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Continuous Optimization

Mixed network design using hybrid scatter search

Zohreh Khooban[a], Reza Zanjirani Farahani[b,*], Elnaz Miandoabchi[c], W. Y. Szeto[d]

[a] System Planning Department, Farab Co. (Energy and Water Projects), Tehran, Iran
[b] Operations Research and Management Science Research Group, Department of Management, Kingston Business School, Kingston University, UK
[c] Logistics and Infrastructures Research Group, Institute for Trade Studies and Research, Tehran, Iran
[d] Department of Civil Engineering, The University of Hong Kong, Hong Kong

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ABSTRACT

This research proposes a bi-level model for the mixed network design problem (MNDP). The upper level problem involves redesigning the current road links' directions, expanding their capacity, and determining signal settings at intersections to optimize the reserve capacity of the whole system. The lower level problem is the user equilibrium traffic assignment problem. By proving that the optimal arc flow solution of the bi-level problem must exist in the boundary of capacity constraints, an exact line search method called golden section search is embedded in a scatter search method for solving this complicated MNDP. The algorithm is then applied to some real cases and finally, some conclusions are drawn on the model's efficiency.

1. Introduction

The Urban Network Design Problem (UNDP) is a classic decision problem in transportation planning and is concerned with the improvement of urban transportation network systems in order to respond to the growth of travel demand. Nowadays, studying urban transportation network systems is crucial because the speed of the increase in urban transportation demand is higher than that in expanding the transportation system, so this system could not accommodate the increase in demand, while resources available for expanding the system capacity remain limited (Yang & Bell, 1998a). Until now, most UNDPs have been formulated as bi-level problems which in the upper level problem, several investment decisions are made by system owners or planners to optimize the desired objective function.

When it comes to decision variables in the upper level problem, UNDPs are divided into three different classes. The first class is known as the discrete network design problem (DNDP) which only involves discrete decisions (e.g., Long, Gao, Zhang & Szeto, 2010; Long, Szeto & Huang, 2014; Miandoabchi, Daneshzand, Farahani & Szeto, 2015; Miandoabchi, Farahani, Dullaert & Szeto, 2012b; Miandoabchi, Farahani & Szeto, 2012a; Szeto, Wang & Wong, 2014). Typical discrete decisions in the DNDP are constructing new streets, adding new lanes to the existing streets, determining the street directions and their lane allocations, and designing the turning restrictions at intersections. The second type is the continuous network design problem (CNDP) (e.g., Jiang & Szeto, 2015; Lo & Szeto, 2009; Sun, Gao, Szeto, Long, & Zhao, 2014; Szeto, Jiang, Wang & Sumalee, 2015; Szeto & Lo, 2006; 2008) which deals only with continuous variables such as signal setting of intersections, determining road tolls, and street capacity expansion. The last type is named the mixed network design problem (MNDP) which involves both continuous and discrete variables. There are few research papers in this category. Some recent related researches are Cantarella, Pavone and Vitetta (2006), Dimitriou, Tsekeris and Stathopoulos (2008), Zhang and Gao (2009), and Gallo, D'Acierno and Montella (2010). The problem in this research is a kind of MNDP because several discrete and continuous variables are involved.

According to Magnanti and Wong (1984), the decisions in UNDPs can be grouped into strategic, tactical, and operational types, each of which deals with long-term, mid-term, and short-term network design issues, respectively. This paper investigates the strategic decision of street capacity expansion, the tactical decision of one-way two-way streets configuration, and the operational decision of signal setting at intersections. After that, a number of comprehensive reviews have been published by Friesz (1985), Migdalas (1995), and Yang and Bell (1998a) which focus specifically on UNDP. Recently, Farahani, Miandoabchi, Szeto and Rashidi (2013) also conducted a comprehensive review on UNDPs' definitions, classifications, objectives, constraints, and solution methods, objectives, constraints, and solution methods, which encompass both road and public transit network design problem.

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[*] Corresponding author. Tel.: +44 020 8517 5098, +44 020 8417 5098; Fax: +44 020 8417 7026.
E-mail address: zanjiranireza@gmail.com, Rezazanjirani@yahoo.com (R.Z. Farahani).

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The street orientation was first considered by Lee and Yang (1994) as the sole network design decision in a bi-level model to maximize the total travel time of the network. After that, in some research, the single level modeling approach along with all or nothing traffic assignment was used for optimizing the street orientations (e.g., Drezner & Salhi, 2000; 2002; Drezner & Wesolowsky, 1997; Drezner & Wesolowsky, 2003). All the other related studies adopted bi-level models with the user equilibrium traffic assignment approach for optimizing the street orientations and other discrete or continuous decisions (e.g., Cantarella et al., 2006; Gallo et al., 2010; Miandoabchi, Daneshzand, Szeto & Farahani, 2013; Miandoabchi & Farahani, 2011).

