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Coordinating a three-level supply chain with learning-based continuous improvement [☆]

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ABSTRACT

Learning curve theory has been widely used as a managerial tool to describe and model product and process improvement. This paper investigates a three-level supply chain (supplier–manufacturer–retailer) where the manufacturing operations undergo a learning-based continuous improvement process. Improvements in the manufacturer's operation are characterized by enhanced capacity utilization, reductions in set-ups times, and improved product quality through the elimination of rework. As a result of these continuous improvements, the manufacturer can justify a production policy that is based on more frequent, smaller lot size production. For this production policy to be practical and not sub-optimal to the supply chain, the manufacturer must integrate its lot-sizing models with the replenishment policies of its upstream raw material suppliers and the demand requirements of its downstream customers (retailers). Mathematical models that achieve chain-wide lot-sizing integration are developed and solution procedures for the models are illustrated by numerical examples. The results demonstrate that learning-based improvements in set-up time and rework allow retailers to order in progressively smaller lot sizes as the manufacturer offers larger discounts and profits and that the entire supply chain benefits from implementing learning-based continuous quality improvements. The results also demonstrate that forgetting effects lead to increases in supply chain costs.

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1. Introduction

The modern market for products is dynamic, global and competitive. This environment imposes pressures on companies to deliver quality products at competitive prices when they are required. Product life cycles are shortening requiring companies to reduce the time from concept to market. Together, these pressures compel companies to be responsive to market changes, efficient and flexible.

The late 1990s and the beginning of this millennium was a period of intense interest in supply chain management providing sustainable competitive advantage for companies (Dell and Fedman, 1999). Effective supply chain management involves the integration of functions such as production, purchasing, materials management, warehousing and inventory control, distribution,

shipping, and transport logistics. This integration is needed within the operations of specific supply chain members and, more importantly, across all members of the supply chain. To maintain sustainable competitiveness, operations within the supply chain will benefit from continuous improvement programmes that include fostering organizational learning. Historically, learning curve theory has been applied to a diverse set of management decision areas such as inventory control, production planning and quality improvement. These decision areas exist both within the individual organizations of the supply chain and, as a result of the interdependencies among chain members, across the supply chain as a whole. By using established learning models to model these learning effects, management may utilize capacity, manage inventories and coordinate production and distribution better throughout the chain.

The lot-sizing problem with learning and forgetting effects in production has received considerable attention from researchers and a detailed review of this literature is found in Jaber and Bonney (1999). Jaber and Bonney (2003) also investigated the effects that learning and forgetting in set-ups and in product quality have on the economic lot-sizing problem. In recent years, the lot-sizing problem with learning and forgetting has been investigated within the context of the economic manufacture quantity model (e.g., Balkhi, 2003; Chiu et al., 2003; Chiu and

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Chen, 2005; Jaber and Guiffrida, 2007; Alamri and Balkhi, 2007; Jaber and Bonney, 2007; Jaber et al., 2009) and to a lesser extent in conjunction with the Joint Economic Lot-Sizing Problem (JELSP) by Nanda and Nam (1992, 1993).

The JELSP forms the basis of a two-level supply chain with order coordination between the chain members. Nanda and Nam (1992) developed a joint manufacturer–retailer inventory (two-level supply chain) model for the case of a single buyer. Production costs were assumed to reduce according to a power form learning curve (Wright, 1936) with forgetting effects caused by breaks in production. A quantity discount schedule was proposed based on the change of total variable costs of the buyer and manufacturer. To meet the demand of the buyer, the manufacturer considers either a lot-for-lot (LFL) production policy (e.g., Banerjee, 1986; Goyal and Gupta, 1989), or a production quantity that is a multiple of the buyer's order quantity (Lee and Rosenblatt, 1985; Goyal and Gupta, 1989). Nanda and Nam (1992) assumed a LFL policy, and did not specify the form of the forgetting curve. They extended their work in a subsequent paper (Nanda and Nam, 1993) to include multiple retailers.

