European Journal of Operational Research 000 (2015) 1–12

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Production, Manufacturing and Logistics

Integrated optimization of safety stock and transportation capacity

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ARTICLE INFO

Article history:
Received 21 February 2014
Accepted 26 May 2015
Available online xxx

Keywords:
Inventory
Vehicle fleet size
Excess transportation capacity

ABSTRACT

In this paper we consider a segment of a supply chain comprising an inventory and a transportation system that cooperate in the fulfillment of stochastic customer orders. The inventory is operated under a discrete time (r, s, q) policy with backorders. The transportation system consists of an in-house transportation capacity which can be extended by costly external transportation capacity (such as a third-party logistics provider). We show that in a system of this kind stock-outs and the resulting accumulation of inventory backorders introduces volatility in the workload of the transportation process. Geunes and Zeng (2001) have shown for a base-stock system, that backordering *decreases* the variability of transportation orders. Our findings show that in inventory systems with order cycles longer than one period the *opposite is true*. In both cases, however, inventory decisions and transportation decision must be taken simultaneously.

We present a procedure to compute the probability distribution of the number of transportation orders and the resulting excess transportation requirements or rather transportation costs. We show that the increase of transportation costs resulting from a safety stock reduction may offset the change of the inventory costs. This effect may have a significant impact on general optimality statements for multi-echelon inventory systems.

1. Introduction

In this paper we investigate the relationship between the performance of an inventory system and a subsequent transportation process within a supply chain. We show that inventory decisions may have a significant impact on the required transportation capacity (and transportation costs) when backorders occur, which is usually the case in inventory systems with uncertain demand.

The relationship between inventory and transportation under random demand conditions has been discussed in many papers. However, most of the research has concentrated on inbound transportation and only comparatively few papers considered the interaction among inventory management and outbound transportation.

Many authors examined the option of using faster inbound transportation modes or selecting a faster supplier at premium costs in order to shorten a stockpoint's replenishment lead time and to reduce the required safety stock through the associated multiple lead time options. Thereby, the focus often is on the influence of the inbound shipping time on the demand during the replenishment lead time. Related works include Axsäter and Grubbström (1979), Allen, Mahmoud, and McNeil (1985), Tyworth (1992), Gallego and Zipkin (1999), Bookbinder and Çakanyildirim (1999), or Kiesmüller, de Kok, and Fransoo (2005). Similar to using multiple lead time options is order expediting, where after the release of a replenishment order, depending on the state of the inventory system, an expediting decision is made (Lawson & Porteus, 2000; Özsen & Thonemann, 2014). Yano and Gerchak (1989) considered the simultaneous determination of safety stock and inbound transportation capacity (in terms of time between shipments and vehicles per shipment) for a production facility. Here, in the event that the contracted transportation capacity for an assembly line with 100 percent service requirements is busy, costly emergency shipments are made. Henig, Gerchak, Ernst, and Pyke (1997) examined the joint optimization of a periodic inventory policy in combination with a supply contract about a prepaid, basic inbound transportation capacity. If the replenishment quantity exceeds this basic transportation capacity the excess demand is shipped at a premium cost. By building up an additional safety stock when basic transportation capacity is still available, requirements for premium shipments are reduced.

Cachon (2001b) as well as Tanrikulu, Şen, and Alp (2010) studied a multi-item system where a stockpoint is replenished from an ample warehouse with the help of an unlimited number of trucks. Through the dispatching of the vehicle fleet, the stockpoint's inbound transportation costs are affected, which in turn has an impact on the optimal replenishment frequencies. The authors propose coordinated replenishment policies which take the inbound transportation costs into account. Gürbüz, Moinzadeh, and Zhou (2007) considered a single item delivered from a supplier to multiple retailers. The replenishments of the retailers are coordinated by a centralized

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http://dx.doi.org/10.1016/j.ejor.2015.05.069
0377-2217/

Please cite this article as: H. Tempelmeier, O. Bantel, Integrated optimization of safety stock and transportation capacity, European Journal of Operational Research (2015), http://dx.doi.org/10.1016/j.ejor.2015.05.069

decision maker who accounts also for the transportation costs to the retailers.

Madadi, Kurz, and Ashayeri (2010) studied an inventory system comprising a warehouse and multiple retailers. They assume that for each retailer and for the warehouse the order size determines the required transportation capacity (number of trucks) which is then included in the replenishment order size decision. The impact of the order size on the number of required trucks is also taken into account by Alp, Erkip, and Güllü (2003) under the assumption of deterministic and dynamic demands as well as random discrete lead times.

Compared to the above-mentioned literature, the current study focusses on the interaction between inventory management and *outbound transportation*. Only a comparatively small number of authors have analyzed this relationship under random demand conditions.

Ernst and Pyke (1993) addressed stocking and transportation capacity decisions within a two-level distribution system in which the warehouse and the retailer operate under base-stock policies. They assume that both excess demand and excess transportation capacity requirements in the warehouse are always met by an external source. Hence, the demand for transportation capacity is equal to the product demand with the result that transportation and inventory decisions can be made in isolation. The decision variables are the safety stocks and the in-house transportation capacity (truck fleet size), with regard to holding, in-house transportation costs and shortage costs. Ernst and Pyke show that in their scenario higher product demand variability tends to make maintaining an in-house truck fleet uneconomical.

