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A simultaneous transit network design and frequency setting: Computing with bees

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ABSTRACT

The transit network design problem belongs to the class of hard combinatorial optimization problem, whose optimal solution is not easy to find out. We consider in this paper the transit network design problem in a way that we simultaneously determine the links to be included in the transit network, assemble chosen links into bus routes, and determine bus frequency on each of the designed routes. Our approach to the transit network design problem is based on the Bee Colony Optimization (BCO) metaheuristic. The BCO algorithm is a stochastic, random-search technique that belongs to the class of population-based algorithms. This technique uses a similarity among the way in which bees in nature look for food, and the way in which optimization algorithms search for an optimum of a combinatorial optimization problem. The numerical experiments are performed on known benchmark problems. We clearly show that our approach, based on the BCO algorithm is competitive with the other approaches in the literature and that can generate high-quality solutions.

1. Introduction

Heavy traffic congestion in many cities has resulted in an increase in travel times, transportation costs, the number of traffic accidents and the level of air pollution and noise. The reduction of the number of trips that are made by cars and increasing the share of public transit in the total number of trips are logical actions that can partially improve the traffic situation. City governments and traffic authorities in many cities are making significant efforts to improve public transit.

Transit network topology and bus frequencies are among the most important factors that determine passengers' choice of public transit. In other words, properly designed public transit network and appropriate bus frequency values can considerably raise public transport mode share. On the other hand, inadequately designed transit network can cause very long passengers' waiting times, and increase uncertainty in bus arriving times. Additionally, improperly designed network can demonstrate high inappropriateness among the designed bus routes and paths of the greater part of passengers.

The designed network should offer good connectivity (high number of routes between major trip generators), as well as good geographic coverage. The chosen transit network and the bus frequencies have a direct influence on the economic results of the transit operator, as well as on the level-of-service offered to the passengers. Low bus frequencies will result in a high average load factor and a large number of passengers being denied space. The greater part of these passengers most often turn to other accessible transportation modes (private cars, taxis). When determining bus frequencies, the interests of both the operator and the passengers must be taken into consideration.

When designing the transit network, one should try to maximize the number of satisfied passengers, to minimize the total number of passenger transfers, to minimize the total travel time of all served passengers, to minimize the fleet size, etc. The transit agencies and transit operators try to satisfy passengers demand. On the other hand, passengers demand significantly depends on the offered transit network. In this way, when designing transit network one should carefully explore passengers' route choices through the transit network, and assignment of passengers to bus routes.

The transit network design problem belongs to the class of hard combinatorial optimization problem, whose optimal solution is not easy to find out. The general network design problem is *NP*-hard (Karp (1975), Magnanti and Wong (1984)). In other words, "there is little likelihood of devising an efficient (polynomial time) algorithm for solving the general network design problem (Magnanti and Wong (1984)). Computational complexity of the network design problem forced many researchers to develop and use

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various heuristic and metaheuristic algorithms. Meta-heuristics have become dominant tool for solving hard combinatorial optimization problems (Holland, 1975; Goldberg, 1989; Kirkpatrick, Gelatt, and Vecchi, 1983; Cerny, 1985; Mladenović and Hansen, 1997; Dorigo, Maniezzo, and Colorni, 1996, etc.). Many authors also used hybrid metaheuristic approaches (Tseng and Liang, 2006; Poorzahedy and Rouhani, 2007; Yildiz, 2008, 2009, etc.

In the majority of cases, metaheuristics provide high-quality solutions within reasonable CPU time. Among metaheuristics, a group of biologically inspired algorithms can be recognized. Bee Colony Optimization (BCO) method, that uses collective intelligence applied by the honey bees during nectar collecting process, is one of them. BCO has been proposed by Lučić and Teodorović, 2001, 2002, 2003a, 2003b and up to now it is successfully applied to a range of real-life optimization problems.

Nikolić and Teodorović (2013a) recently performed an empirical study of the BCO algorithm. The authors applied BCO to optimize 51 numerical test functions from the literature. The set of functions was reasonable large and included various function types (unimodal, multimodal, multidimensional, etc.). The obtained results are compared (by using the Student's *t* test) with the results achieved by the Artificial Bee Colony, Genetic Algorithm, Differential Evolution, and Particle Swarm Optimization. The numerical experiments performed on well-known benchmark functions. The experiments clearly showed that the BCO outperformed competitive approaches. Successful applications to a range of real-life optimization problems, as well the results obtained by the empirical study of the BCO algorithm encouraged us to also use the BCO concept also in this paper. Jakšić Kruger, Davidović, Teodorović, and Šelmić (2014) recently provided theoretical verification of the BCO algorithm by proving some convergence properties.

