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Matheuristics for the single-path design-balanced service network design problem

Xiangyong Li [a], Kai Wei [a,*], Y.P. Aneja [b], Peng Tian [c], Youzhi Cui [d]

[a] School of Economics & Management, Tongji University, Shanghai 200092, China
[b] Odette School of Business, University of Windsor, Windsor, Ontario, Canada
[c] Antai College of Economics & Management, Shanghai Jiao Tong University, Shanghai 200052, China
[d] IBM China, 399 Keyuan Road, Shanghai 201203, China

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ABSTRACT

We introduce and study the single-path design-balanced service network design problem, where flow of a commodity must use only one path from origin to destination. We present an arc-based formulation. We propose two approaches respectively based on matheuristics: local branching and relaxation induced neighborhood search. These approaches hybridize metaheuristic strategies and mathematical programming, and use an idea of defining neighborhoods as small mixed integer programs (MIP), and exploring neighborhoods using MIP solvers. We also present an implementation combining these two approaches. In addition, we propose a Lagrangian heuristic to generate a starting solution. Our computational results demonstrate effectiveness of these approaches.

1. Introduction

Network design models are widely used in many applications including logistics, transportation and telecommunication [20,9,23,5]. In these applications, several commodities need to be transported from their origins to destinations over a network with limited capacity associated with each network arc. When there are also fixed-charge costs for using network arcs, the problem is termed as a fixed-charge capacitated multicommodity network design problem [17,16,10]. Service network design (SND) is an important extension of network design problem [9], where links represent "services" in the transportation system [5]. The SND models address decisions related to the planning, selection and eventually, scheduling of services in consolidation-based transportation systems [23]. The output of the SND is a service plan for all demands. Such a service plan can be repeatedly operated during a given time period (e.g., one day, one week, or one month). For specific applications of SND models, see reviews by Christiansen et al. [6] for maritime transportation, Cordeau et al. [7] for rail transportation, and Crainic and Kim [12] for intermodal transportation.

With increasing pressure on reducing service costs and providing high-quality service, transportation carriers need to improve efficiency of their transportation systems. To do so, service network design planning problems with "Asset Management" (SNDAM) have received considerable research interest lately [23]. The SNDAM model emphasizes using assets continuously following circular routes to improve operation efficiency in transportation systems. The early works addressing asset-management issues in service network design include Kim et al. [19], Armacost et al. [2], and Barnhart et al. [4] for multimodal express network design, and Smilowitz et al. [27] for multimodal package delivery with design-balance constraints for ground vehicles. In all these papers, there is an assumptions of an equal number of assets (arcs) entering and leaving each node in the network. The solution methods use ad hoc techniques that take advantage of the specific structure of the problems.

Pedersen et al. [23] introduced the design-balanced constraints in the SND. The design-balanced constraints emphasize that assets used in the transportation system should be repeatedly operated in the sense that each asset must go back to its starting point at the end of each planning horizon. This requires the same number of assets entering and leaving at each terminal. Pedersen et al. [23] studied the design-balanced capacitated multicommodity network design problem (DBCMND) and proposed a two-phase tabu search metaheuristic. They built neighborhoods by adding or dropping arcs from the design vector of the incumbent, and implement an infeasibility-monitoring scheme to guide the search process for finding feasible solutions of the DBCMND. Vu et al. [29] proposed a

* Corresponding author.
E-mail addresses: xyli@tongji.edu.cn (X. Li), 0359weikai@tongji.edu.cn (K. Wei), aneja@uwindsor.ca (Y.P. Aneja), ptian@sjtu.edu.cn (P. Tian), jcui@cn.ibm.com (Y. Cui).

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three-stage metaheuristic for the DBCMND, which combines an exact and a neighborhood based method. Crainic et al. [11] introduced a heuristic, which combines column generation and slope scaling method, to solve the service network design problem with resource constraints. Chouman and Crainic [5] proposed a cutting-plane metaheuristic, which combines an exact lower bound computing method and a variable fixing procedure and introduce a learning mechanisms into the proposed cutting-plane metaheuristic. This cutting-plane procedure solves linear programming relaxation (LP-relaxation) of the DBCMND to generate violated inequalities.

To the best of our knowledge, in all existing works on the DBCMND, researchers have assumed that flow of one commodity can be split and may use more than one path from origin to destination. However, such an assumption may not cover some applications in transportation systems. For example, consider operations of express package delivery in which shipments, each package with a specific origin and destination, requires being routed over a transportation network [3]. Each set of packages with common origin and destination is considered as a commodity and often must be transported along a single path in the network. Furthermore, in a HAZMAT (hazardous material) transport network design, such dangerous goods should be routed along a single origin-destination path in order to reduce transport risk to the prescribed level in practice [28]. In this paper, we introduce single-path constraints in the DBCMND, and thus study a constrained version of the linear DBCMND. This new problem is called the single-path design-balanced service network design problem (SPDBND). In the SPDBND, flow of each commodity can only use one path from its origin to its destination. The single-path requirements force the flow variables to be binary in the mathematical formulation, and results in many more binary variables in the formulation of the SPDBND, in comparison with that of the DBCMND. This makes the introduced SPDBND much harder to solve than the DBCMND. In some cases, it is even difficult to find a feasible solution.

