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The congested multicommodity network design problem

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ABSTRACT

This paper studies a version of the fixed-charge multicommodity network design problem where in addition to the traditional costs of flow and design, congestion at nodes is explicitly considered. The problem is initially modeled as a nonlinear integer programming formulation and two solution approaches are proposed: (i) a reformulation of the problem as a mixed integer second order cone program to optimally solve the problem for small to medium scale problem instances, and (ii) an evolutionary algorithm using elements of iterated local search and scatter search to provide upper bounds. Extensive computational results on new benchmark problem instances and on real case data are presented.

1. Introduction

Congestion is one of the causes for delay at freight hubs, e.g. yards, ports, or even cities. On 7 May 2012, a headline of a The New York Times article read "Freight Train Late? Blame Chicago", reporting that "Shippers complain that a load of freight can make its way from Los Angeles to Chicago in 48 h, then take 30 h to travel across the city. A recent trainload of sulfur took some 27 h to pass through Chicago – an average speed of 1.13 miles per hour, or about a quarter the pace of many electric wheelchairs." [1] The article also claimed that the freight volume in the United States is projected to grow by at least 80% in the next 20 years which will have significant knock-on effects on delays. It is a well known fact that freight cars, in a rail network, spend most of their time in terminals or classification yards (Li et al., 2014). This is due to the fact that the same facility has to be used for consolidation and classification operations for a variety of vehicles carrying different types of freight. In these yards, cars usually go through the following operations: inspection, classification, assembly, accumulation and connection. As Fernandez et al. (2004) point out, the classification process constitutes the fundamental source of delay in the terminals, and this increases with the amount of classification, which is correlated with the number of cars to classify.

Congestion is prevalent not only in rail but in other transportation networks and modes as well, and has been the subject of recent research. For example, Tirachini et al. (2014) looked at the interplay of traffic congestion and bus crowding in public transport. By explicitly considering the social impact of congestion, the authors experimented with various variables of the system and found, among others, that an optimal frequency of the buses results from the trade-off between the passenger crowd in the bus and the traffic congestion on the streets. The most common way of reducing the assocaited social cost is by charging additional costs and preventing travelers from using particular transportation links (and/or nodes), thus reducing

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[1] http://www.nytimes.com/2012/05/08/us/chicago-train-congestion-slows-whole-country.html.

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congestion (Yao et al., 2010; Laval et al., 2015). Fosgerau (2011) proved that a fast lane can replace congestion tolls at peak times, putting the focus on the balance between the capacity of the network and congestion pricing.

Traffic congestion is also linked with increased vehicle idling, acceleration and braking, which in turn increases engine related emissions. There is a rich literature on the environmental impacts of transportation and distribution logistics, with a particular focus on emissions (e.g., Demir et al., 2014). Chen and Yang (2012) presented different toll schemes for minimizing both congestion and emissions in a bi-objective optimization approach. Franceschetti et al. (2013) looked at the impact of the time spent on a route on the total emissions. In particular, the objective function accounts for traffic congestion which, during peak hours, slows down the vehicles and increases emissions. The proposed model determines the optimum speed for a vehicle on each link of a route aiming at minimizing an objective function that includes emissions. Koç et al. (2014) studied the problem of routing of a heterogeneous fleet of vehicles using environmental objectives.

Designing and building a robust transportation network is a difficult and a multi-faceted decision problem of strategic importance. The fixed-charge multicommodity network design (MCND) model is extensively used to represent a wide range of planning and operation management problems in transportation, telecommunications, logistics and production. In its general form, the network design problem consists of designing a network on a given graph by selecting links to connect a set of nodes and to determine the amount of flow on each link such that the demand of each node for a set of commodities is satisfied. The objective is to minimize the total cost of establishing the links and flows. This basic variant is usually referred to as the *uncapacitated network design problem*, which has extensions incorporating additional restrictions, such as capacity limits on the amount of demand that may be transported on the links. Interested readers on the problem may consult the surveys by Magnanti and Wong (1986), Minoux (1986) and Crainic (2000).

In this paper, we model and study the fixed-charge MCND problem (MCNDP) where congestion at nodes (e.g., yards) is explicitly taken into consideration. This problem, named as the *congested multicommodity network design problem* (cMCNDP), is what we believe to be one of the first to incorporate congestion into this particular setting. Our primary motivation stems from the application of this model in planning freight rail transportation systems and to be able to explicitly capture congestion in the respective models and solution methods. The problem considered here also allows for capacity expansion (Liu et al., 2008) for reducing congestion. The contribution of this study is twofold: (a) to describe a reformulation of problem as a mixed integer second order cone program (MISOCP) which is used to optimally solve the problem for small to medium scale instances, (b) to present an evolutionary heuristic using iterated local search and scatter search.

The rest of the paper is structured as follows. Section 2 provides background on modeling delay. Section 3 formally describes the problem and provides the notation as well as a small numerical example. Section 4 describes an integer programming formulation and the MISOCP reformulation. Section 5 describes the evolutionary algorithm and all of its components. Section 6 presents results of extensive computational experiments on a large set of augmented benchmark instances and on real case data. Conclusions are given in Section 7.

2. Modeling delay

There are various approaches to model yard delays, simulation and queueing models being two of them. The latter are more attractive in the sense that they can be used to derive analytical expressions and are easy to incorporate in tactical decision models. Crainic (2003) mentions that "most time-related functions are built to reflect the increasingly larger delays that result when facilities of limited capacity must serve a growing volume of traffic. Such congestion functions are typically derived from engineering procedures and queuing models".

Various analytical expressions have been proposed in the literature to model yard delays. Petersen (1977a,b) proposed several models for different components of the classification process and studied models that are based on the physical characteristics of the yard. Later, Turnquist and Daskin (1982) proposed a batch arrival queuing model for the same operation. These two approaches are based on individual characteristics of the yard. Crainic et al. (1984) argued that such precise data may be difficult to obtain and may not be necessary within a tactical level planning perspective and proposed two analytical formulas to calculate classification delays, both based on the $M/M/1$ queueing model. The first and the one relevant to our discussion can be used to calculate the mean classification delay at a yard and is as follows:

$$\frac{Tt}{T - tf}, \tag{1}$$

where T denotes the length of the planning period, t is the mean service time for a yard and f is the total amount of traffic to be classified at this yard. Fernandez et al. (2004) proposed to calculate classification delays, not based on trains, but based on individual freight cars. The authors argued that such an approach will result in a more precise and reliable modeling of classification delays. The expression they propose instead to calculate the average classification delay for a freight car in a yard is the following:

$$F + \beta\left(\frac{f}{S}\right)^{\alpha}, \tag{2}$$

where F is the classification delay for a freight car under free flow conditions, f denotes the amount of freight cars to be classified in the yard during the period of analysis, S is the classification capacity of the yard over the time of analysis, and β, α are