Computers & Industrial Engineering 81 (2015) 46–57

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Quantifying and mitigating the bullwhip effect in a benchmark supply chain system by an extended prediction self-adaptive control ordering policy ☆

Dongfei Fu [a,*], Clara Ionescu [a,1], El-Houssaine Aghezzaf [b,3], Robin De Keyser [a,2]

[a] Department of Electrical energy, Systems and Automation, Ghent University, Gent, Belgium
[b] Department of Industrial Management, Ghent University, Gent, Belgium

ARTICLE INFO

Article history:
Received 17 February 2014
Received in revised form 17 December 2014
Accepted 18 December 2014
Available online 27 December 2014

Keywords:
Model predictive control
Supply chain management
Bullwhip effect
Ordering policy

ABSTRACT

An undesired observation known as the bullwhip effect in supply chain management leads to excessive oscillations of the inventory and order levels. This paper presents how to quantify and mitigate the bullwhip effect by introducing model predictive control (MPC) strategy into the ordering policy for a benchmark supply chain system. Instead of quantifying the bullwhip effect with commonly used statistical measure, we derive equivalently the expression of bullwhip metric via control-theoretic approach by applying discrete Fourier transform and (inverse) z-transform when the demand signal is stationary stochastic. A four-echelon supply chain is formulated and its dynamical features are analyzed to give the discrete model. An extended prediction self-adaptive control (EPSAC) approach to the multi-step predictor is implemented in the development of MPC formulation. The closed-form solution to MPC problem is derived by minimizing a specified objective function. The transfer function for MPC ordering policy is then obtained graphically from an equivalent representation of this closed-form solution. A numerical simulation shows that MPC ordering policy outperforms the traditional ordering policies on reducing bullwhip effect.

1. Introduction

A significant phenomenon in supply chain management (SCM), first observed by Forrester (1961), indicates the amplification of orders' variability along the upstream direction in supply chain networks. Subsequently this observation is termed as bullwhip effect by Lee, Padmanabhan, and Whang (1997a, 1997b). In a serial supply chain with a factory, a distributor, a wholesaler, and a retailer, one can observe that the retailer's orders to wholesaler show greater variability than the end-consumers' demand, the wholesaler's orders display even more oscillation, and the factory's manufacturing plan is the most volatile. The common drawbacks of bullwhip effect could be bad demand forecast, insufficient or excessive inventory holding, poor customer service and uncertain production planning (Lee, Padmanabhan, & Whang, 1997a). The bullwhip effect has been recognized in SCM literature as one of the chief barriers in improving supply chain performance.

The majority of earlier research on the bullwhip effect has focused on revealing its existence, identifying its various causes and providing methods for its mitigation (Disney, Farasyn, Lambrecht, Towill, & Van de Velde, 2006; Metters, 1997; Moyaux, Chaib-draa & D'Amours, 2007; Ouyang & Daganzo, 2006; Wright & Yuan, 2008). In the past two decades researchers have tackled this problem from the perspectives of control theory (Aggelogiannaki & Sarimveis, 2008; Chen & Disney, 2003; Dejonckheere, Disney, Lambrecht, & Towill, 2003; Jakšic & Rusjan, 2008) on account of the resemblance of dynamical control systems to supply chain networks. More and more control methods and techniques have been utilized to design SCM strategies for reducing the bullwhip effect. The readers are referred to several excellent review articles on the application of classical control theory to SCM problem (Hoberg, Thonemann, & Bradley, 2007; Ortega & Lin, 2004; Sarimveis, Patrinos, Tarantilis, & Kiranoudis, 2008;

☆ This manuscript was processed by Area Editor Christoph H. Glock.

* Corresponding author at: Department of EeSA, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium. Tel.: +32 09 264 5583.

E-mail addresses: Dongfei.Fu@UGent.be (D. Fu), Claramihaela.Ionescu@UGent.be (C. Ionescu), ElHoussaine.Aghezzaf@UGent.be (E.-H. Aghezzaf), Robain.DeKeyser@UGent.be (R. De Keyser).

[1] Address: Department of EeSA, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium. Tel.: +32 09 264 5608.

[2] Address: Department of EeSA, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium. Tel.: +32 09 264 5585.

[3] Address: Technologiepark 903, 9052 Zwijnaarde, Belgium. Tel.: +32 09 264 5500.

http://dx.doi.org/10.1016/j.cie.2014.12.024
0360-8352/

Subramanian, Rawlings, Maravelias, Flores-Cerrillo, & Megan, 2013). We present a brief literature review in the next section on the problems of quantifying and damping the bullwhip effect with control systems engineering approach.

The body of bullwhip literature is already vast and the studies on the bullwhip effect can be roughly divided into three streams (Dominguez, Framinan, & Cannella, 2014b): (1) research that seeks to determine the impact of forecasting techniques employed by supply chain managers on the bullwhip effect (Chen, Ryan, & Simchi-Levi, 2000a; Chen et al., 2000); (2) research that focuses on quantifying the impact of supply chain's design parameters (such as ordering policy, inventory management policy, and production variation and batching) on the bullwhip effect (Boute, Disney, Lambrecht, & Van Houdt, 2007; Kelepouris, Miliotis, & Pramatari, 2008); (3) research that examines the effect of supply chain dynamics (e.g. information sharing) on the bullwhip effect (Cannella & Ciancimino, 2010; Cannella, Ciancimino, & Framinan, 2011; Chatfield, Kim, Harrison, & Hayya, 2004; Dejonckheere, Disney, Lambrecht, & Towill, 2004). This paper advocates the approaches to achieving bullwhip mitigation by a control engineering oriented formulation and exploits the impact of a novel ordering policy and inventory management policy on the bullwhip effect. This replenishment rule is designed according to the philosophy of model predictive control. Obviously, our study falls into the second research stream.

