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A differential evolution for simultaneous transit network design and frequency setting problem

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ABSTRACT

The urban transit network design problem (UTNDP) is concerned with the development of a set of transit routes and corresponding schedules on an existing road network with known demand points and travel time. It is an NP-hard combinatorial optimization problem characterized by high computational intractability, leading to utilization of a wide variety of heuristics and metaheuristics in an attempt to find near-optimal solutions. This paper proposes a differential evolution approach to address the UTNDP by simultaneously determining the set of transit routes and their associated service frequency with the objective to minimize the passenger cost, as well as the unmet demand. In addition, a combined repair mechanism is employed to deal with the infeasible route sets generated from the route construction heuristic and the operators of the differential evolution. The proposed algorithm is evaluated on a well-known Mandl's Swiss network reported in the literature. Computational experiments show that the proposed algorithm is competitive according to the performance metrics with other approaches in the literature.

1. Introduction

Transit planners and city authorities have been making significant effort to address the heavy traffic and congestion on urban roads owing to the rapidly growing population and urbanization particularly in developing and emerging countries. These have led to the development of a variety of tools or approaches for the urban transit network design problem (UTNDP) that ideally reflects the interests of the transit users, operators, and social factors. These approaches span from manual, analytical, to heuristics and metaheuristics for both theoretical and realistic transportation networks. In fact, a thorough search of the literature reveals no common methodology is utilized for the UTNDP. This is due to the extent of details incorporated in the problem formulation for the proposed network in reflecting the real-life conditions that differ in many aspects. The UTNDP is still attracting a lot of attention among practitioners and planners, particularly the transit system based on buses, because it is more complex and time-consuming to handle compared to other transportation modes. In a real sense, the public transit system can be made considerably attractive through the utilization of an appropriate transit network topology and corresponding vehicle frequencies.

The transportation planning process consists of five broad activities, namely: network design, frequency setting, timetable development, bus scheduling, and driver scheduling. The first two stages of the transportation planning processes represent a long-term planning that seeks to balance the competing objectives of minimizing both passenger and operator costs (Ceder & Wilson, 1986). These stages have been recognized to be the most challenging from the context of the bus planning process (Shih, Mahmassani, & Baaj, 1998). In most of the previous studies, the development of routes and frequencies setting of vehicles is performed separately to avoid extreme complications and computational intractability. In practice, both should be handled simultaneously for interaction and feedback so that the routes constructed will provide support to the defined schedule (Gundaliya, Shrivastava, & Dhingra, 2000).

The UTNDP is considered as inherently multiobjective in nature due to the different and conflicting interests of the user and the service provider. For instance, to provide a better level of service to the transit users, the routes and frequencies must be high enough to serve the demand for those routes. However, the running cost of the service provider will increase. Besides, increasing

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the bus frequency can raise the load for a given route, as transit users are likely to select such route over other alternative routes to reduce their waiting time. On the other hand, low bus frequencies are equivalent to no service in urban context because of high average load factor. As a result, the majority of these passengers often resort to other accessible transportation modes. Therefore, it is reasonable to establish a suitable trade-off level from the viewpoints of both the users and operators. Ideally, this can be achieved through the evaluation of the Pareto frontier (Mauttone & Urquhart, 2009).

Previous efforts focused more on the well-known metaheuristics such as simulated annealing (SA), genetic algorithm (GA), and tabu search (TS) to solve more practical problems of the UTNDP. However, it is desirable to explore the viability of the more recent population-based metaheuristics. In recent times, differential evolution (DE) has emerged as a simple, flexible, and efficient scheme for continuous optimization problems with considerable success. However, not much attention is given to the applicability of DE to discrete optimization problems (Das & Suganthan, 2011).

We (Buba & Lee, 2016b) recently developed an efficient algorithm for urban transit routing problem based on the DE metaheuristic. This paper now presents the extension of that research. The UTNDP is considered in a way that we simultaneously determine the edges to be included in the transit network, assemble the chosen edges into bus route, and determine bus service frequency on each of the developed routes. In the proposed algorithm, the heuristic in Mumford (2013) is used to generate the initial population of vectors for the DE to determine the optimal set of routes and the corresponding service frequency. The genetic operators of DE, namely, mutation and crossover are modified from the standard DE for exchanging solution's routes. To the best of our knowledge, there is no work on UTNDP based on DE approach reported in the literature. By adopting a design approach analogous to the one proposed by Nikolić and Teodorović (2014) and Zhao, Xu, and Jiang (2015), the candidate route sets are evaluated from the perspective of service quality. In addition, we will demonstrate that in terms of solution quality and objective value, the proposed algorithm is competitive with other approaches in the literature. The remainders of the paper are organized as follows: literature review is provided in Section 2. Section 3 describes problem formulation of the problem. Section 4 provides a brief description of the standard DE. The proposed DE framework is presented in Section 5. Comprehensive computational experiments are conducted in Section 6. The conclusions and future work are given in Section 7.