We (Nikolić and Teodorović, 2013b) also recently developed efficient algorithm for public transit network design. The proposed model is based on the BCO metaheuristic. This paper represents the extension of the Nikolić and Teodorović's research. We consider in this paper the transit network design problem in a way that we *simultaneously* determine the links to be included in the transit network, assemble chosen links into bus routes, and determine bus frequency on each of the designed routes.

In this paper we develop the model for the transit network design that is based on the Bee Colony Optimization (BCO) metaheuristics. The BCO algorithm belongs to the class of population-based algorithms.

We compare our approach with other models and algorithms for the public transit network design problem. We clearly show that our approach, based on the BCO algorithm is competitive with the other approaches in the literature and that can generate high-quality solutions within negligible CPU times.

The paper is organized in the following way. Problem statement is given in the Section 2. Section 3 considers passenger assignment problem within public transit network. The description of the BCO algorithm is given in Section 4. The BCO approach for the transit network design problem is given in the Section 5. Section 6 contains performed numerical tests. Conclusions are given in the Section 7.

2. Statement of the problem

Let us consider the road network shown in the Fig. 1. We denote this network by $G = (N, A)$, where N is the set of nodes and A is the set of links. Nodes represent bus stations, while links represent streets segments that connect stations. We also, denote by D the origin–destination matrix:

$$D = \{d_{ij} | i, j \in N\} \tag{1}$$

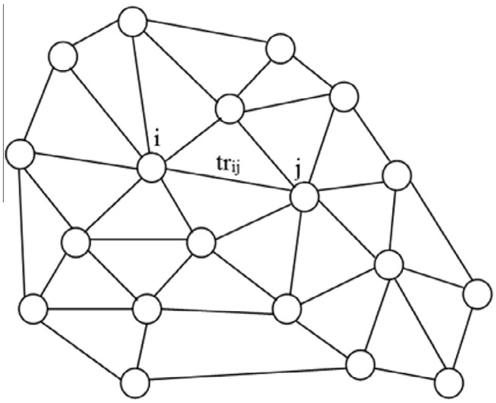

Fig. 1. Road network.

where d_{ij} is the number of passengers that wish to travel between node i and node j during the observed time period.

By TR we denote the travel time matrix:

$$TR = \{tr_{ij} | i, j \in N\} \tag{2}$$

where tr_{ij} is the in-vehicle travel time between node i and node j.

We assume in this paper that the network $G = (N, A)$, the O–D matrix D, and the travel time matrix TR are given. Let us denote by T the total travel time of all passengers in the network. The total travel time equals:

$$T = TT + TW + TTR \tag{3}$$

where:

TT – total in-vehicle time of all served passengers.
TW – total waiting time of all served passengers.
TTR – total time penalties for all passenger transfers (usually time penalty is equal to 5 min per transfer).

The majority of the transit agencies and operators try to offer to the general public high level of service at reasonable costs. Therefore, the minimization of the total number of rejected passengers, the minimization of the total travel time of all passengers, as well as the minimization of the total number of busses needed to serve the passengers demand could be legitimate objective functions. In this paper we consider all three objective functions.

The transit network design problem that we study in this paper could be defined in the following way: For a given network $G = (N, A)$, known origin–destination matrix D that describes demand among these nodes, and known travel time matrix TR, generate set of transit routes on a network and determine bus frequencies along the routes in such a way to optimize considered objective function.

The broad literature review devoted to the transit network design problem is given in our previous research (Nikolić and Teodorović, 2013b).

3. Passenger assignment

Passenger flows in public transit depend on the transit network design. In other words, when performing public transit network design, one should determine the passenger demand on each of the generated routes. The analyst should determine, for every pair of the origin–destination pairs, passenger flows on paths chosen by the passengers. These flows are the results of the individual passenger decisions. Every passenger faces the problem of choosing the path when traveling form origin to destination. We consider