Street capacity expansion can be considered as the most prevalent decision in UNDP studies. Although this has been modeled in most of the previous research as a continuous variable to simplify the solution method for solving the problem, it has been modeled as a discrete variable in a number of other studies. For example, Steenbrink (1974), LeBlanc (1975), Poorzahedy and Turnquist (1982), Yang and Bell (1998b), Poorzahedy and Abulghasemi (2005), Poorzahedy and Rouhani (2007), Szeto et al. (2010), Miandoabchi and Farahani (2011), and Miandoabchi et al. (2013) have investigated discrete capacity expansion in DNDPs. In MNDPs, only Dimitriou et al. (2008) have modeled this as a discrete variable.

The most common objective function among UNDPs is the minimization of total travel time or cost across the network. Other used objective functions include consumer/social surplus, total distance traveled, minimum construction or construction and travel cost, reserve capacity, etc. In this research, the maximization of reserve capacity is adopted as the objective function. Webster and Cobbe (1966), Allsop (1972), and Wong (1996) investigated this concept for network intersections. However, using this concept as the objective function of the UNDPs was only suggested in the study by Yang and Bell (1998a). Yang and Bell (1998b) introduced a paradox related to network design problems and demonstrated that using the concept of reserve capacity into a network design problem is the best way to avoid this paradox. They also mentioned several advantages of the capacity-based formulation for UNDPs such as formulation simplicity. There are many alternative factors to measure the reserve capacity of a system, but the common one is the multiplier of the origin-destination (O-D) demand matrix of network. In this way, reserve capacity can be defined as the largest multiplier which can be applied to the existing travel demand matrix of the concerned network, such that the street flow capacities are not violated. Reserve capacity is often captured in the CNDPs, while in DNDP only Gao, Wu and Sun (2005), Miandoabchi and Farahani (2011), and Miandoabchi et al. (2013) have exploited this as the objective function. However, there is no research on using this as the objective function in MNDPs.

In this paper, an MNDP is introduced to maximize the reserve capacity of the whole network. The problem involves two types of discrete variables, namely (i) capacity expansion and orientation of the existing streets, and (ii) one type of continuous variable, i.e., signal setting. The common approach of bi-level programming is used to model the proposed problem, in which the simple deterministic user equilibrium assignment problem is used in the lower level problem. Table 1 demonstrates a summary on the related studies and compares the main attributes of the problem addressed in this research with them.

In this paper, a hybrid scatter search (HSS) algorithm is developed to solve the proposed problem because of the complexity and non-convexity of MNDPs. In the literature, Gallo et al. (2010) used scatter search to solve their problem, but there are some significant differences between these two works: first, our model is more complicated because of adding street capacity expansion as a discrete variable and also incorporating the reserve capacity concept in the problem; besides, the proposed model in Gallo et al. (2010) did not consider capacity constraints which made their solution

Table 1
A summary of the related studies in NDPs.

Reference	Objective	Traffic assignment	Demand	Decision						Solution Method
				Discrete				Continuous		
				Making some streets one-way	Street capacity expansion	Constructing new streets	Orienting sequences of streets	Traffic light setting	Street capacity expansion	
Wong and Yang (1997)	Max. reserve capacity	DUE	F						•	Sensitivity analysis-based algorithm
Yang and Bell (1998a)	General weighted sum multi-objective	DUE	F			•			•	Enumeration scheme with other methods
Yang and Bell (1998b)	Max. reserve capacity	DUE	F						•	-
Ziyou and Yifan (2002)	Max. reserve capacity	DUE	F					•	•	Sensitivity analysis-based method
Cantarella et al. (2006)	Min. total travel time	DUE	F				•	•		Hill climbing, simulated annealing, tabu search, genetic algorithm, hybrids of tabu search
Zhang and Gao (2009)	Min. total travel cost + construction cost	DUE	F			•			•	Gradient-based method with penalty function
Miandoabchi and Farahani (2011)	Max. reserve capacity	DUE	F	•	•					Hybrid genetic algorithm and an evolutionary simulated annealing
Miandoabchi et al. (2013)	Max. reserve capacity + Min. two travel time related objective functions	DUE	F	•	•	•				Multi-objective algorithms: Hybrid genetic algorithm, evolutionary simulated annealing, and artificial bee colony
Gallo et al. (2010)	Min. Total travel time	SUE	F	•				•		Scatter search algorithm
This Research	Max. reserve capacity	DUE	F	•	•			•		Hybrid scatter search algorithm