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A real-time SPC inventory replenishment system to improve supply chain performances

Francesco Costantino [a], Giulio Di Gravio [a], Ahmed Shaban [a,b,*], Massimo Tronci [a]

[a] Department of Mechanical and Aerospace Engineering, University of Rome "La Sapienza", Via Eudossiana, 18, 00184 Rome, Italy
[b] Department of Industrial Engineering, Faculty of Engineering, Fayoum University, 63514 Fayoum, Egypt

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ABSTRACT

Inventory replenishment rules contribute significantly to the bullwhip effect and inventory instability in supply chains. Smoothing replenishment rules have been suggested as a mitigation solution for the bullwhip effect but dampening the bullwhip effect might increase inventory instability. This paper evaluates a real-time inventory replenishment system denoted as SPC that utilizes a control chart approach to counteract the bullwhip effect whilst achieving competitive inventory stability. The SPC employs two control charts integrated with a set of decision rules to estimate the expected demand and adjust the inventory position, respectively. The first control chart works as a forecasting mechanism and the second control chart is devoted to control the inventory position variation whilst allowing order smoothing. A simulation analysis has been conducted to evaluate and compare SPC with a generalized (R, S) policy in a four-echelon supply chain, under various operational settings in terms of demand process, lead-time and information sharing. The results show that SPC is superior to the traditional (R, S) and comparable to the smoothing one in terms of bullwhip effect, inventory variance, and service level. Further managerial implications have been obtained from the results.

1. Introduction

Inventory control is a major activity for operating supply chains in which each partner attempts to decide how much and when to order for maintaining a high service level. There is a large body of inventory-related theory that optimizes the inventory costs within simple inventory systems but when these optimal policies are used together in a supply chain system, they create the bullwhip effect (Fig. 1), that is, order variability is amplified as moving up the supply chain (Disney & Grubbström, 2004; Lee, Padmanabhan, & Whang, 1997a, 1997b). Bullwhip effect can cause stock outs, low service level, and extra transportation and capacity costs in supply chains. The bullwhip effect has been observed in many real cases such as Campbell Soup's (Fisher, Hammond, Obermeyer, & Raman, 1997), HP and P&G (Lee et al., 1997a), a clothing supply chain (Disney & Towill, 2003), Glosuch (McCullen & Towill, 2000), and fast moving consumer goods (Zotteri, 2012).

Previous research has shown the importance of selecting/designing the appropriate ordering policies integrated with the accurate forecasting methods in order to mitigate the bullwhip effect (Jaipuria & Mahapatra, 2014; Wright & Yuan, 2008). Furthermore, other researchers have developed smoothing replenishment rules to avoid/eliminate the bullwhip effect with modifying the structure of the periodic review (R, S) policy, commonly used in practice, by incorporating smoothing controllers (Dejonckheere, Disney, Lambrecht, & Towill, 2003, 2004). In traditional (R, S), the order is generated to recover the entire gaps between the target and current levels of net inventory (safety stock) and supply line inventory while in smoothing (R, S) only a fraction of each gap is recovered, where the target levels are dynamically updated with demand forecast every review period. However, dampening the bullwhip effect might increase inventory instability causing low service level (Disney & Lambrecht, 2008; Jaipuria & Mahapatra, 2014). Thus, a replenishment rule not only affects order variability amplification which contributes to the upstream partners' costs but also affects the inventory variance which determines the partner's ability to meet a desired service level. Therefore, inventory replenishment systems should be designed to avoid the bullwhip effect without affecting the inventory stability.

The available smoothing replenishment rules in literature are mainly based on the periodic review (R, S) and their rationale is

* Corresponding author at: Department of Mechanical and Aerospace Engineering, University of Rome "La Sapienza", Via Eudossiana, 18, 00184 Rome, Italy. Tel.: +39 3282777914; fax: +39 0644585746.

E-mail addresses: francesco.costantino@uniroma1.it (F. Costantino), giulio.digravio@uniroma1.it (G. Di Gravio), ahmed.shaban@uniroma1.it, ahmed.shaban@fayoum.edu.eg (A. Shaban), massimo.tronci@uniroma1.it (M. Tronci).

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to restrict the over/under-reaction to short-run fluctuations in demand (Ciancimino, Cannella, Bruccoleri, & Framinan, 2012). Recently, some researchers have employed control charts to develop inventory control system that not only improve inventory performance but also can counteract the bullwhip effect through order smoothing (Costantino, Di Gravio, Shaban, & Tronci, 2014a, 2014b; Lee & Wu, 2006). Table 1 represents the trend in integrating control charts to inventory control along with the scope of study, performance measures, and supply chain structure of each study. Most of these studies other than Costantino et al. (2014a, 2014b) have been focusing on improving the inventory performance measures in simple inventory systems. Costantino et al. (2014a, 2014b) have alternatively employed control charts to handle supply chain dynamics, showing a superior ordering and inventory stability compared to the standard (R, S) in a multi-echelon supply chain. However, they have evaluated their model only under normal demand, without investigating its sensitivity to other demand processes, or investigating its sensitivity to other important operational factors such as lead-time. This research extends and extensively evaluates this novel inventory system in a multi-echelon supply chain under various operational conditions.

