Computers & Operations Research 77 (2017) 32–43

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

Lane covering with partner bounds in collaborative truckload transportation procurement

Gültekin Kuyzu

Department of Industrial Engineering, TOBB University of Economics and Technology, Ankara, Turkey

ARTICLE INFO

Article history:
Received 11 April 2015
Received in revised form
6 April 2016
Accepted 20 July 2016
Available online 25 July 2016

Keywords:
Lane covering
Collaboration
Transportation
Column generation
Branch-and-price

ABSTRACT

In collaborative truckload transportation procurement, the collaborating shippers aim to jointly identify and submit tours with little or no asset repositioning to a carrier, as opposed to submitting individual lanes, in return for more favorable rates. In order to maximize savings, the shippers must solve a Lane Covering Problem (LCP), which in more mathematical terms means to cover a subset of arcs in a directed graph by a set of constrained cycles with minimum total cost. Previous works in the literature have proposed effective greedy algorithms or the solution of the NP-Hard LCP variants. This paper incorporates a new constraint into the LCP, motivated by the need to limit the number of partners with whom the collaborative tours must be coordinated. An integer programming model is formulated, and column generation and branch-and-price approaches are developed for the solution of the resulting LCP variant.

1. Introduction

Collaboration has become one of the key strategies to achieve efficiency in modern supply chain management. In traditional supply chains, companies have focused on improving their own internal business processes when faced with pressures to operate more efficiently. Increasing pressure due to fierce price competition, scarce resources, climate change, security and new regulations have forced companies to seek breakthrough solutions which challenge the patterns of traditional thinking. Collaboration has emerged as a promising new strategy since it takes a broader system-wide view which provides opportunities for increased efficiency that is impossible to achieve with an internal focus.

In collaborative truckload transportation procurement (CTTP), which motivates the optimization problems studied in this paper, a group of shippers that regularly send truckload shipments, e.g. several days of the week, get together and seek to identify sets of lanes which can be served by repeatable, dedicated continuous move tours. In situations where shippers regularly send truckload shipments, it is common to find contracts in which carriers dedicate a portion of their fleet to the shipper, but then transfer responsibility for all costs, including repositioning costs, to the shipper. Carriers are often willing to provide more favorable rates for bundles when a bundle of lanes provides repeatable work for a driver and covering the lanes in the bundle involves little or no asset repositioning. In order to maximize savings, the collaborating shippers must solve a lane covering problem (LCP). In practice, many constraints exist on the set of tours which can be used. These constraints lead to highly challenging LCP variants. The focus in this paper is on incorporating an upper bound on the number of partners for each partner into the LCP, and developing column generation approaches for its solution.

The LCP can be stated as follows: given a set of lanes submitted by the collaborating shippers, find a set of tours that covers all of the lanes and that minimizes the total asset repositioning [10]. Formally, the LCP is formulated as a covering problem on a directed graph, which can be solved efficiently as a minimum cost flow circulation problem or a bi-partite matching problem. As soon as additional constraints are imposed on the tours, e.g. maximum lanes per tour or maximum duration of a tour, the associated LCPs become NP-hard. Although these constrained variants can be solved to optimality using a set partitioning formulation over the whole set of feasible tours, heuristics methods have been proposed for efficient and effective solution of large instances due to the exponential growth of the number of feasible tours [9,10].

Collaboration obviously impacts various business processes and implies additional demands on relationship management. Consequently, many shippers want to limit the number of collaborative partners. This innocent looking restriction has a dramatic impact on the complexity of the underlying optimization problem and leads to another NP-Hard variant of the LCP. This paper formally introduces this LCP variant, namely the *partner constrained lane covering problem* (PCLCP), provides an extended formulation which addresses the limits on the number of collaborative partners, and develops a column generation approach for its solution. This is the

E-mail address: gkuyzu@etu.edu.tr

http://dx.doi.org/10.1016/j.cor.2016.07.018
0305-0548/

first study in the literature offering a column generation based solution method for a constrained LCP variant. Previous studies proposed greedy heuristic algorithms only. The column generation approach combines simple heuristic approaches with an exact approach. Stabilized column generation [8] is used to deal with the high level of degeneracy involved.

Erhun and Keskinocak [11] provide a review of various forms of collaboration in the supply chain and define four distinct types of collaboration: intra-enterprise vertical, intra-enterprise horizontal, inter-enterprise vertical, and inter-enterprise horizontal. According to this classification, CTTP is an example of inter-enterprise horizontal collaboration.

A joint survey by McKinsey and EyeForTransport reveals that many shippers are engaged in collaborative activities in areas ranging from order management, demand planning, and forecasting to shared transportation and warehousing [26]. It is reported that 34% of the shippers in the survey currently have collaborative transportation activities while 25% have collaborative warehousing activities. Furthermore, 85–90% of shippers, carriers and 3PL responding to the survey expect widespread horizontal collaboration in the supply chain within the next 3 to 5 years and beyond. The results of recent industrial implementations and case studies indicate that collaboration can help companies achieve up to 30% savings in transportation costs, and 25% reductions in CO_2 emissions [22,26,3].

