ARTICLE IN PRESS
JID: CAOR [m5G;February 28, 2017;15:44]

Computers and Operations Research 000 (2017) 1–13

Contents lists available at ScienceDirect

Computers and Operations Research

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

An exact decomposition method to save trips in cooperative pickup and delivery based on scheduled trips and profit distribution

Yang Yu[a,c], Qi Lou[a], Jiafu Tang[b], Junwei Wang[c,*], XiaoHang Yue[d]

[a] Institute of Systems Engineering, Northeastern University, Shenyang, 110816, PR China
[b] College of Management Science and Engineering, Dongbei University of Finance and Economics, Dalian, 116023, PR China
[c] Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong
[d] Lubar School of Business, University of Wisconsin-Milwaukee, Milwaukee, WI 53201, United States

ARTICLE INFO

Article history:
Received 6 September 2015
Revised 20 May 2016
Accepted 17 February 2017
Available online xxx

Keywords:
Cooperation
Exact algorithm
Decomposition
Profit distribution
Exact Shapley value

ABSTRACT

Compared to the non-cooperative mode, the cooperative mode is a powerful way to reduce operational cost in pickup and delivery service. In order to protect business sensitive information, sometimes participants are unwilling to open the customer's detailed information. Thus, we utilize the publishable trip scheduled results to compute the saved trips brought by cooperation. A mathematical model minimizing trips of cooperation is proposed. To obtain the exact solution, we define the cooperative trip set. We prove that only when cooperative trip set exists it is possible to save trips by cooperation. For a two-trip cooperative trip set, we exactly obtain the saved trips by enumerating all feasible cooperative cases. For a K-trip cooperative trip set, we propose an exact method to obtain the saved trips by decomposing it to at most K-1 two-trip cooperative trip sets. Computational complexity of the based-on-decomposition exact algorithm is $O(N)$, where N is the total number of trips. Using the based-on-decomposition algorithm, we calculate the exact Shapley value to distribute profit. To empirically verify the exact method, we perform the extensive experiment cases of the real cooperative pickup and delivery service, i.e., "picking up and delivering customers to airport service" (PDCA).

1. Introduction

Cooperation is a powerful way to reduce operational cost of pickup and delivery service. Before participants agree to join in a cooperation scheme, an estimation of the profit brought by cooperation must be available. The problems in the transportation have been studied (Caputo and Mininno, 1996; Frisk et al., 2010; Audy et al., 2011; Lozano et al., 2013). These studies calculated cost saving brought by cooperation by integrating the original data of all participants. However, sometimes participants do not like to publish the customer's detailed information in order to maintain business sensitive information, but it is acceptable to open the scheduled results because the scheduled results do not show sensitive customer's information. As a consequence, a method should be developed to estimate the profit brought by cooperation based on scheduled results.

This paper is originally motivated by the cost reduction brought by a real cooperative pickup and delivery service, i.e., "picking up and delivering customers to airport service" (PDCA). In real PDCA, a case of customer's detailed information is shown in Table 1. The customer's detailed information was provided by the companies performing PDCA, such as Zhongshan, Shuntian, and Jiantong Inc. in Shenyang in China (Tang et al., 2008, 2014; Yu et al., 2014, 2016).

Location means the vertical and horizontal coordinates of customer's preferred location to pick up the customer.

Customer's detailed information can reveal company's business sensitive information. For example of Table 1, we can know location (50, 70) is the important customer point. Thus, other companies can lure customers in thus important customer points. However, a company may publish the scheduled result when joining in cooperation. A scheduled result of Table 1 can be shown in Table 2.

As shown in Table 2, the scheduled result can conceal some sensitive business information, such as location of picking up and the number of customers in location. Thus, it is acceptable for a company to open the scheduled trips to participate cooperation.

Before participating cooperation, each company wonders the exact profit distributed by cooperation. Therefore, the first objective of the study is to estimate the exact profit brought by cooperation based on trip scheduled results. The second objective is to obtain the fair profit distribution based on exact Shapley value to stabilize coalition.

* Corresponding author.
E-mail address: jwwang@hku.hk (J. Wang).

http://dx.doi.org/10.1016/j.cor.2017.02.015

Table 1
A case of customer's detailed information.

Location	Airport arrival soft time window	Airport arrival hard time window	Number of customers
(50,70)	[9:20 9:30]	[9:10 9:40]	3
(50,60)	[9:30 9:40]	[9:20 9:50]	1
(50,70)	[9:50 10:00]	[9:40 10:10]	2

Table 2
A scheduled result of Table 1.

