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Mechanism design for collaborative production-distribution planning with shipment consolidation

Minghui Lai [a], Xiaoqiang Cai [b], Xiang Li [c,*]

[a] School of Economics and Management, Southeast University, Nanjing, Jiangsu Province, China
[b] The Chinese University of Hong Kong (Shenzhen) and The Shenzhen Research Institute of Big Data, Shenzhen, Guangdong Province, China
[c] College of Economic and Social Development, Nankai University, Tianjin, China

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ABSTRACT

This paper considers firms making collaborative production-distribution planning with shipment consolidation to reduce costs. However, the firms have private cost information which they are not willing to disclosure. We develop a computable mechanism based on a decentralized local search heuristic combined with simulated annealing, which allows for not only system optimization but also cost allocation. The mechanism is especially applicable to the firms with private cost information, due to its good incentive properties and budget balance in almost all the cases. Computational experiments indicate that the cost savings are significant for both the system and the individual firm.

1. Introduction

As transportation costs typically include a fixed charge and volume discounts of freight rate, it is advantageous for individual firms to collaborate on their products' distribution due to economies of scales in transportation. O'Reilly (2009) reports that 6 confectionery companies including Just Born, Topps and DeMet's join a consolidation program, in which their less-than-truckload (LTL) shipments are sent to cross-docking points in the transportation network and pooled by their common logistics provider, KANE. The freight cost reduction can reach 20%–35% through the consolidation program. Furthermore, the shipment consolidation can also be linked to the production and inventory planning to capture the additional benefits from coordination the entire operational decisions, since many companies have set up integrated planning systems to jointly optimize production and distribution decisions. For example, Hershey and Ferrero not only share distribution and transportation facilities but also collaborate on a joint warehousing plan. The two firms create one North American supply chain with the goal of reducing over-all operational costs as well as improving efficiency and competitiveness (Terry, 2015).

However, a major hindrance for such a collaboration is information privacy. As the participators are usually competing firms within the same industry, they are generally reluctant to reveal their sensitive private information such as production and inventory costs. A big concern from the firms is that the potential risk of critical information exposure can prevail over the benefit obtained from the operational cost savings. Moreover, cost allocation is a challenging problem due to moral hazard among the participating firms who may report false information during the collaboration for their own interest. Hence, it is crucial to design a coordination mechanism that requires as little private information as possible of the firms while ensuring the participation of individual firms and the efficiency improvement of the entire system at the same time.

* Corresponding author.
E-mail address: xiangli@nankai.edu.cn (X. Li).

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Motivated by the above facts, this paper develops a coordination mechanism for the collaborative production-distribution problem under private cost information. Specifically, we consider that the firms form an alliance (*i.e.*, an consortia, a trade association, or a program organized by 3PL) to jointly plan the production and distribution of their products to satisfy demand in a multi-period planning horizon, with the shipments consolidated across a general logistics network. The alliance contracts a common 3PL carrier to deliver the shipments. We consider that the transportation cost is a common knowledge during shipment consolidation (*e.g.*, published by the 3PL carrier), while the firms have private information on individual production and inventory costs confidential to each other. To overcome the difficulty from information asymmetry, the mechanism is implemented by a decentralized local search heuristic combined with simulated annealing, in which each firm iteratively solves private problems to minimize his own cost. Computational experiments indicate that the mechanism can significantly improve system efficiency and generate decent cost savings to the participating firms as well.

Hence, our main contribution is to provide a coordination mechanism for a theoretically difficult problem (NP-hard even under complete information) with more practical usefulness (under a common concern of information privacy among firms). More importantly, this mechanism not only improves entire system performance but also proposes a cost allocation rule applicable to industry due to its good incentive properties and budget balance in almost all the cases. Our paper belongs to the first effort to develop an incentive mechanism for a general multi-period collaborative production-distribution problem with shipment consolidation, under firms' private cost information.

The remainder of the paper is organized as follows. In Section 2, we review the relevant literature. In Section 3, we describe the collaborative production-distribution problem and formulate the optimization model. In Section 4, we propose an iterative mechanism to coordinate the firms' production-shipping plans in the situation of private information. In Section 5, we analyze the properties of the mechanism. In Section 6, we conduct experiments to test the mechanism and present more insights. In Section 7, we discuss an extension. Finally, in Section 8, we conclude the main results of the paper.

2. Literature review

The collaborative distribution problem in our paper integrates dynamic lot-sizing (DLS) with shipping and routing. Our study is closely related to the literature on multi-echelon/item DLS, the literature on minimum concave-cost network flow problems, and the literature on collaborative distribution. In the following, we briefly review these literature and then discuss the contributions of our work.

2.1. Dynamic lot-sizing literature

Since the seminal paper Wagner and Whitin (1958), the DLS model has been extended to a variety of settings. See Brahimi et al. (2006) for an extensive review. We focus on the integrated production, inventory, and transportation optimization studies based on DLS model. Many researchers consider coordinating lot-sizing decisions with shipping decision in multi-echelon distribution systems (Diaby and Martel, 1993; Lee et al., 2003; Jaruphongsa et al., 2007). On the other hand, the DLS model with transportation cost discounts has been extended to the multi-item case (Lee et al., 2005; Chung et al., 1996; van Norden and van de Velde, 2005; Anily and Tzur, 2006; Ertogral, 2008), where products are immediately shipped after production. Very few papers consider shipping policy in this multi-item case, except Ertogral (2008), Jaruphongsa and Lee (2008), and Melo and Wolsey (2012).

In the above stream of literature, shipments are sent directly from the production plants to the customers, and the issue of routing shipments during the distribution stage is ignored. Recently, the multi-echelon DLS model is generalized to include vehicle routing decisions. This new extension is called production routing problem (PRP). See Adulyasak et al. (2015b) for an in-depth review on PRP. Most papers focus on developing heuristic solutions, e.g., tabu search heuristic (Bard and Nananukul, 2009), adaptive large neighborhood search heuristic (Adulyasak et al., 2014), and two-phase iterative search heuristic (Absi et al., 2014). Only a few papers introduce exact algorithms, *e.g.*, branch-and-cut algorithms (Adulyasak et al., 2013), column generation algorithm (Abouee-Mehrizi et al., 2014), and Benders decomposition algorithm (Adulyasak et al., 2015a).

Our model is different from the PRP. The PRP combines DLS and vehicle routing, where the manufacturer uses private vehicles for shipping. Thus the transportation cost has a step-wise structure for truckloads. In our model, we consider that multiple manufacturers contract with a common 3PL to collaboratively distribute their products. The transportation cost has a piecewise linear concave structure for incremental discount, and hence the manufacturers benefit from shipment consolidation.

2.2. Minimum concave-cost network flow literature

The minimum concave-cost network flow problem (MCNFP) requires establishing a minimum cost flow from a se of generating sources to sinks through a directed network with concave cost function of the total flow along each arc. The model arises in many medium- and long-term network planning contexts where cost functions exhibit strong economies of scale, which corresponds to the collaboration transportation scenario in our paper. It is well-known that MCNFP is a *NP*-hard problem, even under some special cases such as single-source, uncapacitated, and piecewise linear concave flow cost (Erickson