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Exploring inventory order policies impact under the non-negative constraint of order quantity: System stability, service level, and cost

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ABSTRACT

Considering the non-negative constraint of order quantity, this study explored inventory system performance, including system stability, service level, inventory cost, and the effect of transportation delay time. Both the non-negative constraint and delay time render the system nonlinear and complicated, which makes it difficult to identify optimal order policy regions that combine system stability with a high service level and low cost. The purpose of this study is to systematically reflect the impact of order policies on inventory system performance from three aspects, including system stability, service level, and cost. The results of the simulation revealed the existence of public optimal order policies for different transportation delay times. Although these optimal order policies are similar when the target inventory parameter changes, lowering the target inventory parameter can also lower the inventory cost. If an appropriate order policy can be adopted, a low target inventory reduces inventory cost while maintaining system stability and a high service level, opening up new options for decision makers in supply chain management.

1. Introduction

The importance of inventory system performance is acknowledged by scholars and practitioners alike. Although firms devote huge amounts of money and time to predict and control their whole inventory system precisely, their efforts often suffer setbacks due to the dynamic and complex features of the inventory system. The optimal order policy of the nonlinear inventory system has caused attention from both scholars and practitioners.

Previous research has indicated that improper inventory policy renders such systems unstable and exponential increases in inventory costs even if the market demand is stable (e.g., [1–6]). This phenomenon is known as the bullwhip effect [7]. As the number of different sources of uncertainty in the supply chain increases, the inventory system becomes ever more complicated and chaotic [8], so maintaining a stable and robust system is one of the main objectives when designing an inventory system. Control theory and the system dynamics literature have now developed to the point where they provide a good research framework to guide efforts to explore complex systems [1], and researchers are beginning to apply this approach to the field of inventory control (e.g., [9–11]). Building on the work of previous researchers in this field, this paper applies a system dynamics approach to analyze inventory system stability.

System stability is a fundamental aspect when developing an inventory management policy, although other features such as inventory cost savings, profits, and service levels have all received a great deal of attention from practitioners (e.g., [12–14,6]). There is, however, the potential for serious conflicts among these performance measurements [15]. For example, more and more managers have recognized the risks inherent in inventory backlogs and have devoted considerable effort to decreasing inventory quantities. Nonetheless, excessively small inventory quantities can degrade service levels, which is clearly also undesirable. Thus, whether existing inventory policies meet the following three conditions, a stable system, low inventory cost, and high service level, is the focus of this research. This paper explores the relationships among system stability, inventory cost, and service level and discusses inventory policies that are capable of satisfying all three performances indicators simultaneously.

Most previous inventory dynamics system studies (e.g., [16–17,14]) have adopted linear system models. The linear assumptions mean that supply capacity is infinite and that order and/or inventory quantity are permitted to take negative values, which severely

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limit the application of study results. The use of switched inventory system models (i.e., nonlinear system models) would be more similar to the real conditions under which inventory systems operate in the real world, but when the linearity assumptions are removed, the models become vastly more complicated.

Time delay is another critical factor that makes an inventory system become complex [18–22,15]. Transportation delays are unavoidable in the supply chain even if the system is supported by advanced information systems. Many studies (e.g. [23–27]) have found that time delays increase the inventory cost and aggravate the bullwhip effect, with a consequent major effect on inventory policy. Existing studies have derived the mathematical relationship between order quantity and arbitrary lead time under a linear model [16], and recently some studies [28–29] have devoted to the relationship between system stability and delay time under the nonlinear model.

When modeling the inventory system, we take into consideration of the two factors, non-negative constraint of order quantity and arbitrary time delay. The two factors happen frequently in practice and increase the complexity of inventory system.

Under the non-negative constraint of order quantity, to our knowledge, most of previous studies explore the impact of order policies on only one aspect of nonlinear inventory system performance (e.g., system stability). However, it is not systematic and sufficient to measure the impact of non-negative constraint of order quantity on nonlinear inventory system performance from only one aspect. In our study, to fully reflect the impact of order policies on inventory system performance, we use three indicators, including system stability, service level, and cost. To address this, for the current study, a nonlinear inventory system model was built that simultaneously considers different performance indicators. The combination of nonlinearity and multiple performance indicators render the system too complicated to apply normative analytical methods [30,31]. The simulation model offers a number of advantages. Therefor this method provides a better option for studying a nonlinear inventory system [32].

