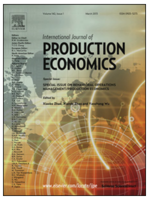
Int. J. Production Economics 179 (2016) 141–152

Contents lists available at ScienceDirect

Int. J. Production Economics

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



Inventory sharing via circular bidirectional chaining

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ARTICLE INFO

Article history:
Received 12 April 2015
Received in revised form
21 February 2016
Accepted 9 June 2016
Available online 11 June 2016

Keywords:
Inventory pooling
Chaining
Supply chain management
Lateral transshipment
Simulation-based optimization

ABSTRACT

We investigate a lean inventory sharing strategy, called "Circular Bidirectional Chaining" (*BDC*), in a single period setting, and quantify the difference between the performance of *BDC* and the performance of other inventory sharing strategies for normally distributed demands. Under *BDC* all the locations, each facing stochastic demand, are connected in a closed loop, such that each location is allowed to cooperate laterally with exactly two adjacent locations. A location is not allowed to serve as a source and a sink of material at the same time. To consider *BDC* vis-à-vis other strategies, one must first optimize the proposed *BDC* strategy. Managing the *BDC* consists of two problems: determining the optimal order quantities, and, for given order quantities and demand realizations, determining how should items be transshipped. The former is a stochastic planning problem with recourse, solved via simulation-based optimization, while the latter, which is the recourse part of the former, can be interpreted as a transportation problem. Sensitivity analysis with respect to problem parameters is provided. It turns out that *BDC* can achieve a considerable portion of the benefits of complete pooling in around 65% of the cases, while the cost required to enable cooperation via *BDC* is lower than that of complete pooling.

1. Introduction

Pooling of inventories aimed at reducing the operational cost of a supply chain (SC) has recently attracted much attention. Inventory pooling in a stochastic-demand environment generally implements the risk pooling principle, according to which the standard deviation of the aggregate demand is smaller than the sum of the standard deviations of the stand-alone demands. When managed optimally, a pooled system is less costly than the unpooled one (Eppen, 1979; Gerchak and He, 2003). Yet, pooling can increase the system-wide optimal order quantity (Gerchak and Mossman, 1992; Yang and Schrage, 2009). Pooling can be either physical, in which case items are stocked at a central location accessible by all locations at the same echelon of a SC, or virtual (often referred to as lateral transshipments), in which case each location carries its own stock, but locations at the same echelon of a SC can send items to and receive items from each other. In a single-period setting placing an additional emergency order from the upstream echelon is not always feasible, and beyond that, lateral transshipments balance stocks across the system, thus reducing mismatch between supply and demand and saving both surplus and shortfall costs. Paterson et al. (2011) provide a thorough review on lateral transshipments. In practice, this method of pooling is common particularly with spare parts and apparel products and is observed in various retail stores, for example, Foot Locker.

The growing interest in inventory pooling gave rise to an interesting question – which pooling strategy one should select. From the standpoint of pooling, the most effective strategy is, undoubtedly, Complete Pooling (*CP*). This strategy, widely addressed in inventory literature (Krishnan and Rao, 1965; Eppen, 1979; Tagaras, 1989; Gerchak and He, 2003; Herer et al., 2006; Nonås and Jörnsten, 2007; Chartniyom et al., 2007; Rosales et al., 2013 and many others), stipulates that all locations at the same echelon of a SC (henceforth "retailers") facing uncertain demand are allowed to share inventory with each other with no limitations, but possibly with transshipment costs. The transshipment cost is assumed lower than the shortfall cost, so the transshipment will take place if needed. Yet, the value of the transshipment cost affects the original inventory decision. This way the amount transferred in the system equals the aggregate pre-transshipment surplus or the aggregate pre-transshipment shortfall, the smaller of the two. In the absence of transshipment cost, *CP* is often viewed as a single location facing the aggregate system demand. A review of inventory (risk) pooling is available in Cai and Du (2009).

However, in recent years, there has been an increasing number of studies on *restricted* inventory pooling strategies (Tagaras, 1999; Herer et al., 2002; Axsäter, 2003; Kranenburg and van Houtum, 2009; Olsson, 2010; Lien et al., 2011; Smirnov and Gerchak, 2014).

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http://dx.doi.org/10.1016/j.ijpe.2016.06.012
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Lederman et al. (2014) addressed the question of selecting a restricted pooling strategy in a decentralized SC where transshipment is performed only if a pair of retailers with opposite stock level signs chose to contact each other, assuming each retailer is allowed to contact exactly one other retailer. With restricted pooling, allowed cooperation within the system is limited, so that each retailer is allowed to cooperate with a predetermined set of other retailers. Limited pooling is motivated by the complexity (both computational and operational) of managing and optimizing a *CP* system. Decreasing marginal returns with respect to the number of retailers (e.g., Cai and Du, 2009) have raised a hypothesis that marginal returns, in the sense of optimal expected cost per retailer and optimal order quantity per-retailer, might decrease with respect to the number of connections as well. Limited pooling also discourages long-distance transport, saving variable costs, and is thus worth studying. Furthermore, there exists a tradeoff between the effectiveness of pooling and the cost needed to establish links and operate transshipment between each pair of retailers. This fixed cost (henceforth “establishment cost”) can include payment for the infrastructure that would allow information sharing between two particular retailers, administrations associated with pooling, the cost of drivers, trucks, fixed payments to a third party for delivery, etc. Although we do not explicitly consider the savings achieved by pooling versus the establishment cost, this fixed cost could easily be incorporated at the end.

