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A column generation based approach for the Train Network Design Optimization problem

Jian Gang Jin [a], Jun Zhao [b], Der-Horng Lee [a,*]

[a] Department of Civil & Environmental Engineering, National University of Singapore, Singapore
[b] School of Transportation & Logistics, Southwest Jiaotong University, Chengdu, China

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ABSTRACT

This paper investigates the Train Network Design Optimization problem arising from railroad industry which involves the integration of three inter-related decision sub-problems: train routing which is to identify origin, destination and itinerary for individual trains; block-to-train assignment detailing the block movements with trains and swaps between trains; and crew-to-train assignment specifying the crew services for train routes. A column generation based hierarchical approach with two stages is designed: the first stage generates a pool of promising train routes iteratively based on the crew segments by the column generation technique; and the second stage develops an integer linear programming model for the subsequent decisions including train route selection and block-to-train assignment. Numerical experiments with realistic test instances are conducted and the outcome demonstrates the capability of the proposed approach in solving the Train Network Design Optimization problem competently.

1. Introduction

Being an important logistic system supporting global and regional economy, railroad freight transportation handles the movement of millions of cargo shipments on a 24/7/365 service. Behind the scene there exist a broad spectrum of complex and challenging railroad operations. Various decision problems emerge in the railroad planning and operation stages. This makes railroad freight transportation an ideal area for applying *operations research* techniques to support the planning and operation processes and also to advance the efficiency and reliability. Decision problems of railroad operations can be organized into strategic, tactical and operational levels (Assad, 1980). At the strategic planning level, resource acquisition and the construction of the railroad infrastructure in the long-term should be determined. With the given physical railroad network, tactical planning is conducted to construct a service network based on the freight transportation demand from a medium-term planning perspective (monthly or weekly). The output of the tactical planning problems is used as the guideline for the scheduling of daily activities at the operational level.

Given a physical network consisting of rail stations and tracks with restricted capacity and shipments with various origins and destinations, a common planning method is firstly to consolidate shipments into blocks based on cargo attributes, subsequently to combine blocks into trains, and finally to assign locomotives and crews to the created trains. Although straightforward, this planning method for railroad freight transportation has been widely adopted and is still well employed currently by railroad practitioners. Typical decision problems involved in the tactical level of railroad freight transportation

* Corresponding author. Address: Block E1A #07-16, 1 Engineering Drive 2, National University of Singapore, Singapore 117576, Singapore. Tel.: +65 6516 2131; fax: +65 6779 1635.
E-mail addresses: jin_jiangang09@nus.edu.sg (J.G. Jin), dhl@nus.edu.sg (D.-H. Lee).

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generally include railroad blocking problem, train routing problem, block-to-train assignment problem, locomotive assignment problem and crew assignment problem. Readers may refer to Cordeau et al. (1998), Ahuja et al. (2005), Harrod and Gorman (2010), and Nemani and Ahuja (2010) for comprehensive surveys. In this study, we investigate the combined train routing, block-to-train assignment and crew-to-train assignment problem which is also referred as *Train Network Design Optimization* problem in the railroad freight transportation area. Actually, Train Network Design Optimization problem plays an essential role in the service network design at the tactical decision level of railroad freight transportation. However, due to the increased difficulty from the integration of various decisions, this problem, to the best of our knowledge, has not been explored in the research community until the INFORMS Railway Application Section organized a problem solving competition in 2011 (INFORMS, 2011).

This study is the first attempt to address the Train Network Design Optimization problem integrating the train routing, block-to-train assignment and crew-to-train assignment decisions. State-of-the-art mathematical optimization techniques are utilized to build a unified framework for the integrated problem. To address the integrated problem, we design a column generation based approach with two stages. The train routing and crew-to-train assignment is integrated in the first stage to generate a pool of promising train routes with the aid of column generation technique. In the second stage, we model the train route selection and the block-to-train assignment problem as an integer program. Several operational costs and constraints (train work event, block swap operation, crew and train imbalance) that were not considered in previous literature are specifically included in the model formulation. Numerical experiments with realistic test instances are conducted and the outcome demonstrates that the proposed approach is able to generate good train plans competently.

The remaining paper is organized as follows. A brief literature review of relevant studies is presented in Section 2. In Section 3, we provide a detailed description and formal definition for the Train Network Design Optimization problem. Section 4 presents the implementation procedures of the two-stage solution approach based on column generation strategy. Two realistic instances are used to test the effectiveness and efficiency of the proposed approach in Section 5. Finally, Section 6 concludes this paper.

2. Literature review

In the past few decades, many efforts have been made in the literature to tackle various decision problems of railroad freight transportation.

Models and algorithms for the railroad blocking problem have been studied by Bodin et al., 1980, Newton et al. (1998), Barnhart et al. (2000), Ahuja et al. (2007), Yaghini et al. (2011), and Yue et al. (2011). Bodin et al. (1980) formulated the railroad blocking problem as a mixed integer nonlinear programming model. Newton et al. (1998) and Barnhart et al. (2000) both proposed a network design formulation with side constraints for the railroad blocking problem which were solved by branch-and-price algorithm and Lagrangian relaxation algorithm, respectively. In their approaches, column generation technique is employed to generate block path candidates. Focusing on algorithm efficiency, Ahuja et al. (2007) developed a very large-scale neighborhood search algorithm to solve the real-life railroad blocking problem. Yue et al. (2011) and Yaghini et al. (2011) both designed ant colony algorithms to build blocking plan for real-life instances. Among the approaches introduced above for the railroad blocking problem, the approaches of Bodin et al. (1980), Newton et al. (1998), and Barnhart et al. (2000) can be classified as exact approaches, and the remaining approaches are all heuristic methods.

Jha et al. (2008) was the first effort to address the daily version of the block-to-train assignment problem with given blocking plan and train schedule. They defined the problem on a special constructed time-space network and provided arc-based and path-based formulations. Exact and heuristic solution approaches were both developed. In the exact approach, the problem was directly solved by CPLEX using the path-based formulation. Heuristic methods based on Lagrangian relaxation and greedy construction were also designed.

Railroad service network design is another important tactical decision problem as studied in Crainic et al. (1984), Keaton (1989, 1992), Marín and Salmerón (1996), Gorman (1998), and Lulli et al. (2011). Crainic et al. (1984) developed a heuristic algorithm based on decomposition and column generation principles. Keaton (1989, 1992) designed a Lagrangian relaxation heuristic approach for the static railroad service network design problem. Marín and Salmerón (1996), Gorman (1998), and Lulli et al. (2011) developed meta-heuristic based methods including simulated annealing, hybrid tabu-enhanced genetic algorithm and specialized tabu search procedure to solve their practical problems.

Haghani (1989) and Zhu et al. (2011) were two typical efforts in addressing the dynamic integration of car blocking, train routing and block-to-train assignment problem at the tactical level. Integrating the train routing, block-to-train assignment and empty car and locomotive distribution problem, Haghani (1989) constructed a one-layer time-space network and developed a mixed integer nonlinear program. The complex model was solved by a heuristic decomposition technique exploiting the special structure of the original problem. Zhu et al. (2011) firstly integrated car blocking, train routing, block-to-train assignment and car distribution problem on a three-layer time-space network to simultaneously capture the detailed movement of trains, blocks and cars in the railroad network over a planning horizon. After determining the train and shipment route candidates, the problem was formulated as a mixed integer linear programming model and solved it by a hybrid heuristic combining slope scaling, enhanced by long-term memory-based perturbation, and ellipsoidal search.