The remainder of this paper is organized as follows. In Section 2, we briefly review the related literature. Section 3 describes our research model, investigates the system stability conditions under different delay times using simulation approaches and also verifies the simulation result by comparing to the analytical method. Section 4 discusses how these results affect optimal order policy and analyzes the optimal order policy regions obtained for different parameter settings using simulations. Section 5 discusses the research result and Section 6 concludes the research.

2. Literature review

2.1. Inventory control model

The inventory control model utilized in this research was APVIOBPCS (the automatic pipeline variable inventory and order-based production control system). The SD (system dynamics) model presented by Forrester (1961) [1] became the basis of a family of inventory control models that grew out of the work by Towill (1982) who dubbed it the *Inventory and Order Based Production Control System* (IOBPCS) [33]. The original structure of IOBPCS has a single feedback loop to control the inventory system, but this was extended by John, Naim and Towill (1994) to create the *Automatic Pipeline, Inventory and Order Based Production Control System* (APIOBPCS) by adding a work-in-process feedback loop [34]. The model was developed further by Axsater (2000) [9], who proposed a discrete time countertype of APIOBPCS that incorporated an order-up-to (OUT) policy. In these order policies, the target inventory is linked to the market demand. In order to express the varying features of demand, Dejonckheere, Disney, Lambrecht, and Towill (2003) proposed a new APVIOBPCS order policy that adjusts the desired inventory and work-in-process quantity based on the demand forecast [7].

The APVIOBPCS model is the general form for many typical order policies. The popular DE-APIOBPCS and order-up-to policies are both special cases of this model. The APVIOBPCS model includes two balanced feedback loops, one of which adjusts for inventory discrepancies and the other work-in-process discrepancies, thus requiring only two adjustment parameters, the adjustment rate for the desired inventory discrepancy and the adjustment rate for the work-in-process discrepancy. Different parameter combinations represent different ordering policies.

2.2. System stability analysis

System stability means the ability to recover from disturbances or deviation and return to an equilibrium state. Many studies have explored inventory system stability, including Riddals and Benett (2000, 2002) [17], who investigated the stability conditions for the APIOBPCS model; Warburton, Disney and Towill (2004), who developed further insights into the continuous time settings by applying Laplace transforms [11]; and Disney (2008), who studied the stability analysis of order-up-to policies using a Jury's inners approach and investigated the conditions for system aperiodicity [35]. Sipahi and Delice (2010) explored the dynamic features of the APIOPBCS model for three different delays [36], Bijulal, Venkateswaran and Hemachandra (2011) computed the stability conditions based on certain control parameters using the APVIOBPCS model [16], and Wei, Wang and Qi (2013) conducted a comprehensive stability analysis for arbitrary lead times [25]. White and Censlive (2016) built a three tier supply chain model to investigate APVIOBPCS polices for any value of production delay as a guide for practitioners [37].

The studies mentioned above were based on the fundamental assumption of a linear system. Unfortunately, although they demonstrated a wide range of dynamic behaviors for different order policies, real world supply chains are not always linear systems and thus their results are not always applicable. In many cases a nonlinear model produces results that are closer to reality (e.g. [38]), but a nonlinear system is also considerably more complex and dynamic than a linear one, which greatly increases the research difficulty of the problem.

Extant research has generally focused on illustrating the existence of nonlinear dynamics in inventory systems. For example, Mosekilde and Larsen (1988) found two- and three-dimensional chaotic attractors in the beer production distribution model [39], and their findings were confirmed by Larsen and Morecroft (1999) [40]. Wang, Wee and Gao (2005) examined the chaotic state in an inventory system using an Lyapunov Exponent [41], while Mosekilde and Laugesen (2007) found border-collision bifurcations phenomenon in the beer model [3]. Wang, Liu and Yang (2009) showed that different order policy parameters affect the system stability due to the constraint of the supply capacity [42]. Buchmeister et al. (2014) found that the inventory cost of a switched system could be 500 times higher than that of a linear system [43]. However, ways to maintain a stable system and avoid chaotic systems require further study. Taylor (2016) constructed the nonlinear control system and gave six-step approach for reducing bullwhip effect [6].

Recently, related research has been conducted by Hwarng and Xie (2008) [8], Hwarng and Yuan (2014), who applied chaos theory to analyze nonlinear behaviors in supply chain systems and identified a clear distinction in dynamic characterizations with different demand processes [44]. Cannella, Ciancimino and Marquez (2008) studied the supply chain system under the constraint of supply capacity [48]. The results revealed that the collaborative