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Multi-objective discrete urban road network design

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ABSTRACT

This paper addresses the problem of designing urban road networks in a multi-objective decision making framework. Given a base network with only two-way links, and the candidate lane addition and link construction projects, the problem is to find the optimal combination of one-way and two-way links, the optimal selection of network capacity expansion projects, and the optimal lane allocations on two-way links to optimize the reserve capacity of the network, and two new travel time related performance measures. The problem is considered in two variations; in the first scenario, two-way links may have different numbers of lanes in each direction and in the second scenario, two-way links must have equal number of lanes in each direction. The proposed variations are formulated as mixed-integer programming problems with equilibrium constraints. A hybrid genetic algorithm, an evolutionary simulated annealing, and a hybrid artificial bee colony algorithm are proposed to solve these two new problems. A new measure is also proposed to evaluate the effectiveness of the three algorithms. Computational results for both problems are presented.

1. Introduction

Continuous growth of travel demand in urban transportation networks is one the most challenging and important issues which decision makers often face with. Some engineering solutions to deal with this issue are: road expansion, road construction, changing the configuration of transportation networks, modification of one-way street orientations, revising toll, signal, and parking charge settings, and so on. These engineering solutions can be determined either in an ad hoc manner or by formulating and then solving the Network Design Problem.

The Network Design Problem, or NDP in short, can be defined as the problem of determining the optimal engineering solutions to improve the transportation network (e.g., [12,58,59,60,11,10,66,14,48,35,61,62]). For the detailed reviews of NDP, the readers can refer to [56,38,22,45,73,20].

The NDP model has been shown to have a bi-level structure [73]. In this type of bi-level optimization problems, the The NDP model has been shown to have a bi-level network authority declares its strategy and the users respond to the strategy. Historically, bi-level optimization problems were investigated in the field of game theory. Game theory provides a framework to determine the optimal decisions of the players. The framework can be regarded as a set of coupled optimization problems. Wardrop [69] was the first one to use the concept of game theory to traffic assignment problems. In fact, the variational inequality formulation of the user equilibrium traffic assignment was the result of the finding that the conditions of equilibrium for the Nash *N*-person non-cooperative game are the same as those of a zero sum two person game. This kind of game can be modeled by a variational inequality formulation [21]. Therefore, having a close correspondence with the concept of Stackelberg or leader–follower game, this problem is formulated as a bi-level program which can be reduced into a single-level program by expressing the lower level problem as constraints. Many authors have discussed different solution methods of NDP from the view point of Stackelberg and Nash equilibrium conditions [21,24,9,75,72] and many others used these results in their network design problems.

The NDP can be categorized in terms of strategic or long-term decisions (such as street expansions or constructions), tactical or medium-term issues (like street orientations), and operational or short-term issues (like signal setting) [38]. Based on the decisions made on network topology and network parameters, the NDP can also be categorized in three types, namely the Continuous Network Design Problem (CNDP), the Discrete Network Design Problem (DNDP), and the Mixed Network Design Problem (MNDP).

The input of the CNDP is the network topology, and the output is the optimal values of continuous decision variables or network parameters, such as signal setting, toll setting, and capacity

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expansion. Some studies related to the CNDP are: [56,1,15,39,40,67].

The DNDP, in contrast, is concerned with just discrete decision variables like street orientation or street construction. This type of problem has been investigated by Steenbrink [57], LeBlanc [32], Poorzahedy and Turnquist [52], Lee and Yang [34], Drezner and Wesolowsky [18,19], Drezner and Salhi [16,17], Gao et al. [26], Poorzahedy and Abulghasemi [50], Poorzahedy and Rouhani [51], Meng and Khoo [41], and Meng et al. [42].

The MNDP or mixed network design problem, as can be implied by its name, involves both discrete and continuous network design variables. It deals with both network topology and network parameters. Compared with the CNDP and the DNDP, the MNDP has received less attention (e.g., [8,7,25,37]).

Concerning the solution methods, it should be noticed that the combinatorial nature of the DNDP and MNDP makes them much harder to solve than the CNDP. The exact method such as branch and bound algorithms can only deal with small networks which are not realistic enough. Therefore, meta-heuristics and their hybrids have been commonly developed or applied to solve the DNDP and MNDP with large, realistic networks.

There are a number of observations that can be drawn from the existing NDP literature, which are the base of motivation for investigating the problem introduced in this paper. These observations are concerned with the type and number of objective functions, decision variables and their combinations.