This research mainly attempts to formulate and evaluate a real-time inventory replenishment system with smoothing capability that relies on a control chart approach to be used in dynamic and complex environments like multi-echelon supply chains. The inventory replenishment system denoted as SPC utilizes two control charts integrated with a set of decision rules to estimate the expected demand and adjust the inventory position, respectively. The first control chart denoted as 'demand control chart' works as an improved forecasting mechanism to dynamically estimate the expected demand every review period without over/under-reacting to demand changes. The second control chart is employed to adjust the inventory position and to control order smoothing with restricting the over/under-reaction to inventory position variation. The replenishment order is determined in each period as the sum of the expected demand and a fraction of the amount needed to recover the inventory position to enhance order smoothing. Therefore, SPC has two dimensions for order smoothing. Similar to (R, S), the SPC approach can be very suitable to environments that replenish inventory frequently (daily, weekly, monthly) such as in retailing that needs regular repeating schedules of inventory replenishments (Disney, Farasyn, Lambrecht, Towill, & de Velde, 2006). This kind of inventory control system is preferred in competitive markets with high variability, where tracing the time series of orders and demand gives more information on future trends than applying traditional and static forecasting and inventory planning system that often over/under-react to market demand changes. Dynamic retailing, as for consumer goods, fashion industry or high tech portable devices, where customer profile of requirements may harshly vary and different products from different suppliers can easily substitute each other, is the main field of application.

A simulation approach is adopted to evaluate the effectiveness of the SPC policy in a four-echelon supply chain. An exhaustive comparison is conducted between the SPC policy and a generalized order-up-to (R, S) policy in terms mainly of bullwhip effect, inventory variance and service level. The sensitivity of both policies to different demand processes, lead-time, and information sharing is evaluated. The simulation results show that SPC outperforms the traditional (R, S) and is comparable to the smoothing one where SPC can eliminate the bullwhip effect whilst achieving acceptable inventory performance, under various operational settings. The results have provided further insights for supply chain managers on how to control instability propagation in supply chains.

The paper is organized as follows. Section 2 presents the related literature review. Section 3 describes the formulation of the SPC inventory replenishment system. Section 4 describes the supply chain model, generalized (R, S) policy, performance measures, and simulation model validation. Sections 5 and 6 present simulation results and sensitivity analysis. The discussion and implications are provided in Section 7, and the conclusions are summarized in Section 8.

2. Related work

The replenishment orders variability often increases as one moves up the supply chain, causing severe problems across the supply chain. Lee et al. (1997a, 1997b) identified five fundamental causes of the bullwhip effect: demand signal processing, lead-time, order batching, price fluctuations and rationing and shortage gaming. Of our particular interest is the demand signal processing in which forecasting methods and replenishment rules are integrated to regulate the replenishment orders and inventory levels. Extensive studies have quantified the impact of the different bullwhip effect causes using three modeling approaches: statistical modeling (Chen, Drezner, Ryan, & Simchi-Levi, 2000; Chen, Ryan, & Simchi-Levi, 2000; Cho & Lee, 2013), control theoretic (Dejonckheere et al., 2003, Dejonckheere, Disney, Lambrecht, & Towill, 2004; Hoberg, Bradley, & Thonemann, 2007) and simulation modeling (Chatfield, Kim, Harrison, & Hayya, 2004; Ciancimino et al., 2012; Costantino et al., 2014a, 2014b, Costantino, Di Gravio, Shaban, & Tronci, 2014c). These studies have shown that the bullwhip effect can be mitigated with selecting the proper forecasting method and ordering policy (Chatfield et al., 2004; Chen et al., 2000; Chen & Ryan et al., 2000; Jaipuria & Mahapatra, 2014; Li, Disney, & Gaalman, 2014; Zhang, 2004), reducing the lead-time (Chen et al., 2000; Chen & Ryan et al., 2000; Ciancimino et al., 2012; Zhang, 2004) and reducing the uncertainty in supply chains through increasing the collaboration and information visibility (Ciancimino et al., 2012; Costantino, Di Gravio, Shaban, & Tronci, 2014d; Dejonckheere et al., 2004).

Inventory replenishment policies have been recognized as a major cause of the bullwhip effect and thus it has received a signif-

Fig. 1. The bullwhip effect in supply chain (Chatfield et al., 2004; Costantino et al., 2014a,d).