Trips	Airport arrival time window	Number of customers
1	[9:28 9:32]	4
2	[9:48 10:02]	2

The remainder of this research is organized as following. The literature review on cooperative cases in the transportation, profit distribution, and picking up and delivering customers to airport service (PDCA) is given in the second section. The third section constructs the mathematical model minimizing trips of cooperation. We define cooperative trip set and prove that if no cooperative trip set exists the trips cannot be saved by cooperation. For a two-trip cooperative trip set, we obtain the exact solution by enumerating all feasible cooperative cases. For a cooperative trip set with K trips, we propose a novel decomposition method to obtain the exact solution by decomposing it to at most K-1 two-trip cooperative trip sets. Section four develops a based-on-decomposition algorithm to accurately calculate saved trips by cooperation. The computational complexity of the exact algorithm is $O(N)$, where N is the total number of used trips in non-cooperative companies. The fifth section demonstrates the profit distribution based on Shapley value. The Shapley value can be easily obtained by the exact algorithm. Section six gives the extensive computational cases from PDCA and states how to compute exactly Shapley value based on the decomposition algorithm. In the last section conclusions and future research are given. The results of extensive experiments are given in Appendices A–C.

2. Literarily review

2.1. Cooperative case in transportation sector

Compared to the non-cooperative mode, cooperative pickup and delivery is a powerful way to reduce operational costs. Profit calculation and profit distribution are the two keys. The two problems in the transportation have been researched (Lozano et al., 2013), such as grocery distribution (Caputo and Mininno, 1996), distribution in rural areas (Hageback and Segerstedt, 2004), freight carriers (Krajewska et al., 2008), forest (Frisk et al., 2010), and railway transportation (Sherali and Lunday, 2011).

Other researchers have approached cost saving and profit distribution from theoretical points of view. Cruijssen et al. (2007) carry out extensive experiments in order to measure cost savings on a number of characteristics of the distribution problem and found that significant cost savings are achievable. Cruijssen et al. (2010) present an approach for the initiative entering the cooperation among logistics service providers.

These researches compute the saved cost by integrating the data of all participants in cooperation. To maintain business sensitive information, a participant is unwilling to open the customer's detailed information, but can publish the scheduled results. Therefore, our study focuses on how to estimate the cost saving brought by cooperation based on the publishable scheduled results of participants.

In addition, some prior studies used heuristic or meta-heuristic algorithms to estimate cost saving of cooperation due to the larger-scale instances caused by cooperation. Krajewska et al. (2008) use the heuristic proposed by Ropke and Pisinger (2006) to solve their problem. The heuristic is based on the large neighborhood search heuristic. To minimize execution costs for a coalition of freight forwarders, Ergun et al. (2007) use a greedy heuristic as well as set partitioning, sets of cycles to solve the instance. As a result, the profit brought by cooperation is not exact. So we focus on exactly computing the profit brought by cooperation.

2.2. Profit distribution

Most profit sharing cases were studied based on cooperative game theory. The set of solutions includes the kernel, the bargaining set, the stable set, the core, the Shapley value and the nucleolus (Ordeshook, 1986; Osborne and Rubinstein, 1994). Engevall et al. (1998) investigate the routes costs allocation among the customers based on a traveling salesman game. Krajewska et al. (2008) use the Shapley value for sharing profits in cooperative freight carriers in order to balance their request portfolios. The profits are estimated through a multi-depot Pickup and Delivery Problem with time windows. Özener and Ergun (2008) propose several cost-allocation schemes based on cooperative game concepts (such as stability and others) applied to a logistics network in which shippers collaborate. Frisk et al. (2010) study a cooperative forest transportation planning problem and investigate some classical cost-allocation methods (including the Shapley value and the nucleolus). Sherali and Lunday (2011) analyze four alternative schemes to apportion railcars to manufacturers and propose a new railroad allocation scheme.

The Shapley value (Shapley, 1953) is one of the solution methods most common in cooperative game theory. We shall retain here the Shapley value as the mechanism to share the dividend of cooperation among participants. The exact Shapley value for some special cases has been studied. Littlechild and Owen (1973) give a famous simple expression for the Shapley value for airport runway cost games. Kuipers et al. (2013) study the exact expression of Shapley value for the cost sharing in highways.

2.3. Picking up and delivering customers to airport service

Flight Ticket Sales Agency (short for FTSA) operates as a typical service company in China aviation service industry. The major services include ticket sales, flight lines design, and delivering tickets to customers. To win the competition, some new services and value-added program are proposed to facilitate customers in some FTSAs, among which 'picking up and delivering of customers to airport' (short for PDCA) is a recently provided new service in some FTSAs, e.g., Zhongshan Flight Ticket Sales Service Company Inc. With the PDCA service, the customers who bought the flight tickets have the rights to be picked up at his preferred time and position, and delivered to airport within his specified deadline. This new service can facilitate customers to airport in a way of more convenient, and thus earn high customer satisfaction. To diminish operational costs, the cooperative PDCA is proposed because the total operational costs can be saved by cooperation. Moreover, there are at least three FTSAs providing PDCA in Shenyang, such as Zhongshan, Shuntian, and Jiantong FTSAs.

PDCA is a real case of Pickup and Delivery Problem. Pickup and Delivery Problem has received widely attention (Cherkesly et al., 2015; Gouveia and Ruthmair, 2015; Iori and Riera-Ledesma, 2015; Madankumar and Rajendran, 2016). However, PDCA has the following distinctive characteristics: 1) the capacity of the vehicles is small, because the used vehicles in PDCA service are