Transportation Research Part E 89 (2016) 215–233

Contents lists available at ScienceDirect

Transportation Research Part E

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

Lead time aggregation: A three-echelon supply chain model

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ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form 4 February 2016
Accepted 11 March 2016
Available online 2 April 2016

Keywords:
Supply chain coordination
Lead time aggregation
Stochastic lead time
Three-echelon supply chain

ABSTRACT

In this paper, destructive effects of upstream aggregated stochastic lead times on the supply chain (SC) performance are analyzed. For this purpose, a three-echelon SC consisting of one producer, one distributor, and one retailer is modeled. Both the producer and distributor face stochastic lead times, which can be also aggregated to create a long unpredictable lead time. In order to scale down shortages at the retailer site, an incentive scheme is proposed to convince the upstream members to increase their reorder points. Applying the coordinated model considerably increases the total profit earned by the whole SC as well as all SC members.

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1. Introduction

Supply chain is a system in which all participants cooperate to make a product and deliver it to end customers. Steady flow of materials is a key factor to create an integrated supply chain. The goal of all SC members is to provide a product/service for customers and in turn gain profit from the customers. To achieve this goal, coordination between SC members is required. Supply chain decision structures can be divided into three types based on the relationship between members, namely decentralized, centralized, and coordinated decision making models. Under the decentralized model, each member decides according to its own profit function, while in the centralized model, decisions are made based on the overall SC goal. However, applying the centralized model is often impossible from the practical point of view, because it is disadvantageous for some members (Heydari, 2014b). So, there is a need for an incentive mechanism to entice SC members to shift from the decentralized model to the centralized one (Govindan et al., 2013). In other words, all SC members need enough incentives to be committed to the jointly agreed decisions, which is called coordinated decision making. Meanwhile, lead time can affect the flow of materials throughout the supply chain and reduce the overall SC performance.

Lead time is the duration between placing an order and receiving it. This duration is due to production, transportation, batch processing, etc., which may be long and stochastic. Long and stochastic lead times can interrupt the production process and inventory planning and also decrease service level (Louly and Dolgui, 2013). In real cases, a supply chain may encounter long and stochastic lead times because of the competitive condition of today's global trades (Blackburn, 2012). Change in production process, transportation, and inspection procedures leads to fluctuations in lead times and, consequently, unexpected shortages/surplus in inventory systems (Sajadieh et al., 2009).

The discussed lead time issue is critical in most companies, because the long and uncertain lead times may lead to many disruptions in SC performance. For example, JAM Electronics that is a Korean manufacturer with five facilities in different countries stores the finished products in a central warehouse in Korea and ships them from to different distributors or final

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http://dx.doi.org/10.1016/j.tre.2016.03.006
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customers. In the late 90s and early 2000s, the company's service level in the USA market was constantly low and about 30% of the orders were not delivered on time. The major reason for the low service level was long lead time within the supply chain. There were two primary reasons for the long lead time: first, long processing time in the central distribution center and, second, very long transits (Simchi-Levi et al., 2000). In another case, in 2014, Nepal's domestic footwear industry was confronted with raw material shortage due to the halt of raw material imports from Chinese suppliers which were in contract for supplying 40% of the required raw materials. As a result, some small factories were closed down and some confronted lost sales due to supply disruption and supply uncertainty (Kathmandu Post, 2014). There are many real instances of long and uncertain lead times that make downstream members and SC service level inefficient. For example, in 1997, Boeng Company faced a write-down of 2.6 billion dollars which was caused in part from part-suppliers shortages. In 1999, Apple Company could not respond to the customers' demand due to the late supply of G4 chips supplied by Motorola Company.

Another evidence of the investigated issue in this study is Okuma America Corporation, a machine tool builder. Okuma requires each of its 46 distributors to carry a minimum inventory to ensure there is enough inventory at all times either in its warehouse or somewhere in the distribution channel. Using this strategy, Okuma prevents shortages due to long and uncertain supply lead time (Narus and Anderson, 1996). Similar to the case of Okuma, in this study, we propose a model to ensure enough inventories in both producer and distributor centers while avoiding the propagation of undesirable effects of supply lead time uncertainties.