This paper develops the work of Nanda and Nam (1992) and Jaber and Bonney (2003) to investigate a joint replenishment inventory model for a three-stage (supplier–manufacturer–retailer) decentralized supply chain with the manufacturer encountering learning and forgetting effects in set-ups, production, and product quality. The objective of the research is to fill gaps in the literature with respect to quality improvement in the supply chain. Our model integrates research from the fields of economic lot sizing in supply chains and learning theory to construct a quality based supply chain model. Quality improvement in supply chain management has not been addressed in detail within the supply chain literature (Sila et al., 2006). The majority of research on quality improvement in supply chains is based on two dimensions (i) empirical survey based research that attempts to identify the importance of quality improvement in the supply chain as well as identifying the key factors that support the need for quality in the supply chain (see for example; Lo and Yeung, 2006; Kuei et al., 2001; Kanji and Wong, 1999) or (ii) the development of two-stage supply chain decision models for implementing quality issues into supply chains (see for example Zhu et al., 2007). In this paper we present a decision model for analyzing quality improvement. Our model bridges the current gap in supply chain quality management by introducing a quantitative decision model for investigating quality improvement in a more realistic three-stage (supplier–manufacturer–retailer) environment.

Munson and Rosenblatt (2001) were the first to model a three-level supply chain. They assumed that all parameters were deterministic and that: (i) the retailer orders a single product according to its economic order quantity (EOQ), (ii) the manufacturer optimises its lot-sizing policy according to the lumpy order pattern, which is an integer multiple of the retailer's order quantity, and (iii) an integer multiple of the manufacturer's order quantity the supplier orders based on the lumpy ordering pattern of the manufacturer. Munson and Rosenblatt (2001) further assumed that the manufacturer is the most influential player in the supply chain who offers quantity discounts to the retailer to entice him/her to order in larger quantities than the retailer's economic order quantity. Quantity discounts were computed in the model (e.g., \$/unit) as the difference in holding and ordering costs between the retailer's old ordering policy (no coordination) and its new ordering policy (with coordination) divided by the annual demand. Jaber et al. (2006) extended the work of Munson and Rosenblatt (2001) by assuming a price discount approach, a price-dependent demand and profit sharing scenarios. This paper, like Jaber et al. (2006), adopts a centralized decision-making

process for coordinating the supply chain model and assumes that the savings (increased profits) arising from coordination will be shared among the players in the supply chain. The coordination of decisions within a supply chain can be broadly classified into two types of decision-making structures: *centralized* or *decentralized*. A centralized decision-making process assumes a unique decision-maker managing the whole supply chain with an objective to minimise (maximise) the total supply chain cost (profit) whereas a decentralized decision-making process involves multiple decision makers who have conflicting objectives. A casual review of the literature of recent supply chain publications illustrates that both orientations (centralized and decentralized) routinely appear in the literature. Recent literature on SC management classified by type of decision-making process is tabulated below:

<i>Models with centralized decision making</i>	<i>Models with decentralized decision making</i>
1) Üster et al. (2008)	1) Disney et al. (2008)
2) Zou et al. (2008)	2) Bernstein et al. (2006)
3) Majumber and Srinivasan (2006)	3) Mishra et al. (2007)
4) Schwart et al. (2006)	4) Güllü et al., (2005)
5) Van Hoesel et al. (2005)	5) Huang and Irvani (2005)

The remainder of the paper is organized as follows. The next section, Section 2, provides a brief description of the learning–forgetting process. Section 3 describes the notation and assumptions. Section 4 develops a mathematical programming model with its sub-cost functions and its solution procedure. Section 5 provides numerical examples and discusses the results. Section 6 summarises and concludes the paper.

2. The learning and forgetting process

Most researchers and practitioners accept the Wright (1936) learning curve because of its simple mathematical form and its ability to fit empirical data quite well (e.g., Yelle, 1979; Jaber, 2006) and so it is understandable that most works that have investigated the economic order (manufacture) quantity model with learning and forgetting use the power form learning curve, usually written as

$$y_x = y_1 x^{-b} \quad (1)$$

where y_x is the time to produce the x th unit, y_1 is the time to produce the first unit, x is the cumulative quantity produced, and b is the learning exponent; where $0 < b < 1$, $b = -\log(\phi)/\log(2)$, and ϕ is the learning rate expressed as a percentage.

The learn–forget curve model (LFCM) developed by Jaber and Bonney (1996) will be adopted in this article. The LFCM has been shown to be a potential model to capture the learning–forgetting process. Interested readers may refer to Jaber and Bonney (1997), Jaber et al. (2003), and Jaber and Sikström (2004a; 2004b) for further background. The LFCM suggests that the forgetting curve is of a power form similar to (1) with the forgetting exponent in cycle i , f_i , computed as

$$f_i = \frac{b(1-b)\log(u_i + n_i)}{\log(1 + B/t(u_i + n_i))} \quad (2)$$

where $0 \leq f_i \leq 1$, n_i is the number of units produced in cycle i up to the point of interruption, B is the break time to which total forgetting occurs, b is the learning curve exponent in (1), and u_i is the number of units remembered at the beginning of cycle i ,

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