European Journal of Operational Research 243 (2015) 815–825

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Production, Manufacturing and Logistics

Analysis of the bullwhip effect in two parallel supply chains with interacting price-sensitive demands

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ARTICLE INFO

Article history:
Received 11 September 2013
Accepted 24 December 2014
Available online 30 December 2014

Key Words:
Supply chain management
Bullwhip effect
Multiple supply chains
Interaction
Price-sensitive

ABSTRACT

This paper offers insights into how the bullwhip effect in two parallel supply chains with interacting price-sensitive demands is affected in contrast to the situation of a single product in a serial supply chain. In particular, this research studies two parallel supply chains, each consisting of a manufacturer and a retailer, and the external demand for a single product depends on its price and the other's price in a situation in which each price follows a first-order autoregressive process. In this paper, we propose an analytical framework that incorporates two parallel supply chains, and we explore their interactions to determine the bullwhip effect. We identify the conditions under which the bullwhip effect is amplified or lessened with interacting price-sensitive demands relative to the situation without interaction.

1. Introduction

The adoption of the simple serial supply chain structure model assumption is a powerful technique for studying the bullwhip effect; see, e.g., Lee, Padmanabhan, and Whang (1997a), Chen, Drezner, Ryan, and Simchi-Levi (2000a), Chen, Ryan, and Simchi-Levi (2000b), and Alwan, Liu, and Yao (2003). However, in many industries (e.g., automotive, electronic equipment, telecommunication, fast food, and apparel), the traditional model of a serial supply chain that addressed the issue of the bullwhip effect is giving way to a new paradigm of chain-to-chain interactions (e.g., potential competitions or collaborations). It is clear that in such interactions, either an upstream firm tier or a downstream firm tier in one supply chain interacts not only with its corresponding firm tier but also with the entire other chain. The performance of a supply chain will be influenced by the chain-to-chain interaction. However, it is not obvious in such interactions that the supply chain or the industry will be benefited or not from the bullwhip aspect. Boyaci and Gallego (2004), Ha and Tong (2008), Zhang and Zhao (2010), and Ha, Tong, and Zhang (2011) have investigated supply chain coordination and information sharing in two competing supply chains based on the non-serial supply chains assumption. However, these research works do not report any insight on the bullwhip effect in supply chain networks. Instead, we investigate the impact on the bullwhip effect of the two parallel supply chain interaction caused by product substitutability or complementarity.

In this paper, we use the bullwhip effect as a measure of the supply chain performance, and we consider an industry with two parallel supply chains that display interactions at the level of their demand streams. A number of industries meet the criteria of our model. In the automotive industry, which includes Honda and Toyota, each forms a chain with its downstream dealer, who shares the same demand market. It is clear that the car's selling price plays an important role in its market share. For example, the higher the Honda car's selling price, the lower its market demand will be, and vice versa. However, because of the substitutability between Honda and Toyota, if the Toyota car's selling price is too high, a strategic consumer will switch to Honda and therefore increase its market share if the two brands have nearly the same configurations and if there are no brand preferences. Similarly, a lower Toyota car's selling price will restrain the Honda market share. In other words, consumers make purchase decisions based not only on the Honda car's selling price but also on that of the Toyota. This situation is also relevant in the mobile telecommunication industry for competing products (e.g., Samsung Galaxy Note II and Apple iPhone 5) and in the food industry for complementary products (e.g., pizza and soft drink).

The objective of this paper is to offer insights into how the bullwhip effect is affected in two parallel supply chains with interacting price-sensitive demands as opposed to a single product in a serial

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http://dx.doi.org/10.1016/j.ejor.2014.12.043
0377-2217/

supply chain. To do so, we consider two supply chains in which each distributes a single product and each consists of a manufacturer and a retailer. The demand in each supply chain is price-sensitive, and its market demand scale depends on the two product prices. In other words, because the two products are substitutable/complementary or the two supply chains are competitors/partners, the market demand scale in each supply chain depends not only on its own price but also on the price in the other supply chain. Assuming that both retailers use an optimal order-up-to-inventory policy and an optimal minimum mean-squared error (MMSE) forecasting technique, we explore their interactions in determining the bullwhip effect and derive conditions under which the bullwhip effect is amplified (or lessened) relative to the situation without interaction.

This paper is organised as follows. Section 2 reviews the literature. Section 3 presents the interacting demand and price processes in two parallel supply chains. Section 4 introduces the inventory policy and the forecasting technique for each supply chain. Section 5 investigates the interactions between the two parallel supply chains in determining the bullwhip effect and derives the conditions under which the bullwhip effect is amplified (or lessened) with interacting price-sensitive demands relative to the situation without interactions. Section 6 provides a numerical study to explain the conditions and reveal managerial insights. Finally, Section 7 concludes the paper and suggests follow-up research directions.

2. Literature review

The bullwhip effect describes the phenomenon of information distortion as ordering information percolates upstream, which means that a downstream demand fluctuation will lead to larger fluctuations in the variance of upstream ordering (Lee et al., 1997a; Lee, Padmanabhan, & Whang, 1997b). This effect can lead to tremendous inefficiencies in a supply chain, including excessive inventory, poor product forecasts, insufficient or excessive capacities, poor customer service due to unavailable products or long backlogs, and uncertain producing planning (Lee et al., 1997b). Because the bullwhip effect is recognised as one of the main obstacles to improving supply chain performance, it has received much attention in recent years from supply chain managers and researchers.

