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A robust optimization approach to reduce the bullwhip effect of supply chains with vendor order placement lead time delays in an uncertain environment

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ABSTRACT

Supply chain management is important for companies and organizations to improve their business and enhance competitiveness in the global marketplace. The bullwhip effect problem of supply chain systems with vendor order placement lead time delays in an uncertain environment is addressed in this paper. Among the numerous causes of bullwhip effect, we focus on uncertainties with respect to demand, production process, supply chain structure, inventory policy implementation and especially vendor order placement lead time delays. Minimizing the negative effect of these uncertainties in inducing bullwhip effect creates a need for developing dynamical inventory policy that increases responsiveness to demand and decreases volatility in inventory replenishment. First, a dynamic model of supply chain with above uncertainties is developed. Then, a novel uncertainty-dependent robust inventory control method using inventory position information is proposed. Additionally, the maximum allowable vendor order placement lead time delay that ensures the stability of supply chains and the suppression of bullwhip effect under the proposed inventory control policy is explored and measured. We find that vendor order placement lead time delays do play important role in supply chain dynamics and contribute to its turbulence and volatility. The effectiveness and flexibility of proposed method is verified through simulation study.

1. Introduction

As a typical network system which mainly consists of suppliers, manufacturers, distributors and retailers, supply chains (SC) refer to all the activities associated with the transformation of raw materials, products and the distribution of finished products to customers. There are three important flows among SC entities, namely material flows, information flows and financial flows [1]. As a general topic in the process of globalization with intensifying global competition, supply chain management (SCM) has received considerable attention from both SC practitioners and academics. The underlying motivation of the need for efficient SCM lies in reducing multifarious costs (e.g., the rising cost of manufacturing, inventory and transportation), improving service (e.g., improving stock availability and asset utilization), satisfying customer demands (e.g., accelerating the speed of response, improving after-sale service) and finally bringing competitive advantages to companies [2–5]. An effective SCM will integrate internal and external SC resources, optimize resource allocation and production processes, and finally improve supply chain efficiency.

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An undesirable phenomenon, also known as "the bullwhip effect" (the observed variation amplification of order quantities moving up a supply chain from end-customers to raw material suppliers), is common in real world and receives much attention [6]. Having its root in J. Forrester's Industrial Dynamics [7], the bullwhip effect (or whiplash effect) has been recognized as one of the most problematic issues to be faced in SCM [8,9]. It not only indicates the vulnerability of supply chain system to external interference, especially the demand fluctuations, but also imposes great human, financial and resource burden on supply chain participants. Numerous researches have been carried out to study its causes and countermeasures. Lee et al. [10] studied the effect of demand processing, game rationalization, order lot sizing and price fluctuations on bullwhip effect from the perspective of information distortion. Through comparative analysis of a variety of traditional contract types, He et al. [5] pointed out that only a properly designed returns policy with sales rebate and penalty contract is able to achieve channel coordination and lead to a Pareto situation for SC members who face stochastic demands. A similar study can be found in [11]. Not only the direct factor of end demand fluctuations, other factors such as batching of orders, pricing policy, lead time delays, etc., have been identified as major causes of bullwhip effect [12,13]. These causes, on the one hand, are related to operational complications (or more precisely the various uncertainties in supply chain process), such as demand changes, price fluctuations, lead time variabilities and information sharing [14,15], and on the other hand, have to do with cognitive limitations on the part of supply chain participants, such as overreaction to backlogs and underlying tendency of underweighting supply lines [16,17]. In this paper, we study the bullwhip effect from the perspective of analytical rather than behavioral approaches and focus explicitly on uncertainties among its various causes.

So far there is no ideal practical method for avoiding the bullwhip effect in SC. Even some advanced SCM method may induce amplification of order information distortion and stock variations [18,19]. Nevertheless, some feasible methods have been proposed in SCM researches, and most of them focus on controlling the uncertainty causes of bullwhip effect. Seferlis and Gianellos [20] developed a two-layered hierarchical decentralized inventory control policy which applies an autoregressive integrated moving average (ARIMA) forecasting model for demand prediction. Similar studies about the value of reducing information uncertainty in SCM can be found in [21,22]. Pishvaee et al. [4] proposed a robust optimization model and relative robust counterpart for handling the inherent uncertainty of input data in a closed-loop supply chain network design problem. To the stochastic lead time problem, Abginehchi and Farahani [23] developed a model for optimal suppliers. In addition, study carried out by Springer and Kim [24] showed that dynamical order pipeline provides better customer service and reduces supply chain volatility. Different analytical methods have been applied in these studies: dynamical programming algorithm [25,26], heuristic methodology [27,28], simulations [29,30], for instance.

In previous studies, most methods related to the reduction of bullwhip effect, however, are static – either they formulate the problem as a static deterministic problem where the supply chain object is modeled based on its average performance and steady-state conditions (supply chain structure, partner relationship, transaction costs, etc.) [31,32], or they are based on standard static inventory control policies where certain stationary demand patterns are relatively pre-established [33,34], such as the static re-order point and the static order-up-to-level policies. Considering the dynamic characteristics of SC in real-world situation, it is clear that these models and methods are insufficient for they neglect, from a dynamic perspective, the endogenous trigger mechanism of bullwhip effect and thus are not able to provide appropriate remedies for this problem. The goals of this paper is, first, to shed light on the endogenous mechanism and dynamic characteristics of bullwhip effect in an uncertain environment from the perspective of inventory dynamics, and second, to find possible countermeasures and develop effective strategies (more specifically, inventory control policies) to improve supply chain management.

Recently, many researchers have addressed the bullwhip effect problem from the perspective of control system [35–37]. Due to the resemblance of supply chain systems to dynamical control systems in engineering, methods in control theory are applied in SC studies, especially in analyzing SC dynamics and in designing SCM strategies for reducing bullwhip effect, such as the classical linear control theory [38,39], model predictive control [40,41] and so forth. Applying robust control theory, Boukas et al. [42] studied the asymptotic stability of an inventory-production system with uncertainty in processing time. They also extended their study by taking into consideration other uncertain system parameters. In their study (also in many other SC researches, e.g., [43,44]), they considered the inventory-production system as a continuous system. But many activities in SC, such as ordering and inventory replenishment, should be described as discrete events. In addition, given that uncertainties exist in nearly all aspects of supply chain systems, researches limited to only one or few sources of uncertainty would affect the accuracy of study and influence their guidance in practical application.

In this paper, we address the bullwhip effect control problem in context of a supply chain system that faces uncertainties with respect to demand, production process, supply chain structure, inventory policy implementation and vendor order placement lead time delays. Based on SC endogenous dynamics, we build a SC state transition model and focus on the effect of uncertain vendor order placement lead time delays on replenishment performance and on supply chain dynamics. In addition, we derive the sufficient linear matrix inequality conditions, corresponding to the proposed inventory control policy in this paper, for the suppression of bullwhip effect and the improvement of SC stability. The rest of this paper is organized as follows: In Section 2, we introduce the SC state transition model and its corresponding inventory control policy. In Section 3, we propose an optimization model for the maximum allowable vendor order placement lead time delay that ensures the stability of supply chain systems and the suppression of volatility in inventory replenishment. We extend our analysis in Section 4 through simulation studies. Finally, conclusions with future research directions are presented in Section 5.