Lead time aggregation means crossing an SC member's lead time with some or all of the upstream members' lead times. In other words, the aggregation of lead times may occur when the upstream is out of stock at time of issuing an order by the downstream. In the case of lead time aggregation, the downstream member faces an unpredictable long lead time, which in turn causes large shortages.

In this paper, a three-echelon supply chain is investigated in which both the producer and distributor are confronted with stochastic lead times. The retailer plans a reasonable service level based on the received demand and its fixed lead time. However, in some replenishment cycles, where all members concurrently replenish their stock, lead time aggregation may occur, which in turn causes substantial lowering in the service level. Our investigation revealed that the major reason for these situations is lead time aggregation of two successive or whole supply chain members. According to the definition of lead time aggregation, if upstream is out of stock at the time of issuing an order by downstream, then lead times are aggregated. Accordingly, if the upstream replenishes its stock earlier by setting its reorder point in a higher position; then, the possibility of lead time aggregation diminishes. Lead time aggregation occurs due to supply uncertainty or unreliable supply system. Avoiding lead time aggregation reduces shortage occasions and, therefore, increases SC service level as well as SC profitability. However, shifting reorder point to a higher position leads to more surplus inventory for upstream members; therefore, they refuse to do so and do not participate in this scheme unless their benefits are guaranteed.

Questions that will be answered during this study are: (1) is it possible to create a replenishment policy for upstream members in order to reducing risk of lead time aggregation? (2) What are the optimal replenishment policies consisting of reorder point and order quantity decisions for SC upstream members in presence of lead time aggregation? (3) How can an appropriate incentive mechanism be proposed to induce upstream members to accept these optimal policies? To answer these questions, a three-echelon supply chain model with one producer, one distributor, and one retailer is modeled. When the inventory level at the retailer site reaches the reorder point level, an order is placed to the distributor; if the distributor has enough inventories, then after a fixed lead time, the issued order will be delivered. Similarly, at the distributor site when the inventory level reaches the distributor's reorder point, an order will be sent to the producer that will be delivered after a stochastic lead time with the known mean and variance. Also, the producer orders from an external supplier with a stochastic lead time. If lead time aggregation happens at the retailer site, then shortages occur. It is assumed that shortages will be backordered with a penalty cost at the retailer site. While the retailer faces shortage costs, the upstream members will never incur shortage costs due to their higher bargaining power. Supply chain is modeled under two different settings: (1) Decentralized decision making model in which each SC member decides based on its own profit and (2) Centralized decision making model in which all SC members collaborate to increase the overall SC profitability. Under the decentralized decision making, upstream members may choose a lower reorder point to decrease their inventory holding costs. However, under centralized decision making model, to reduce shortage costs, it is expected from upstream members to raise their reorder points to prevent costly shortages at the retailer site. Therefore, in the centralized model, upstream inventory holding costs will increase, so there is a need for an incentive scheme to compensate for the increased costs of the upstream members. Such an incentive scheme guarantees the participation of all SC members in the joint decision making. A company may apply two kinds of strategies, namely adapter and shaper strategies, when confronting uncertainties. In the adapter strategy, the company does not focus on uncertainty levels, but controls the company's own operations and planning processes to adapt to the uncertainties such as increasing inventory levels and keeping more safety stocks. In contrast, by applying a shaper strategy, company tries to form uncertainties in a desired shape. Shaper strategies let the company adjust the risk of uncertainties (Gupta and Maranas, 2003). In this study, a strategy is applied which is shaper from the retailer's perspective and, at the same time, is considered an adapter strategy from the whole SC viewpoint; we can call the proposed strategy a semi-shaper strategy. Based on the proposed strategy, upstream members raise their reorder points in order to decrease the likelihood of lead time aggregation.

In the proposed model, the optimum inventory control policy in a three-echelon supply chain is extracted in light of stochastic lead time between upstream members by considering the probability of crossing these stochastic lead times. In addition, the proposed model includes an applicable scheme to induce upstream members to accept the optimal policy.

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