First, among the above NDP studies, we observe that total travel time is a widely used objective function but reserve capacity is not. Reserve capacity is defined as the largest multiplier applied to a given, existing demand matrix without violating the street flow capacities, and has been previously investigated for network intersections by Webster and Cobbe [70], Allsop [2], and Wong [71]. The reserve capacity as an objective function of NDP was first suggested by Yang and Bell [73] but has only been adopted in a few CNDP papers such as Ziyou and Yifan [80] and Yang and Wang [76]. The reserve capacity concept has not been considered in MNDP studies, and in only one DNDP study [43].

Indeed, minimizing the total travel time or cost is not equivalent to maximizing reserve capacity [76]. Moreover, according to Yang and Bell [74], there are at least two advantages of adopting reserve capacity as an objective function. First, the occurrence of capacity paradox can be avoided when reserve capacity is considered in network design. Second, it allows us to predict how much additional demand can be accommodated by the road network after improvement, and hence other related policies for traffic restraint and growth can be established. Third, the upper-level objective function takes a simple linear form and hence the problem is much easier to solve than the NDP with other non-linear objective functions. Fourth, the optimal decision based on reserve capacity is not sensitive to the demand level. This is desirable when uncertainty exists in traffic demands. All these facts seem to indicate that reserve capacity should be considered in DNDPs and MNDPs.

Second, we observe that most NDP papers deal with just one objective function for simplicity. Only few studies have considered multiple objectives for the NDP (e.g., [23,8,7,53,76]). But as known, both the network authority and the network users in urban transportation areas are concerned with a wide range of evaluation criteria and the problem is multi-objective in nature. The only multi-objective study with reserve capacity is done with Wang and Yang [76], which consider reserve capacity and total travel time as the two objectives.

The third observation suggests that apart from using single strategic, tactical or operational decisions in discrete network design, their combination has been studied in a number of studies. For example, the following types of combinations of strategic and tactical decisions can be distinguished in the literature: (a) street expansion and new street construction (e.g. [52,50,51,73,78]), (b) street orientation and lane allocation (e.g. [8]), (c) new street construction and street orientation (e.g. [19]), and (d) street expansion with street orientation and lane allocation (e.g. [43]).

In regard to reserve capacity optimization for DNDPs, Miandoabchi and Farahani [43] is the only existing study in the literature that considers various decisions to improve reserve capacity. While the construction of new streets can increase the capacity of the network like other strategic and tactical decisions, this improvement strategy has not been used for improving the reserve capacity. Thus, this strategy can be considered together with other decisions simultaneously to further improve the reserve capacity.

Following the above considerations, in this paper we study the discrete network design problem with multiple objective functions, having the reserve capacity maximization as one of the objective functions. Explicitly, the following decisions are investigated:

(a) adding lanes to the existing network streets,
(b) constructing new streets,
(c) determining the orientation of one-way streets, and
(d) lane allocations in two-way streets.

Although the first two decisions are strategic and the last two are tactical in the NDP context, simultaneously considering all of them can lead to better results in terms of the network performance. Modifying two-way streets to one-way streets can result in improved network performance with fewer requirements for street construction and expansion projects. This can be very advantageous, since such projects require high levels of budget and also require the utilization of land that is expensive and valuable in urban areas.

The proposed problem has three objective functions; reserve capacity and two new travel related objective functions. These objective functions are included, as the maximization of reserve capacity cannot always minimize travel time related measures [76], which are concerned by network users and network authority.

We define two variations of the DNDP: one restricts two-way links in which there is the same number of lanes in each direction and the other one does not, i.e. the number of lanes in one direction can be different from that of the opposing direction. The problems are formulated as bi-level mathematical programs with equilibrium constraints (MPEC), in which each problem model is bi-level, Stackelberg model with two lower level problems. The inherent complexity of the proposed problem variations and their non-convex nature suggests the application of meta-heuristic solution procedures. Since the problems are new and there are many constraints, directly applying existing metaheuristic to solving them is not possible. In this regard, we developed three new multi-objective hybrid evolutionary algorithms. All algorithms generate as set of Pareto-optimal solutions. To summarize, the following are the contributions of the paper in the literature:

1. Using the combination of street construction with other strategic and tactical decisions to improve the reserve capacity;
2. Adapting a unique combination of triple objective functions in the DNDP;
3. Proposing two new travel-time related objective functions; and
4. Developing three improved meta-heuristics for the two new problems.

Table 1 compares the proposed problem in this paper with the problems examined in the existing NDP studies. In this table, only studies with strategic or tactical decision variables are included.