A system with independent retailers who perform no inventory pooling (*NP*) generally serves as a benchmark for the performance of all pooling strategies. In this case each retailer operates alone, and faces a separate Newsvendor problem (see, e.g., Arrow et al., 1951). This strategy will be mentioned in the current study for comparison purposes. The reader is referred to Smirnov and Gerchak (2014) for a quantitative review of *NP* and *CP*.

The primary interest of the current study is to quantify the gap between a particular inventory sharing strategy, namely, Circular Bidirectional Chaining (*BDC*), and other strategies mentioned in the literature, in terms of both optimal expected costs and optimal order quantities. In particular, we aim to check whether using *BDC* instead of *CP* results in a major loss. However, to perform the comparison, one must first explore *BDC* in detail.

In the setting under investigation, all retailers are connected in a bidirectional closed loop, such that each retailer has exactly two neighbors for potential cooperation. Cooperation means sending items to and receiving items from both neighbors if needed and available, such that the amount transferred is, at most, the minimum between the surplus of the sender and the shortfall of the receiver. However, a retailer who received items from one of her neighbors to cover her shortfall is not allowed to further transfer any items to her other neighbor. Similarly, a retailer who serves as a source of items is not allowed to receive any items from any of her neighbors. Our rules are thus more restrictive than in previous literature on transshipments (Herer et al., 2006; Lien et al., 2011). If a retailer could serve as a source and a sink of material, from the modeling perspective the situation would be one of complete pooling, widely investigated previously, or a setting similar to Lien et al. (2011). Our main idea is to explore an incomplete pooling scheme and to compare it to complete pooling. From the practical perspective, a direct cooperation between two retailers is simpler than transshipping items through an intermediate retailer. However, a direct cooperation without limitations would, again, result in complete pooling and in transshipment between distant retailers.

Concrete restricted pooling strategies previously studied include grouping (Lien et al., 2011), circular unidirectional chaining (*UDC*, see, e.g., Lien et al., 2011; Smirnov and Gerchak, 2014), and many others (Lien et al., 2011). Even the strategy of *BDC* has been addressed by Lien et al. (2011), but they make transshipment decisions before satisfying demand locally (for our order of events, see Section 2), and allow a retailer to send and receive items at the same time, up to her order-up-to level. Moreover, they provided comparisons only between strategies with the same number of links, while we make other comparisons of *BDC*, including to *CP*.

For completeness, and since in the sequel we compare *BDC* to *UDC* (Smirnov and Gerchak, 2014), let us describe the strategy of unidirectional chaining. In *UDC* all retailers are connected in a unidirectional closed loop, such that each retailer cooperates with exactly two neighbors by sending items (if needed and available) to the right neighbor and receiving items (if needed and available) from the left, and a retailer who receives items from one neighbor is not allowed to send any items to her other neighbor. The amount transferred between each pair of cooperating retailers is the minimum between the surplus of the sender and the shortfall of the receiver. This strategy is particularly lean and requires only a single connection for each retailer added to the system.

The strategy of bidirectional chaining seems promising and interesting to explore. It is easier to establish than *CP* as fewer resources are needed. It is also easier to operate since a retailer need not be confused by potential cooperation with all others (in a multi-period setting, there might be a different actual cooperation each period, so transactions could become complex). Such sharing strategy can also model a real-life situation in which each retailer has two neighbors located in close proximity, while all other retailers are located far away, making cooperation with them impractical. This is another argument in favor of not allowing sending material through intermediate retailers. As opposed to Smirnov and Gerchak (2014) who investigate just the restrictive strategy of *UDC* and compare it to the extreme strategies, we focus on a more reasonable strategy of sharing inventories bidirectionally. In particular, *BDC* makes more sense than *UDC* if the unit costs are identical across retailers. While *BDC* is more “liberal” (allows more types of transshipment) than *UDC*, it is, as we will see, considerably more difficult to optimize. Yet we propose an effective method for doing so.

Car dealers who are short of some requested model or color often practice “dealer trade” with other dealers in the vicinity. Similar patterns occur with other, especially heavy, products. Our assumption that you only deal with your nearest “neighbors” reflects this geographical consideration. Moreover, since transshipment cost may depend on the distance traveled, even with smaller products (e.g., shoes from Foot Locker) it is not always economical to execute transshipments between retailers who are not geographically close to each other.

In this work each retailer is interpreted as a node in a graph, while each transshipment possibility between two retailers is interpreted as an arc. Two arcs are thus required to enable bidirectional transshipment between two nodes. Thus, a system of n retailers requires only $2n$ arcs to handle *BDC*, while *CP* would require as much as $n(n-1)$ arcs – a considerable difference for large n's. Fig. 1 schematically illustrates the *BDC* configuration.

The concept of “a little flexibility goes a long way” also emerges in the context of production process flexibility (Jordan and Graves, 1995). A single closed loop (both uni and bidirectional) appears to capture most of the benefits of total flexibility with far fewer arcs. This has raised the hypothesis of the effectiveness of *BDC* in the context of inventory pooling, and thus quantifying the gap between *BDC* and *CP* is particularly emphasized in the current study. The motivation for studying the specific configuration of *BDC* originates from the fact that, according to Jordan and Graves (1995), a single closed loop encompassing all products and plants performs better than multiple closed loops encompassing a subset of products and plants each. Also Lien et al. (2011) show that a strategy of a single chain outperforms several other strategies,