on a daily basis. BRT systems are especially popular in Latin America, where BRT systems are currently in use in 56 cities. One of the largest among those is operated in Bogotá (Colombia), covering a network of 106 km and offering 1.98 million passenger trips per day (see WWW, 2013).

BRT systems deliver fast and cost-effective public transportation through busses. The route design problem for BRT systems involves the design of routes given the current infrastructure, as well as the determination of their frequencies they will be operated. The network under consideration consists of a single corridor and stations, which are located within the corridor in a predefined way. Busses may be operated on designated lanes, allowing them right-of-way with respect to regular traffic. For the problem under consideration the network of the BRT system is given. A typical network consists of corridors (composed of several individual lanes), as well as the sequence and the location of stations along them. The travel time of busses is assumed to be given. Additional time will be taken into account for ac- and deceleration of busses after or before stopping at a station. Similarly we assume waiting times at stations to be fixed and given.

The demand for the public transport system can be represented in terms of an origin–destination matrix, which provides us with an estimate of the number of passengers requiring transportation between any pair of stations within the time horizon under consideration. This matrix is assumed to be known beforehand and is assumed not depend on the set of routes offered. Depending on the variation of demand throughout the day, the demand during peak hours should be taken into account preferably. The actual demand will depend on the offered set of routes and their frequencies, as passengers may react upon the offer. For the purpose of this paper we assume the demand to be constant and independent of the set of routes offered. The reaction can be seen as a dynamic process (see Guihaire & Hao, 2008), which is beyond the scope of this paper.

We consider a homogeneous and limited fleet of busses. Passengers may enter, leave or transfer among routes, at any station a route stops. As passengers tend to become confused if the number

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of offered routes is too large, the total number of routes offered will be limited from above. Besides, due to managerial efficiency it is desirable to operate the system with a limited number of routes (see Walteros, Medaglia, & Riaño, (forthcoming)).

We refer to Levinson, Zimmerman, Clinger, and Rutherford (2002) and Walteros et al. (forthcoming) for a more detailed overview on BRT systems.

The problem at hand can be defined as follows: given a connected network we try to design a set of routes and determine their frequencies, such that the total travel time by passengers can be minimized, while taking into account capacity restrictions. Frequencies determine how often a route will be served within the planning horizon, which might be in regular intervals (cyclic timetable) or in an aperiodic way. Routes do not necessarily need to stop at all stations among a specific corridor, but may skip stations along their way.

We assume passengers decide upon their route using a common objective function, such as the total travel time of all passengers spent in the system. This is a common objective function chosen in the literature in the sense of a system optimum (Borndörfer, Grötschel, & Pfetsch, 2008).

For a route to be feasible it needs to stop at least at two stations. Furthermore we assume that the provided routes are symmetric, i.e. will be operated in both directions. This should make the system easier to be used from a customers' point of view. The underlying model and the proposed solution approach can be extended easily to cope with asymmetric route designs as well (see Walteros et al., forthcoming).

A graphical representation of a simple instance is shown below. Fig. 1 shows a simple network consisting of one corridor and four stations, labeled 1 to 4, as well as a selection of 5 feasible routes. Routes may operate on the given corridor and may only stop at stations in the designated order.

For a single corridor the number of routes grows exponentially and can be calculated as $2^S - S - 1$, given the number of stations S. For systems with several corridors the number of different routes can be calculated in a similar way, but in addition the structure of the network, i.e. the number of segments and stations several corridors might share, also needs to be taken into account. It is important to mention that for any realistically sized instance the total number of routes is too large to be explored or enumerated, let alone to be offered. The large number of routes makes it practically impossible to solve instances of realistic size. Hence we propose an efficient hybrid metaheuristic to solve the problem at hand.

The contribution of this paper is threefold. In this paper we are going to introduce a new mixed integer problem formulation for the problem at hand. In order to solve the problem we decompose the problem into two interrelated subproblem, the design of routes and determining the frequencies together with the resulting passenger flows. We then propose an iterative hybrid metaheuristic. A metaheuristic component is focused on designing promising

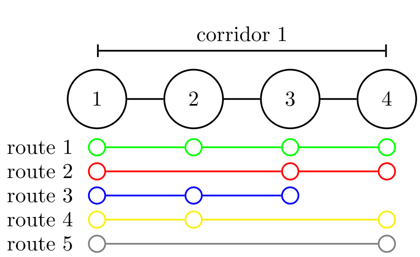

Fig. 1. Example of an instance with 1 corridor, 4 stations and a selection of 5 possible routes.

routes, which then can be (optimally) evaluated by determining their frequencies as well as the flow of passengers while ensuring feasibility. They key contribution in terms of the proposed algorithm is the notation of feedback, which will guide and bias the decisions of the metaheuristic in the route design phase. Feedback will be provided in terms of estimates upon the consequences on the (global) objective function, based on the solution obtained in the previous iteration.

The paper is structured as follows. We discuss literature on related problems and similar solution approaches in Section 2. We then introduce the mathematical model in Section 3. Our hybrid solution approach, as well as its core components, will then be sketched in Section 4. Results obtained on benchmark instances available in the literature will be presented in Section 5.

2. Related literature

Mathematical optimization has gained considerable attention for optimizing line planning problems in public transportation. We refer to Odoni, Rousseau, and Wilson (1994) and Bussieck, Kreuzer, and Zimmermann (1997) for an overview. Planning of public transportation services includes several steps that are usually performed in a sequential manner (see Ceder & Wilson, 1986; Liebchen & Möhring, 2007). The problems as such however are highly interrelated. Interactions made possible by handling several problems at the same time will be beneficial to the final results (see Guihaire & Hao, 2008). First, decisions based on the physical *layout* of the transportation system need to made. We refer to Laporte, Mesa, and Ortega (2000) on optimization methods for the planning of rapid transit systems. Bruno, Gendreau, and Laporte (2002) propose a heuristic for locating a rapid transit line, by optimizing the total population covered by the alignment. Laporte, Mesa, and Ortega (2002) deal with deciding on where to locate individual stations given the alignment. Based on information related to its infrastructure, public transport lines and frequencies can be determined within the scope of *strategic* planning, taking into account expected demand. Within the *tactical* planning phase, in the subsequent timetabling step, a set of public transport lines and frequencies is instantiated with actual departure times, usually minimizing transfer times. During the an *operational* planning phase (vehicle scheduling), vehicles are then assigned to individual trips in order to cost-efficiently realize public transport operations (vehicle scheduling, operational planning, see Bunte & Kliewer (2009)). The planning process is concluded with the determination of crew schedules for a given set of vehicle schedules. A general overview on optimization for planning of public transport operations is provided in Desaulniers and Hickman (2007). In this paper we will focus on a fundamental strategic planning problem for public transport, i.e. determining routes and their frequencies for BRT systems. According to the classification provided in Guihaire and Hao (2008) the problem can be seen as Transit Network Design and Frequency Problem (TNDFP), planning both the transit network design (i.e. the set of routes offered), as well determining the frequencies, simultaneously.

We focus on the network planning and not the actual operation. Hence given the strategic nature and the planning horizon of the problem we focus on a frequency-based approach, as opposed to a schedule-based approach. Actual schedules or time tables will not be considered at this planning stage. Rather we focus on determining service frequencies. However, frequency-based approaches only allow taking into account average number of passengers on board of a vehicle (Nuzzolo, Russo, & Crisalli, 2001). We accept this and believe it can be overcome by considering an appropriate time horizon (during peak hours) and the respective demand, i.e. designing a set of routes for those and later adjust frequencies