In CTTP, solving the LCP yields the set of lanes and firms to be included in the collaboration, who will collaborate with whom, and the maximum amount of efficiency gains which can be achieved through collaboration under the restrictions imposed by the participants. The optimization approach presented in this paper can help facilitate the formation of successful CTTP coalitions.

The rest of the paper is organized as follows. Section 2 provides a review of the related work in the literature. Section 3 presents a formal statement of the optimization problem under consideration and a mathematical model for its solution. Section 4 provides the details of the column generation approach. Section 5 contains the results of the computational experiments undertaken to analyze the empirical effectiveness of the solution method proposed. Concluding remarks are provided in Section 6.

2. Related literature

Collaboration is an increasingly widespread practice in the supply chain. Accordingly, there is a significant and growing stream of research literature on collaborative logistics and supply chain management. Inter-enterprise horizontal collaboration in logistics and supply chain has received an increased level of attention in recent years. The rest of this section is focused on a review of the literature on CTTP and the lane covering problems. The interested reader is referred to Erhun and Keskinocak [11] for a general review several forms of collaboration in the supply chain and the potential benefits of each. In addition, Audy et al. [2] present five different coordination mechanisms found in the literature to support collaborative logistics.

There are only a handful of papers in the literature on CTTP. These papers focus on solving the LCP variants arising in CTTP and/or allocating the cost of the LCP to the participants of CTTP. Ergun et al. [9,10] are the first to study the optimization problems arising in CTTP, referred to as shipper collaboration, motivated by collaborative transportation networks managed by 3PL companies in the U.S. They introduce the LCPs as well as greedy heuristics for the solution of large scale instances of some NP-Hard variants. Immorlica et al. [15] give a $(1+\ln 2)$-approximation for the cardinality constrained LCP. Ozener and Ergun [19] study the cost/benefit allocation problem of the LCP and design allocation methods based on optimal dual prices to maintain the collaboration among selfish collaborators. Hezarkhani et al. [13] further characterize the theoretical properties of dual based methods for allocating the cost of the LCP.

The LCP and its variants have been studied in settings outside of CTTP as well. Ozener et al. [20] solve the multi-carrier LCP to quantify the maximum possible benefit from lane-exchange based collaboration among a given set of carriers. Rajapakshe et al. [21] analyze a generalization of the LCP, i.e. the problem of identifying a dedicated transportation subnetwork by a shipper when deadheading and/or lane sharing are allowed, and develop an efficient network flow based heuristic to find near-optimal solutions to practical instances of this NP-hard problem. Xu and Huang [25] devise auction mechanisms for distributed transportation procurement such that the dominant strategy of each carrier is to submit his real cost for each lane bundle, which is obtained by solving the LCP. Kuyzu et al. [16] assume that the carriers heuristically solve the length constrained LCP to determine the cost of serving a given set of lanes and formulate stochastic optimization based bidding strategies for bidding on multiple independent single-lane auctions simultaneously.

There exists a body of research on related graph covering problems in the literature. The cycle covering problem (CCP) looks for a least cost cover of a graph with simple cycles, each containing at least three different edges. This constrained version of the CCP was shown to be NP-hard on general graphs by Thomassen [23]. Hochbaum and Olinick [14] develop heuristic algorithms that find near optimal solutions for the bounded cycle-cover problem based on solution techniques for other problems. Fernandes et al. [12] show that the minimum cycle cover problem on a strongly connected mixed graph can be solved in polynomial time if the graph has bounded tree-width. Amaldi et al. [1] present a very efficient polynomial time algorithm for finding a minimum cycle basis in undirected graphs.

The constrained lane covering problems are closely related to the capacitated arc routing problem (CARP). LCPs lack a depot, and hence each variant may be considered as a relaxation of a CARP. Column generation based solution approaches for CARPs usually first transform the problem into a node routing problem, and then solve the resulting node routing problem. Bode and Irnich [7] present the first full-fledged branch-and-price algorithm designed for the capacitated arc-routing problem. They propose a solution approach called “Cut-First Branch-and-Price-Second”, and provided computational results which show that the approach is effective. Bartolini et al. [5] develop an exact algorithm for the capacitated arc routing problem with deadheading demand based on cut-and-column generation and branch and price, and report extensive computational results on a large set of benchmark instances. They test the same exact algorithm on classical CARP benchmark sets and show that it improves upon the best known exact algorithms for the CARP. Bartolini et al. [6] develop a new lower bounding method based on cut-and-column generation to solve different relaxations of the problem and dynamic programming for generating routes. An exact algorithm based on the new lower bounds improves most of the best known lower bounds for the open benchmark instances and can solve several of these for the first time.

The existing works in the literature related to the LCPs can be divided into two groups by the type of LCP involved, which drives the choice of the solution method. In the first group, the LCP to be solved does not include any constraints on the (simple) cycles which can be used in covering the lanes, and the LCP in question is solved using a minimum cost flow circulation problem formulation [19,20,13,25]. In the second group, there are one or more constraints on the cycles which can be used in the LCP solution, a set partitioning formulation over the set of all feasible cycles is