2. Literature review

Over the decades, the improvement of search algorithms together with the advancement of computing technologies have led to diverse problem-solving and optimization techniques, mostly metaheuristic approaches for the UTNDP. Specifically, methods such as SA, TS, GA, bee colony optimization (BCO), and particle swarm optimization (PSO) have played significant roles in recent research on UTNDP. Having said that, the transit planners and practitioners still consider the problem challenging (Amiripour, Mohaymany, & Ceder, 2015). In addition, the UTNDP is comprehensively surveyed in Chua (1984), Farahani, Miandoabchi, Szeto, and Rashidi (2013), Guihaire and Hao (2008), Ibarra-Rojas, Delgado, Giesen, and Muñoz (2015), Kepaptsoglou and Karlaftis (2009), and Buba and Lee (2016a).

Pattnaik, Mohan, and Tom (1998) introduced a GA to tackle the problem with the objective of minimizing the costs incurred by both the passenger and the operator. The methodology involves the use of route generation algorithm to generate a candidate route set, and a GA to determine the optimum set of the route. The fixed and variable string length codings are developed. However, the quality of the solution is not compared with benchmark network in the literature. Tom and Mohan (2003) developed a model that minimizes the overall system cost per trip. A binary string length scheme similar to Pattnaik et al. (1998) with route frequency incorporated as a variable is utilized. The methodology involves constructing a huge set of routes by a candidate route generation procedure before the optimal route set is determined by a GA. Several evolutionary operators are proposed to improve the solution quality. The model is tested on a medium-sized network in Chennai, India.

Ngamchai and Lovell (2003) presented a GA to optimize the total cost of bus transit system. Two-stage processes for the network design that first employed a route improvement procedure using evolutionary operators, then headways coordination for network efficiency improvement is proposed. Various computational experiments are performed on a theoretical network. Zhao and Zeng (2006) developed a SA-GA approach that optimizes the transfers with reasonable route directness and coverage of service. Aiming to provide a robust computational tool for transit network that are of larger instances, the method consists of a representation of route set solution search spaces, transit routes and constraints of the network, as well as a hybrid SA-GA solution scheme. The proposed approach is tested with previously published results and real-life transit network. Numerical results indicate that the hybrid model is able to solve large-scale transit network.

Fan and Machemehl (2006a) proposed a GA to systematically explore the underlying features associated with optimal UTNDP with elastic travel demand. The components of the objective function include passenger cost, operator cost, and unmet demand cost. The methodology is composed of initial candidate route set construction algorithm, a network analysis algorithm, and a GA that integrates the two components and determines the optimal route set. The GA is tested on a theoretical network and compared with local search heuristic, SA, and TS. The results indicate that the GA outperforms the local search method, and gives no worse solution quality than either SA or TS. Later in the same year, Fan and Machemehl (2006b) introduced a SA to determine optimal transit network design for a system based on buses with the level of node distribution. The optimization framework consists of a SA that integrates an initial candidate construction procedure together with network analysis algorithm to determine the optimal route network from a vast search space. The proposed SA approach is compared with a standard GA as the benchmark. In most cases, the results show that the SA outperforms the GA.

Fan and Machemehl (2008) employed a TS to solve the UTNDP with elastic travel demand. The framework of the method consists of a TS that combined the candidate route generation algorithm with network analysis algorithm. A GA is taken as the benchmark, and the TS outperformed the GA as indicated by the results. Liu, Olszewski, and Goh (2010) proposed a hybrid strategy to solve the bus route design and frequency setting problem simultaneously. The methodology involves the construction of an initial feasible candidate route sets, followed by a SA-GA to determine the best route set with the objective of minimizing the weighted combination of passenger and operator costs. The SA-GA approach is evaluated on four theoretical networks. The results indicate that the computational efficiency depends on the genetic operators used.

Szeto and Wu (2011) developed a hybrid solution procedure to simultaneously solve the transit network design and frequency setting problem with the objective of minimizing the number of transfers together with passengers' overall travel time. The methodology consists of hybridizing a GA with a neighborhood search algorithm, aiming to improve the existing bus services. Numerical experiments are conducted with different travel demand matrices. In comparison with the existing network, both the total