Early studies attempted to demonstrate the existence of the bullwhip effect and identify the causes of such an effect (Forrester, 1958, 1961; Sterman, 1989). In the ensuing years, numerous studies focused on quantifying the bullwhip and searching for remedies in a serial supply chain using different approaches. The majority of the existing research applies a statistical approach to establish a closed-form expression used to quantify the bullwhip effect under an autoregressive demand process, such as the first-order autoregressive demand (AR (1)) that was published in Kahn (1987), Lee et al. (1997a), and Aviv (2002), the autoregressive and moving average (ARMA) demand of (1, 1) that was published in Graves (1999) and Miyaoka and Hausman (2004), and the more general ARMA demand of (p, q) that was published in Zhang (2004) and Gaur, Giloni, and Seshadri (2005). Additionally, Gilbert (2005) and Chen et al. (2000a, 2000b) made an important contribution by recognising the role of demand forecasting as a filter for the bullwhip effect. Chen et al. (2000a) quantified the bullwhip effect for a two-level supply chain in which the retailer used the moving average (MA) forecasting technique. Following this paper, Chen et al. (2000b) demonstrated that the use of exponential smoothing (ES) technology by the retailer could also cause the bullwhip effect. However, although MA and ES are the most commonly used forecasting techniques, these methods are not optimal. Alwan et al. (2003) studied the bullwhip effect that occurred when the MMSE-optimal forecasting technique was employed. This group found that the bullwhip effect approaches a limiting value when the demand process follows a positively correlated AR (1) process, and there is no bullwhip effect for a negatively correlated process. Similar or more advanced demand models have also been adopted by Aviv (2003), Croson and Donohue (2006), Chen and Lee (2009), Zhang and Zhao (2010), and Ma, Wang, Che, Huang, and Xu (2013a, 2013b).

In addition to the statistical approach, a system control theoretic framework based on the serial supply chain assumption was recently introduced to investigate the bullwhip effect in the 'frequency domain' (Daganzo, 2004). Based on the Laplace transform introduced by Simon (1952), Vassian (1955) discussed the application of control engineering to design an inventory control scheme that will minimise the variance of the inventory balance subject to the imposed conditions. Dejonckheere, Disney, Lambrecht, and Towill (2003) measured the bullwhip effect using discrete control theory and z-transform techniques. Similarly, using the control theory, Disney, Towill, and Van De Velde (2004) derived an analytical expression for the bullwhip effect and combined this expression with the expression of inventory variance to determine suitable ordering system designs. Ouyang and Daganzo (2006) modelled the supply chain as a single-input/single-output control system driven by arbitrary customer demands and derived robust analytical conditions to predict the presence of the bullwhip effect.

In addition to the above theoretical efforts for determining mathematical representations of the bullwhip effect in a serial supply chain, attempts were also made to validate its existence in empirical and simulation studies. Lee et al. (1997b) used examples such as Procter & Gamble (P&G) and Hewlett–Packard (HP) to exemplify the existence of and remedies for the bullwhip effect. Wu and Katok (2006) simulated a multi-echelon serial supply chain following the basic protocol of the 'beer distribution game' to investigate the impact of learning and communication on the bullwhip effect, and this group found that the bullwhip effect is caused by insufficient coordination between supply chain partners. In contrast, Baganha and Cohen (1998) reviewed selected empirical results concerning the destabilising effect of inventory in a multi-echelon supply chain. They showed how the optimal behaviour of the firms could lead to a stabilising effect of inventories and that variance amplification is not always present throughout the supply chain. Consistent with the previous theory, Cachon, Randall, and Schmidt (2007) collected macroeconomic industry-level data and also found that demand volatility does not necessarily increase as one moves up the supply chain. In contrast to the natural consequences of the bullwhip effect in the existing literature, this group observed that most manufacturers generally do not have substantially greater demand volatility than retailers. The authors explained these results with seasonally unadjusted data that provide a strong motivation for firms to attenuate variability and mitigate the incentives to amplify.

In contrast to the work of Cachon et al. (2007), we employ the statistical approach to provide another strong force that mitigates the bullwhip effect, and we focus on measuring and analysing the bullwhip effect analytically. We investigate the bullwhip effect in two parallel interacting supply chains as opposed to that in a serial supply chain. Our findings reveal that managers who ignore the interaction between supply chains may overstate the bullwhip effect. For example, in our research, we show that no bullwhip effect exists for the two competitive supply chains if the product properties meet certain conditions.

Undoubtedly, the adoption of the simple serial supply chain structure model assumption has represented and continues to represent a powerful technique for studying the bullwhip effect. However, due to the network structure complexity of the supply chains in industry, modern supply chains often exhibit strong interactions in the content of multiple interacting demand streams caused by market effects. Thus, the assumption of a simple serial supply chain is out of sync with the times. Only few studies are available based on the non-serial supply chains assumption (Boyaci & Gallego, 2004; Ha & Tong, 2008; Ha et al., 2011; Zhang & Zhao, 2010). However, these research works focus on investigating supply chain coordination