Int. J. Production Economics 136 (2012) 37–44

Contents lists available at SciVerse ScienceDirect

Int. J. Production Economics

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

# Lead time reduction strategies in a single-vendor–single-buyer integrated inventory model with lot size-dependent lead times and stochastic demand

Christoph H. Glock*

*Chair of Business Management and Industrial Management, Faculty of Economics, University of Wuerzburg, Sanderring 2, 97070 Wuerzburg, Germany*

ARTICLE INFO

*Article history:*
Received 21 July 2010
Accepted 2 September 2011
Available online 10 September 2011

*Keywords:*
Lead time reduction
Variable production rate
Single vendor
Single buyer
Integrated inventory model

ABSTRACT

This paper studies alternative methods for reducing lead time and their impact on the safety stock and the expected total costs of a $(Q,s)$ continuous review inventory control system. We focus on a single-vendor–single-buyer integrated inventory model with stochastic demand and variable, lot size-dependent lead time and assume that lead time consists of production and setup and transportation time. As a consequence, lead time may be reduced by crashing setup and transportation time, by increasing the production rate, or by reducing the lot size. We illustrate the benefits of reducing lead time in numerical examples and show that lead time reduction is especially beneficial in case of high demand uncertainty. Further, our studies indicate that a mixture of setup time and production time reduction is appropriate to lower expected total costs.

## 1. Introduction

Lead time plays an important role in today's logistics management. Defined as the time that elapses between the placement of an order and the receipt of the order into inventory (see Silver et al., 1998), lead time may influence customer service and impact inventory costs. As the Japanese example of just-in-time-production has shown, consequently reducing lead times may increase productivity and improve the competitive position of the company (see also Tersine and Hummingbird, 1995).

In the inventory management literature, lead time has often been treated as a decision variable that may be varied within given boundaries. If it is assumed that lead time can be decomposed into several components, such as setup time, process time, or queue time, for example (see Tersine, 2002), it can be assumed that each component may be reduced at a crashing cost. For example, one could restructure the production process or use a sophisticated factory information system to reduce setup time or increase setup accuracy (see Shingo, 1985; Trovinger and Bohn, 2005), modify the production equipment to speed up the production process or implement a batch transfer policy to benefit from overlapping production cycles (see Hopp et al., 1990). Reducing lead times is especially important in situations where customer demand is uncertain, since long lead times put the company at a high risk of running out of stock before an order arrives. In this context, a variety of studies illustrate that reducing replenishment lead time may lower the safety stock, reduce the stock-out loss, and improve the customer service level, which results in lower expected total costs. Further, it has been shown that lead time is correlated with financial performance indicators, such as ROI or average profit (see Christensen et al., 2007), which underscores the importance of managing lead time.

One major drawback we identified when studying the literature on lead time reduction in inventory models is that the vast majority of authors assumed that lead time is independent of the lot size quantity and that a piecewise linear function is appropriate to describe the relationship between lead time reduction and lead time crashing costs. While the resulting models may be suitable to describe a variety of industries, lead times often vary with the manufacturing lot size in practice. Further, we may assume that the relationship between lead time reduction and lead time crashing costs is not necessarily linear in nature and that more complicated cost structures may be found in reality.

To close the research gap identified above and to provide both practitioners and researchers with a comparison of alternative methods for reducing lead time, this paper studies an inventory model with stochastic demand and variable, lot-size dependent lead time under different lead time reduction strategies. We assume that lead time consists of production and setup and transportation time, and that lead time may be reduced by shortening setup and transportation time and/or by increasing the production rate, which results in reduced production time. We explicitly focus on a two-stage production system with a manufacturer and a buyer to study the impact of individual decisions on the total expected costs of the system.

The paper is organized as follows: in the next two sections, the article reviews related literature and outlines the assumptions and definitions which are used in the remaining parts of the paper. Subsequently, we develop a formal model and propose a solution method to find an approximate optimal solution.

---

* Tel.: +49 931 31 82408; fax: +49 931 31 2405.
*E-mail addresses:* christoph.glock@uni-wuerzburg.de, christoph.glock@gmx.de
*URL:* http://www.ibl.wifak.uni-wuerzburg.de

0925-5273/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijpe.2011.09.007

Numerical examples and the results of a simulation study are presented in Section 5. Section 6 concludes the article.

## 2. Literature review

One of the first papers dealing with a variable lead time in an inventory model is due to Liao and Shyu (1991). The authors assume that lead time can be decomposed into several components, each having a different piecewise linear crashing cost function for lead time reduction, and that each component may be reduced to a given minimum duration. Under the assumption that the lot size is predetermined and that demand is normally distributed, they calculate an optimal lead time and show that reducing lead time may result in lower expected total costs.

Ben-Daya and Raouf (1994) revisit Liao and Shyu (1991) and propose a model that treats both lead time and order quantity as decision variables. They develop two models, one that uses the lead time crashing cost-function proposed by Liao and Shyu and one that uses an exponential crashing cost function. Ouyang et al. (1996) introduce another extension and include shortages in the model. They assume that a certain fraction of the demand during the stockout period is backordered and that the remaining fraction results in lost sales. Chandra and Grabis (2008) develop a model with lead time-dependent procurement costs and assume that shortening lead time results in increased procurement costs. The relationship between lead time and procurement costs is established with the help of a linear and a nonlinear procurement cost function.

