European Journal of Operational Research 221 (2012) 317–327

Contents lists available at SciVerse ScienceDirect

European Journal of Operational Research

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

Production, Manufacturing and Logistics

# Enhanced lateral transshipments in a multi-location inventory system

Colin Paterson [a,*], Ruud Teunter [b,1], Kevin Glazebrook [a,2]

[a] Lancaster University Management School, Lancaster, LA1 4YX, UK
[b] University of Groningen, PO Box 800, 9700 AV, Groningen, The Netherlands

ARTICLE INFO

*Article history:*
Received 25 November 2010
Accepted 4 March 2012
Available online 12 March 2012

*Keywords:*
Inventory control
Lateral transshipments
Dynamic programming

ABSTRACT

In managing an inventory network, two approaches to the pooling of stock have been proposed. Reactive transshipments respond to shortages at a location by moving inventory from elsewhere within the network, while proactive stock redistribution seeks to minimize the chance of future stockouts. This paper is the first to propose an enhanced reactive approach in which individual transshipments are viewed as an opportunity for proactive stock redistribution. We adopt a quasi-myopic approach to the development of a strongly performing enhanced reactive transshipment policy. In comparison to a purely reactive approach to transshipment, service levels are improved while a reduction in safety stock levels is achieved. The aggregate costs incurred in managing the system are significantly reduced, especially so for large networks. Moreover, an optimal policy is determined for small networks and it is shown that the enhanced reactive policy substantially closes the gap to optimality.



## 1. Introduction

Lateral transshipments (LTs) are stock movements between locations in the same echelon of an inventory system. They provide a valuable tool to supply chain managers who are looking to reduce the penalties associated with a lack of stock at one or more inventory points. By strategically reallocating excess stock it can be possible to improve the system wide service levels and/or lower the cost of operating the system. These goals have traditionally been sought within spare part networks, where there is a high penalty attached to a shortage. However the benefits of LTs have also been realized in sectors ranging from retail to energy generation. The challenge that LTs bring is in managing when and where it is beneficial to instigate a stock movement. An LT may reduce the short term shortage risk at the receiving location but it inevitably increases the longer term risk at the sending location. A transshipment policy must therefore balance these contrasting risks and decide when the cost of transshipment is outweighed by the benefit it is expected to deliver.

The suitability of a given LT policy will often depend on the attributes of the inventory system in which it is employed. However, a key distinction within the literature on LTs is that between reactive and proactive policies. Reactive LTs are performed when a shortage or potential shortage occurs, by shipping either the whole customer demand or the number of units short from a different location. Proactive transshipments are performed periodically to rebalance the whole system's stock levels. This paper's principle motivation is in considering an enhanced reactive policy which falls between these two distinct sets so as to maximize the benefit each transshipment can deliver. Rather than merely looking to meet the excess demand, the proposed policy views each triggered transshipment as an opportunity to proactively rebalance the two interacting locations' inventory.

Often when a transshipment occurs the cost associated with the stock movement will primarily be a fixed cost, independent of the size of the transshipment. The reason for this is that regardless of whether one item is transported or several, the costs such as using a vehicle and the associated fuel cost of instigating the journey will be highest for the first item. The marginal cost for subsequent items will typically be much lower. When such cost structures exist it is important to know how best to carry out transshipments. Economies of scale are considered throughout inventory management, from ordering in batches to centralizing warehouses. It is therefore natural to want to know how best to operate a transshipment policy when the opportunity to extract similar benefits exists.

Within the existing literature Reactive LTs have been studied under both a periodic and continuous inventory review setting. For periodic review models, Krishnan and Rao (1965) develop optimal transshipments in a single period for a system with two locations. This is expanded to a multi-location, multi-period setting by Robinson (1990), although here the optimal reactive solution can only be determined for either two locations or multiple identical locations and when the transshipment cost structure does not

* Corresponding author. Tel.: +44 1524 594673.
*E-mail addresses:* c.paterson@lancaster.ac.uk (C. Paterson), r.h.teunter@rug.nl (R. Teunter), k.glazebrook@lancaster.ac.uk (K. Glazebrook).
[1] Tel.: +31 50 3638617.
[2] Tel.: +44 1524 592697.

0377-2217/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ejor.2012.03.005

include a fixed element. This highlights the complexity of determining optimal transshipment policies. These papers perform LTs once all demand is known but before it has to be satisfied. In contrast, Archibald (2007) and Archibald et al. (2009, 2010) develop approximately optimal policies which can respond to continuous demand within each period. The former proposes heuristics to deal with the transshipment decision process, while the latter papers look to improve upon this and relax some of the restrictions using dynamic programming policy improvement techniques. The results obtained from these policies show them to be reasonably close to optimal when used in small networks. This method of validation is one which this paper looks to emulate. The above models focus on single echelon centralized models. However, additional research in the periodic setting considers the benefit of LTs within two echelon models (e.g. Dong and Rudi, 2004), decentralized models (e.g. Rudi et al., 2001) and production based models (e.g. Zhao et al., 2008). The latter of these is closely related to this paper as it also considers an enhanced transshipment policy. However, it considers a production model where stock can be reallocated upon production whilst also allowing reactive transshipments. It therefore falls between a production allocation model and a reactive transshipment model.

