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Stochastic models for the coordinated production and shipment problem in a supply chain ☆

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A R T I C L E I N F O

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A B S T R A C T

In this study, we consider the coordination of transportation and production policies between a single supplier and a single retailer in a stochastic environment. The supplier controls the production, holds inventory and ships the products to the retailer to satisfy the external demand. We model the system as a Markov decision process, and show that the optimal production and transportation decisions are complex and non-monotonic. Therefore, we analyze two widely-used shipment policies in the industry as well, namely time-based and quantity-based shipment policies in addition to a hybrid time-and-quantity based shipment policy. We numerically compare the performances of these policies with respect to the optimal policy and analyze the effects of the parameters in the system.

1. Introduction

In this study, we consider an integrated production and transportation problem between a single supplier and a single retailer in a stochastic environment. The supplier produces the items in a random amount of time, and sends them to the retailer to satisfy the external demand. Customers are willing to wait at the expense of a waiting cost. Consequently, the retailer does not hold inventory, instead he accumulates the orders to satisfy them at a later time when a shipment is received from the supplier. This kind of supply chains are typical for companies that carry on the sales process through sales agents, and for stores making catalog sales. Other examples include the supply chains involved with products that are unreasonable to keep in stock such as large items like photocopy machines, or luxury items like luxury watches or expensive sports cars. The retailers of such products are reluctant to keep them in stock since the inventory holding cost for the retailer is high, and the customer waiting cost is relatively low for a reasonable amount of waiting time. We assume that the supplier makes all the decisions, so that she decides when and how much to ship to the retailer, in addition to when and how much to produce.

Shipment consolidation and its economic consequences have been investigated in literature for more than 30 years. Our paper is closest to a subcategory of this literature, namely to the coordination of inventory and shipment decisions. For a review in this area, we refer to Çetinkaya (2004). Below, we review the studies most closely related to our paper.

We first consider the deterministic models. Çetinkaya and Lee (2002) consider a supply chain in which the supplier replenishes immediately, as opposed to producing the items, and the retailer does not hold inventory. They prove that the transportation cycle lengths in a replenishment cycle can be of two different time lengths. Kaya, Kubali, and Ormeci (2011) consider the same system in Çetinkaya and Lee (2002), except that the supplier produces the items instead of replenishing them instantly. In this case, the transportation cycles can be of three different lengths. Lee, Cetinkaya, and Jaruphongsa (2003) analyze optimal shipment policies with inventory lot sizing at a third-party warehouse. There are a number of studies which analyze the integrated production and shipment policies in a deterministic supply chain, where the retailer holds inventory and the supplier produces, see e.g., Hill (1999), Goyal (1995) and Lu (1995). Finally, the coordination of production and delivery schedules are considered in just-in-time systems in a deterministic environment, see e.g., Hahm and Yano (1995a, 1995b, 1995c).

When the demand arrivals are stochastic, finding and implementing optimal policies pose serious difficulties. Hence, existing literature identifies three types of simple consolidation policies: (1) time-based policies (2) quantity-based policies, and (3) time-and-quantity (TQ) based policies. In a time-based policy, orders are dispatched in every pre-determined time interval, T, whereas under a quantity-based dispatch policy, a shipment is scheduled when the amount of the accumulated orders reaches a pre-determined consolidation quantity, Q. In both of these policies,

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shipments have to satisfy all the outstanding orders. TQ based policies are a hybrid of these two policies, so that they consolidate all orders until the earliest of a pre-determined shipping date, or a minimum pre-determined shipment quantity is reached.

Most of the initial work on the systems with random demand arrivals evaluated the performance of shipment consolidation practices, rather than optimizing the operational policy parameters, see e.g. Bookbinder and Higginson (2002). Çetinkaya and Lee (2000) are one of the first to develop a model to compute the optimal replenishment quantity and dispatch frequency for a stochastic system. They analyze a vendor-managed inventory (VMI) system, where the demand arrivals are stochastic and the retailer does not hold inventory. The system operates under an (s,S) inventory replenishment policy with $s = 0$, and a time-based shipment consolidation policy. Their work has generated a sequence of studies on the subject. Axsater (2001) provides a simple procedure to optimize the exact model in Çetinkaya and Lee (2000). Chen, Wang, and Xu (2005) analyze this system with an (R,Q) inventory replenishment policy under both time-based and quantity-based shipment policies. Çetinkaya, Tekin, and Lee (2008) consider a quantity-based policy in the setting of Çetinkaya and Lee (2000), but now the retailer faces a general stochastic demand process with bulk arrivals, and the vendor uses an (s,S) policy for replenishment with $s = 0$.