Geunes and Zeng (2001) extend the work of Ernst and Pyke by assuming that excess demand in the base-stock inventory system is *backordered*. This smoothens peak transportation requirements and postpones them into future periods with the result that the *variability* of the demand for transportation capacity *decreases*. The authors show that in this case inventory and transportation decisions cannot be made independently anymore, because the safety stock decision has an impact on the variability of the transportation requirements and hence on the transportation costs.

Kutanoglu and Lohiya (2008) considered a system with multiple stockpoints for service parts using a base-stock inventory policy, where the delivery of the items to geographically spread customers is subject to a response time window constraint. If a demand can be filled from a stockpoint's on hand inventory, then delivery is performed by a transportation mode that is fast enough to meet the target response time window. If the on hand inventory is depleted, then the demand is fulfilled through a direct emergency shipment from a warehouse. Hence, backorders do not occur and their impact on the variability of transportation demand that we focus on in the current study is not an issue.

Çetinkaya, Tekin, and Lee (2008) analyzed an inventory system where demands are not satisfied from available inventory immediately upon arrival. By contrast, in order to save transportation costs, the demands are shipped only after a waiting time caused by a quantity-based shipment consolidation. The authors present a model for the simultaneous calculation of the optimum replenishment order size and the optimum shipment quantity taking holding costs, transportation costs and penalty costs related to waiting into account.

Zhao, Chen, Leung, and Lai (2010) studied a warehouse and several subsidiaries operating a vendor-managed inventory system, where the warehouse (the vendor) makes decisions about the quantities to be delivered to the subsidiaries, taking into consideration holding and transportation costs, whereby the latter depend on the required transportation capacity. They propose to represent the problem as a Markov decision process.

Tempelmeier (2005) considered a discrete time inventory system and a subsequent transportation process with a limited number of vehicles. In this system, customer demands may observe a waiting time in the inventory system as well as in the transportation system. The author approximates the probability distribution of the backlog that exists at the arrival of a replenishment order and then he uses a discrete-time Markov chain to model the development of the transportation backlog over time. Eventually an optimization model for the simultaneous computation of the optimal safety stock and the optimal number of vehicles under the constraint of a given average total customer waiting time is formulated. Compared to this research, in the current paper we propose an improved characterization of the arrival process of transportation orders (the departure process from the inventory system). In addition, we assume that the in-house vehicle fleet can be extended by external capacity. Therefore, all transportation orders are delivered without delay.

Büyükkaramikli, Gürler, and Alp (2014) considered a warehouse that observes Erlang-Q demands from a retailer using a continuous review reorder-point reorder-quantity (r, Q) inventory system with Poisson unit sized demands and backorder penalty costs. The warehouse is an ample supplier (hence backorders do not occur) with a fixed transportation capacity. As in the model of Tempelmeier (2005), waiting times in the transportation system may occur. In this setting, the transportation system can be represented as a queueing system with Erlang-Q arrivals, deterministic service times (the travel time of a truck) and multiple servers (the capacitated vehicle fleet). Based on these assumptions, the waiting time distribution of the retailer is calculated and an optimization model is used to find the optimum safety stock for the retailer and the optimum order size as well as the optimum number of vehicles. In an extended setting, the authors assume that the warehouse uses a base-stock policy and that it serves multiple retailers. In this case, the transportation process is modelled as a $G/D/K$ queueing system. Like Geunes and Zeng (2001), the authors observe a smoothing effect on the transportation demand caused by the backorders which may now occur in the warehouse. They construct an optimization model that includes all decision variables in the whole system, namely the order-up-to level and the vehicle fleet in the warehouse as well as the reorder point and the order quantity of the retailer. Our study differs from this paper in that we assume a discrete time axis, an inventory policy other than a base-stock policy leading to longer reorder cycles, an arbitrary demand distribution and an in-house vehicle fleet that is extended, if required, by external capacity. Hence, waiting times in the transportation system do not occur.

In particular, we study the case that an $(r = 1, s, q)$ inventory policy is in effect. With this policy the inventory is reviewed every r periods. If it has reached or has fallen below the reorder point s, an order of size q is released such that the inventory position rises to a level between s and $s + q$. In contrast to the general definition of the $(r, s, n \cdot q)$ policy that allows for the case that a multiple n of q is ordered, we assume that in each period at most one order of size q is released. The (r, s, q) policy is often used in industrial practice when fixed ordering costs play a significant role and hence replenishment cycles significantly longer than one period are economically favorable. We show that in this case, when backorders occur, the *variability of the transportation requirements* does *not decrease* (as observed by Geunes and Zeng (2001) and Büyükkaramikli et al. (2014) for the case of a base-stock policy), but in fact it *increases*. The reason is that whenever demands are backordered, the arrivals of orders in the transportation system are interrupted and resumed only after the next replenishment. Hence, after a time period with no transportation demand follows a single period with large transportation demand.

We state several optimization models that explicitly take into account this phenomenon and demonstrate that neglecting it may lead to significant cost penalties. As a result, inventory decisions must be made under consideration of their impact on the subsequent transportation process, as a cost decrease caused by a safety stock reduction may be offset by an associated increase of the transportation costs. Consequently, whenever transportation plays a role in a distribution process, which is certainly the case in multi-echelon

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