Other authors permit further parameters to be varied as well. Ben-Daya and Hariga (2003), for example, study a model wherein both lead time and setup costs may be reduced at a crashing cost. Further, they assume that learning effects occur in the production process and that the time which is necessary to produce one unit of output, decreases with an increasing production quantity. For other lead time components, they adopt the formulation introduced by Liao and Shyu (1991) and propose an algorithm that minimizes total expected costs. Similarly, Ouyang and Chang (2002) develop a model with lead time and setup cost reduction and study the effect of an imperfect production process on the optimal lead time length. In contrast to Ben-Daya and Hariga (2003), the authors assume that the lead time crashing cost factor varies with the lot size. Further extensions can be found in Pan and Lo (2008), who study both lead time reduction and learning effects in setup time, or in Zequeira et al. (2005), who analyze the impact of lead time-dependent stockout costs on lead time reduction.

Pan and Yang (2002) are the first authors who study lead time reduction in a setting with more than one economic actor. They consider a system where a single vendor delivers a product to a single buyer and assume that the vendor may reduce lead time according to the scheme proposed by Liao and Shyu (1991). Under the assumption that lead time crashing costs incurred by the vendor are fully transferred to the buyer if shortened lead time is requested, they calculate an optimal lead time length that minimizes total system costs. Ouyang et al. (2004) revisit Pan and Yang (2002) and include shortage costs in the model formulation. Further, they assume that only the first and second moments of the probability of lead time demand are known and finite and solve the model using the minimax distribution-free approach. Further extensions can be found in Hoque and Goyal (2006) and Hoque (2007), who study the effect of lead time reduction and different batch sizes on the coordination of a single-vendor–single-buyer system, or in Yang and Pan (2004) and Wu et al. (2007), who include quality considerations in the model formulation.

One of the few models that consider lot size-dependent lead times is due to Kim and Benton (1995), who assume that production lead time varies linearly with the lot size and that a queuing factor has to be considered to account for the time a lot spends in queues or materials handling processes. The model is extended by Hariga (1999). Maiti and Maiti (2007) propose another inventory model with lot size-dependent lead time and assume that lead time is subject to learning effects and fuzzy in nature. However, all three models do not take lead time reduction into account.

In this paper, we extend the previous literature by considering a single-vendor–single-buyer integrated inventory model with lot size-dependent lead time and lead time reduction. We assume that lead time consists of production time and setup and transportation time and that lead time may either be reduced by shortening setup and transportation time or by increasing the production rate, which results in a reduced production time.

## 3. Model assumptions and definitions

The following terminology is used throughout the paper:

| | |
|---|---|
| $a_1$ | per unit time costs of running the machine independent of the production rate |
| $a_2$ | the increase in unit machining cost due to one unit increase of the production rate |
| $c_O$ | order costs per order |
| $c_P(P)$ | unit production cost function |
| $c_S$ | setup costs per setup |
| $c_T$ | transportation costs per shipment |
| $c_{C,i}$ | crashing cost of setup time component $i$ |
| $D$ | demand rate in units per unit time |
| $\varepsilon$ | fraction of transportation time $t_T$ in setup and transportation time $t_S$, i.e. $\varepsilon = t_T/t_S$ |
| $h^{(b)}$ | unit inventory carrying charges per unit of time at the buyer |
| $h^{(v)}$ | unit inventory carrying charges per unit of time at the vendor |
| $L$ | lead time |
| $m$ | number of lead time components |
| $n$ | number of shipments from the vendor to the buyer |
| $k$ | safety factor |
| $p$ | $1/P$ |
| $P$ | production rate in units per unit time |
| $\pi$ | backorder costs per unit backordered |
| $Q$ | production lot size |
| $S$ | safety stock |
| $s_1$ | reorder point of batch 1 |
| $s_2$ | reorder point of batches $2,\ldots,m$ |
| $\sigma$ | standard deviation |
| $R(L)$ | setup time crashing costs |
| $t_S$ | setup and transportation time |
| $t_{S,i}$ | $i$th component of setup and transportation time |
| $t_T$ | transportation time of a batch shipment |
| $U_i$ | normal duration of lead time component $i$ |
| $u_i$ | minimum duration of lead time component $i$ |
| $x_1$ | demand during lead time of shipment 1 |
| $x_2$ | demand during lead time of shipments $2,\ldots,m$ |

Further, the following definitions will be used:

| | |
|---|---|
| Max$[a,b]$ | denotes the largest element of $\{a,b\}$ |
| Min$[a,b]$ | denotes the smallest element of $\{a,b\}$ |
| $[a]$ | denotes rounding a non-integer value $a$ to the nearest integer |

Finally, the following assumptions were made in developing the proposed model:

- This paper considers a single buyer ordering a product at a single vendor.