Much of the literature on reactive LTs in a continuous order review setting is motivated by applications in the spare parts industry. Here, practical settings include electronic component manufacturing and electricity generation companies. Building on the METRIC repairs model of Sherbrooke (1968), Lee (1987) proposes a model which uses complete pooling within preset groups of identical locations. This shows the benefit of LTs within the area and the model is expanded by Axsäter (1990) to allow non-identical locations. Several papers have been written which further expand these ideas by relaxing or tightening some constraints such as making repair capacity finite (Jung et al., 2003), using lost sales rather than backordering (Dada, 1992) or considering a model where backorders have to be minimized rather than costs (Sherbrooke, 1986). In addition to this, inventory systems that supply more than one type of item are investigated by papers such as Wong et al. (2006b) and Kranenburg and van Houtum (2009). The latter examines the benefits of partial pooling, where only certain transshipments are performed. All of these papers assume an order-up-to replenishment policy for each location. Wijk et al. (2009) consider a single item system where parts are repaired at each location and use dynamic programming to determine an optimal transshipment policy. Kukreja and Schmidt (2005) consider a more general $(s,S)$ policy, but have to resort to a simulation based approach to determine the optimal order policy.

Away from spare parts, Archibald et al. (1997) shows that in a periodic review model without fixed order costs, an order-up-to policy is optimal. However, positive order costs or minimum order quantities often suggest that an $(R,Q)$ policy is more appropriate in practice. Several papers take this approach. Evers (2001) and Minner et al. (2003) develop heuristics that can be used to determine when and how much to transship for systems with lost sales. Axsäter (2003) does the same, but for a model with backorders. He proposes a decision rule which is constructed to make optimal decisions under an assumption that no further transshipments will be made. This assumption enables the exact myopic benefit of transshipping to be calculated and optimized. A related model by Axsäter et al. (2010) considers an $(R,Q)$ inventory system in practice. They determine approximately optimal replenishment policy parameters when transshipments are sourced from a support warehouse.

Research on proactive LTs explores their use to rebalance an entire system's stock on hand. This rebalancing is done at a set point during a review period and before all demand has been realized. Allen (1958) and Agrawal et al. (2004) consider this problem independently of replenishment decisions. Allen (1958) looks to perform the transshipments at the start of the demand period, whilst Agrawal et al. (2004) devise a method to calculate the best time to redistribute stock during the period.

Other authors study proactive transshipment and replenishment decisions together. However, due to the periodic nature of proactive redistribution all known studies only consider their use alongside a periodic review replenishment policy. Gross (1963) provides optimality results for a two-location system, where both ordering and redistribution decisions take place at the beginning of the review period. This idea is further developed by Das (1975), who allows the redistribution point to occur at an arbitrary time during the review period. Gross and Das both assume negligible transshipment times. Jönsson and Silver (1987) and Bertrand and Bookbinder (1998) allow positive transshipment times. The main difference between these two studies is that Jönsson and Silver (1987) consider how best to meet service levels whilst Bertrand and Bookbinder (1998) examine the goal of cost reduction.

For a detailed overview of the literature we refer to Paterson et al. (2011). However, the highlighted literature shows that both reactive and proactive LTs provide cost benefits, but the cost benefits of proactive LTs have only been exploited in a periodic review setting. In this study, we analyze the first 'hybrid' transshipment policy which tries to secure the benefits of both under a continuous review replenishment policy by enhancing a traditional reactive approach. Our policy can quickly react to shortages by allowing transshipments at any time when they occur, as for previously proposed reactive LT policies. However, the policy also seeks to proactively redistribute stock between the sending and receiving locations whenever such an LT is triggered. This will allow maximum benefit to be extracted from each transshipment instance and will be especially beneficial in systems where there is a significant fixed cost involved in carrying out a transshipment.

The specific setting that we consider is as in Axsäter (2003), with backordering and an arbitrary number of stocking locations which all apply $(R,Q)$ ordering policies. Axsäter (2003) derives an algorithm that determines near-optimal reactive transshipment decisions. These are shown in a simulation study on small networks (with two and three locations) to provide a significant cost benefit compared to not transshipping at all and to applying a simpler transshipment policy. In this paper, we generalize this algorithm with the goal of determining an approximately optimal enhanced reactive transshipment policy that allows additional stock redistribution when reacting to a stock out. The results of a comparative numerical study show that, for small networks, the enhanced policy significantly outperforms the original Axsäter reactive proposal, achieving an average 1.6% cost saving over 600 experiments. Such a recurrent saving is of major practical importance, considering that inventory costs typically account for a substantial proportion of a business's total turnover. To analyze the closeness to optimality of our enhanced policies, we also develop a dynamic programming (DP) approach to finding an $\epsilon$-optimal transshipment policy which also allows for a proactive element in each transshipment. More significantly we show through numerical results that the optimality gap is closed by over 95% on average compared to a policy of not transshipping and by 88% compared to the original reactive policy. This is strong evidence that our development of an enhanced reactive approach makes an important contribution to the application of transshipments and enables benefits which are close to optimal.

In a further numerical study, we compare the traditional and enhanced algorithms for larger networks with 5–20 locations. The exact DP algorithm is too numerically intensive to be applied in these experiments. The results of a comparison of the policies show that the improvement of the enhanced reactive policy over the traditional reactive policy is even larger than for small