The goal of this paper is to introduce single-path constraints in the well-known DBCMND, and study the new service network design problem, SPDBND. We first present an arc-based integer programming formulation. As the SPDBND is a special case of network design [20], it is also an $\mathcal{NP}$-hard problem. Therefore, it is impractical to use exact algorithms to solve practical instances of this problem. Consequently, we present approaches based on matheuristic strategies known as local branching (LB) [14], and relaxation induced neighborhood search (RINS) [13]. The LB and the RINS are matheuristics that combine mathematical programming techniques with typical metaheuristic ingredients including neighborhood definition, local search, intensification and diversification. The LB approach builds neighborhoods by introducing the so-called local branching constraints in the mixed integer programming (MIP) model of the SPDBND, and thus partition the solution space into two subregions. One of the subregions has a certain number of variables different from the current incumbent. An MIP solver is used to explore this subregion heuristically to obtain a new incumbent. Based on the new incumbent, the remaining region is partitioned into two parts, iteratively. The LB approach alternates between “high-level branchings” to define the solution neighborhood and, “low-level tactical branchings” to explore them. We implement the LB approach as a heuristic by putting a time limit to the total computation and exploration of each subregion. The RINS approach solves the arc-based model of the SPDBND, using an MIP solver, and every specific number (e.g. f) of nodes in the branch-and-bound (B&B) search tree, implements a neighborhood exploration to improve the quality of the current incumbent. The neighborhood corresponds to a sub-MIP built from the original MIP model by fixing variables that have the same values in the incumbent and the current continuous relaxation, and explored by solving this much smaller restricted MIP model. The LB and RINS approaches both depend on the availability of a starting feasible solution to the SPDBND. Coexistence of single-path and design-balanced constraints makes it very difficult to find a feasible solution, even if one exists. We, therefore, introduce a Lagrangian heuristic which includes two steps: (1) Obtain a feasible solution by adjusting solution to the LP relaxation of the proposed arc-based formulation; (2) get better feasible solutions by adjusting solution to each Lagrangian relaxation of the formulation. Since the LB and RINS approaches can be individually implemented as a local search approach, we further present an implementation hybridizing them. To see how the proposed three approaches perform when applied to the SPDBND, we compare them and MIP solver CPLEX. Our approaches were terminated after 600 s, whereas CPLEX was implemented respectively with three time limits: 600, 1800 and 3600 s. Numerical experiments based on 31 benchmark instances show that our approaches are computationally efficient for the SPDBND. With identical time limit of 600 s, these three presented approaches significantly outperformed CPLEX. In comparison of CPLEX with 1800 s, the RINS approach and the hybrid approach both reached better results. In comparison with CPLEX with 3600 s, the RINS approach yields the best results.

In our view, contributions of this paper include the following:

(1) We introduce single-path constraints in designing service network schedules, and study a new service network design problem: single-path design-balanced service network design problem.
(2) We present a Lagrangian relaxation based approach to find feasible solutions to the SPDBND instances.
(3) To solve the new service network design problem, we propose two matheuristics respectively based on the local branching and relaxation induced neighborhood search. In addition, we also propose an implementation hybridizing these two approaches.
(4) We implement and evaluate our algorithms using a set of 31 benchmark instances. Our computational results show that both the LB approach and the RINS approach are computationally efficient matheuristics for the SPDBND. In general, the RINS approach outperformed the LB approach over most of the instances. The hybrid implementation of these two approaches further improved results for some instances.

The remainder of this paper is organized as follows. In Section 2, we present the problem definition and mathematical formulation of the SPDBND. We propose a Lagrangian heuristic to generate feasible solutions in Section 3. We detail the presented matheuristics in Section 4, and present experimental results in Section 5. Finally, we conclude this work in Section 6.

2. Problem description and mathematical formulation

The introduced SPDBND is a variant of the DBCMND, which is defined in the context of the scheduled service network design problem with asset-management constraints [23,29]. Given a potential network in terms of arcs and a set of node-to-node demands (commodities), one must select a set of arcs such that in the resulting network, each commodity can be transported from its origin to destination along a single path at minimum cost, while enforcing the design-balanced constraint: for each node, the number of design arcs entering that node equal the number of design arcs leaving that node. The objective is to minimize the sum of transportation costs and fixed costs of used arcs.