Çetinkaya, Mutlu, and Lee (2006) numerically compare the performances of the quantity-based, time-based and hybrid policies for the VMI modeled in Çetinkaya and Lee (2000). More recently, Mutlu and Çetinkaya (2010) extend the model of Çetinkaya and Lee (2000) to systems for which it is economical to use common carriage, rather than a private fleet of vehicles. Çetinkaya and Bookbinder (2003) derive analytical expressions of optimal policy parameters for time-based and quantity-based policies for the settings with private or common carriage opportunities. Mutlu, Bookbinder, and Çetinkaya (2010), on the other hand, derive analytical expressions of optimal policy parameters for TQ based policies, and compare the performances of the three policies analytically. Finally, Toptal and Çetinkaya (2006) address the issue of supply chain coordination in the presence of transportation considerations, and provide insights about how the channel coordination and contractual agreements are affected.

These studies analyzing stochastic models assume that the supplier can replenish immediately. In contrast, we consider a system where the items are produced by the supplier in a random amount of time. Hence, we consider the coordination of production (as opposed to inventory) and shipment decisions with the aim of minimizing the total holding and shipment costs. We analyze the simple consolidation policies, namely time-based, quantity-based and TQ-based policies that are analyzed in literature in the context of warehouse dispatching. In addition, we formulate and solve for an integrated optimal policy and compare the performances of all policies with the optimal one. The randomness in the production process results in a non-monotonic structure in the optimal policy. The production process in the system brings an additional dimension to the model and complicates the analysis. Even for the simple consolidation policies, the solutions cannot be obtained analytically, instead we optimize their parameters by numerical methods.

The information sharing in VMI settings can be carried on at different levels. We develop our first model for the case in which the retailer informs the supplier continuously about the number of outstanding orders. Given this information, the supplier decides on the timing and the quantity of the shipments, in addition to when to start and stop the production. We will refer to this model as the full-information model. Typically, it is not optimal to satisfy the orders immediately, but to let them accumulate for a while in order to satisfy the economies of scale, which results in significant cost savings in certain settings. Therefore, the first model of this study aims to answer the following questions: (i) When and how much should the supplier produce? (ii) When to dispatch a vehicle in order to satisfy the customer orders? (iii) In what quantity to dispatch so that economies of scale are satisfied? For this purpose, we formulate a Markov decision process (MDP) model, and observe that the resulting optimal policies behave in a non-monotone way.

Next, we focus on the three heuristic policies analyzed in literature frequently, namely the time-based, quantity-based and TQ-based policies. These policies are also commonly-used in logistics industry, because of their easy implementation. The underlying information scheme under these policies corresponds to a partial information sharing, as the retailer shares only the probability distribution of the demand process with the supplier. We note that in this case, it is very difficult to determine the optimal solution under general conditions. Hence, we determine the optimal decision variables for the heuristic policies by constructing appropriate MDP models as a part of the optimization procedures. Finally, we numerically compare their performances with respect to the optimal solution in the full information case.

We start our analysis by presenting the full-information model for the system where the supplier has continuous access to the demand information of the retailer. Then, we present the models corresponding to the time-based, quantity-based and TQ-based dispatch policies in Sections 3–5, respectively. Section 6 numerically compares the performances of all the models, and investigates their behavior with respect to different parameters. Finally, we conclude in Section 7.

2. Full-information model

We consider a single-supplier single-retailer supply chain system. The retailer does not hold inventory but accumulates orders to satisfy the customer's demand, where customers are willing to wait at the expense of waiting cost. Waiting cost per unit time, denoted by w, is taken as a penalty associated with delayed shipment. The supplier produces and holds inventory. The supplier's cost of carrying one unit of inventory per unit time is denoted by h. We assume that there is no relationship between w and h, so our results are valid for all possible values of h and w. We assume that an item is produced in an exponential amount of time with mean $1/\mu$, and the demand arrivals follow a Poisson process with an arrival rate of λ. These assumptions aim to model the randomness in demand and production, and are common in literature, see e.g., Carr and Duenyas (2000), de Vericourt, Karaesmen, and Dallery (2002), Örmeci, Burnetas, and Emmons (2002), and Gayon, Benjaafar, and de Vericourt (2009). The supplier incurs a setup cost, denoted as K_p, every time a production process starts. In addition, every time a shipment is dispatched to the retailer, a transportation cost, denoted as K_t, is incurred. We assume that the shipments are made with trucks of capacity P and thus $\lceil Q/P \rceil$ trucks are required for each shipment, where $\lceil a \rceil$ is the ceiling of a real number a. The transportation cost includes a fixed cost R that is independent of the shipment quantity, Q, and the cost of each truck, S, that depends on Q such that $K_t = R + S\lceil Q/P \rceil$. The transportation time between the supplier and the retailer is assumed to be negligible. Finally, we assume that the supplier has the option of outsourcing some of the products instead of producing them, and we let s denote the additional per unit cost of outsourcing instead of producing them in-house. We note that this is without loss of generality for the full-information model, as s can be chosen high enough if outsourcing is not allowed. However, as we will see later, it poses certain restrictions for the time-based, quantity-based and TQ-based models. Hence, we will provide an alternative interpretation for the cost of outsourcing in the context of these models.