The studies utilizing MPC have been found to provide attractive solutions to SCM problems (Subramanian et al., 2013). Compared to other methods in (Dejonckheere et al., 2003; Lin, Wong, Jang, Shieh, & Chu, 2004; Towill, Zhou, & Disney, 2007; Warburton & Disney, 2007), most of the results in literature have demonstrated a qualitative improvement in damping the phenomenon by applying MPC strategy to specific supply chain network. Along the years many researches on quantifying the bullwhip effect only used statistical approach to obtain the order variance amplification ratio (VAR) as the measure under certain ordering policy and customer demand. Quantification of bullwhip effect in the context of an MPC control strategy has been disregarded in previous studies owing to structure limitations and implicit formulations of their MPC controllers. Motivated by these gaps, the aim of this paper is to contribute to the following aspects:

1. We develop the EPSAC formulation for controlling the benchmark supply chain network and for quantifying the bullwhip effect from control systems engineering approach. By this implementation, each supply chain member optimizes for its own ordering policy so the variation of customer demand is able to be tracked, excess inventory is minimized and the order variance amplification is effectively suppressed compared to traditional ordering policies. The proposed control scheme facilitates the development of explicit transfer function for this ordering policy.
2. Our contribution to the extensive bullwhip quantification literature lies in presenting an analytical expression of the bullwhip when MPC-based ordering policy is used. The bullwhip measure is related to the control-theoretic metric via discrete Fourier transform and inverse z-transform. This closed-form solution is directly equivalent to the common statistical measures used in previous studies.

In a numerical case study, the performance of MPC-based ordering policy is compared with the conventional *order-up-to* (OUT) and *fractional* ordering (FO) policies in terms of demand variation tracking, inventory holding profile and improvement on bullwhip evaluation indicators. The bullwhip quantities are calculated using the analytical solution presented in this paper.

The remainder of this paper is organized as follows. In Section 2, we provide a review of related literature on analysing the bullwhip effect from control systems engineering approach. In Section 3, we describe the dynamics analysis and modelling problem for the benchmark supply chain network. Section 4 derives the analytical expression of bullwhip metric under the condition that the transfer function for a particular ordering policy has been obtained. With the developed models, the MPC-EPSAC control strategy is formulated in Section 5 and the closed-form solution of control algorithm is provided. Section 6 quantifies the bullwhip effect produced by MPC ordering policy and makes comparison with conventional ordering policies in numerical simulation. Finally, some conclusions are given in Section 7.

2. Review of related literature

There is a large body of literature has focused on quantifying the bullwhip effect by *variance ratio*. Therefore the dominant orientation to analyse the bullwhip effect in these studies is statistical approach (Nepal, Murat, & Chinnam, 2012). Of particular interest in this paper is the use of control systems engineering approach (transfer functions, frequency response, z-transform, etc.) to quantify and mitigate the bullwhip effect. Therefore, the selection criteria of the reviewed papers are: (1) involving control-theoretic approach to quantification of; and (2) relying on control techniques, especially MPC, to mitigate the bullwhip effect. Our research builds on these two lines of literature.

On quantifying the bullwhip effect: The variance amplification ratio of orders is by far the most widely used statistical measure to detect its existence. Some researchers examined the single-echelon supply chain and compared the VAR of placed orders to demands (Chen, Drezner, Ryan, & Simchi-Levi, 2000b; Lee, Padmanabhan, & Whang, 1997b; Lee et al., 1997a). The reports concerning the analysis in the multi-echelon supply chains exist for a specific family of demand (e.g., AR, ARMA) and traditional ordering policies (e.g., OUT policy or smoothing replenishment rule) (Gaur, Giloni, & Seshadri, 2005; Ouyang & Li, 2010; Wright & Yuan, 2008). These results hold dependently of the customer demand, ordering policy, and supply chain configuration. The paradigmatic works of Dejonckheere et al. (2003) and Disney and Towill (2003) draws on control theory and z-transform techniques. They quantified the VAR as the noise bandwidth by employing the transfer function and frequency response plot. Moreover, they analysed this transfer function to reach conclusions about the bullwhip effect for different ordering policies, demand, and forecasting techniques. This quantifying method has been the fundamental of their subsequent studies (Disney, Towill, & Van de Velde, 2004; Disney et al., 2006; Towill et al., 2007). In the work of (Ouyang & Daganzo, 2006; Ouyang & Li, 2010), the bullwhip metric is the ratio of the root mean square errors of order and demand, instead of conventional VAR, because the modified metric makes the transfer function of ordering policy easier to derive via spectral analysis. The maximum modulus of the transfer function is defined as the bullwhip metric.

On mitigating the bullwhip effect: Whereas much has been done on understanding and reducing the bullwhip effect in two echelon or multi-echelon supply chain, prior efforts for limiting VAR largely focused on information sharing. In fact information exchange has been regarded as one of the main ways for taming the bullwhip effect. A number of authors have explored and discussed the value of information sharing to reduce the bullwhip effect (Cannella et al., 2011; Dejonckheere et al., 2004; Dominguez, Framinan, & Cannella, 2014a; Kelepouris et al., 2008; Lee, So, & Tang, 2000; Moyaux, Chaib-draa, & D'Amours, 2007). The prior research shows that the bullwhip effect cannot be completely removed even with