European Journal of Operational Research 233 (2014) 566–579

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Production, Manufacturing and Logistics

Interpreting supply chain dynamics: A quasi-chaos perspective

H. Brian Hwarng *, Xuchuan Yuan

NUS Business School, National University of Singapore, 15 Kent Ridge Drive, Singapore 119245, Singapore

ARTICLE INFO

Article history:
Received 28 September 2012
Accepted 16 September 2013
Available online 28 September 2013

Keywords:
Supply chain management
Chaos theory
Lyapunov exponent
Quasi-chaos
System dynamics

ABSTRACT

Chaotic phenomena, chaos amplification and other interesting nonlinear behaviors have been observed in supply chain systems. Chaos can be defined theoretically if the dynamics under study are produced only by deterministic factors. However, deterministic settings rarely present themselves in reality. In fact, real data are typically unknown. How can the chaos theory and its related methodology be applied in the real world? When the demand is stochastic, the interpretation and distribution of the Lyapunov exponents derived from the effective inventory at different supply chain levels are not similar to those under deterministic demand settings. Are the observed dynamics of the effective inventory random, chaotic, or simply quasi-chaos? In this study, we investigate a situation whereby the chaos analysis is applied to a time series as if its underlying structure, deterministic or stochastic, is unknown. The result shows clear distinction in chaos characterization between the two categories of demand process, deterministic vs. stochastic. It also highlights the complexity of the interplay between stochastic demand processes and nonlinear dynamics. Therefore, caution should be exercised in interpreting system dynamics when applying chaos analysis to a system of unknown underlying structure. By understanding this delicate interplay, decision makers have the better chance to tackle the problem correctly or more effectively at the demand end or the supply end.

1. Introduction

Recent waves of product recalls that have taken place in the auto industry reaffirm the criticality of good supply chain management (SCM) to the competitiveness of companies. This is true because the demand and supply bases have become so connected and at the same time very dispersed globally. Various types of uncertainties originated from demand, design, production and delivery, as well as time delays and feedback between decision making and their effect render supply chain systems rather complicated. A case in point is a faulty design, a non-conforming manufacturing process or a failure in proper usage resulting in out-of-place floor mats or defective accelerator pedals, and eventually leads to a global product recall. Due to complex and dynamic characteristics, a seemingly insignificant change or deviation in system conditions such as the above-mentioned may usher the system into a chaotic state (Hwarng & Xie, 2008). Therefore, it is valuable to study the dynamics and intricate behaviors in a complex supply chain (Thomas, Kevin, & Rungtusanatham, 2001). By adopting a system dynamics approach with a complexity perspective, the intriguing nature of such systems can be better understood.

There have been considerable interests in applying chaos theories and tools in finance, economics and management studies (Lorenz, 1993), while limited studies in SCM. A majority of the literature is based on the beer distribution model, such as Mosekilde and Larsen (1988) on two- and three-dimensional chaotic attractors, Thomsen, Mosekilde, and Sterman (1992) on hyperchaotic and higher-order hyperchaotic phenomena, Sosnovtseva and Mosekilde (1997) on chaos-chaos intermittency, Larsen, Morecroft, and Thomsen (1999) on stationary periodic, quasi-periodic as well as chaotic and hyperchaotic dynamics, Laugesen and Mosekilde (2006) and Mosekilde and Laugesen (2008) on border-collision bifurcations. These studies focus on showing the existence and categories of chaotic/hyperchaotic behaviors and various modes exhibited in a supply chain system. They highlight the role of decision making, e.g., the decisions on the adjustment of the actual inventory and the supply line, in the cause of system chaos. To further understand the chaotic dynamics, Hwarng and Xie (2008) conducted a comprehensive study of a complex supply chain system modeling after the well-known beer distribution model (Sterman, 1989), under some known deterministic settings with deterministic demand processes such as a step function or a broad-pulse function. The simulation results indicate that supply chain factors (Cachon & Fisher, 2000; Chen, Drezner, Ryan, & Simichi-Levi, 2000; Lee, Padmanabhan, & Whang, 1997a; Lee, Padmanabhan, & Whang, 1997b; Sterman, 1989) such as decisions on adjustment of discrepancy between inventory and supply line, demand pattern, ordering policy, information sharing, lead time, and supply chain level, have direct impact on the chaotic behavior of inventory dynamics.

* Corresponding author. Tel.: +65 6516 6449; fax: +65 6779 2621.
E-mail address: hwarng@nus.edu.sg (H.B. Hwarng).

0377-2217/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ejor.2013.09.025

However, pure deterministic settings rarely exist in reality. In fact, the underlying structures of real-world data are typically unknown. Facing the situation with unknown demand processes, how should we interpret the result when applying the chaos theory to analyze historical data of which the underlying structure is unknown? Motivated by the theoretical limitation and practical utility, we investigate the impact of stochastic nature in demand on the system dynamics from a chaos perspective. A simulation model based upon the beer distribution model is developed to investigate system dynamics across all levels of the supply chain. Using the Lyapunov exponent (LE), we characterize the system dynamics in terms of inventory across all supply chain levels. The main idea is to ascertain the interplay of randomness and chaos and offer some insights into the practical utilities of the chaos analysis in complex supply chain systems.

The structure of the paper is organized as follows: Section 2 describes the model under study; Section 3 presents concisely the methods and tools that we will adopt in our analysis; Section 4 explains the simulation and experiment settings as well as results and analysis; Section 5 discusses a few key findings; Section 6 closes with conclusions.

2. The model

2.1. The supply chain system

Various forms of the beer distribution model (for example, Chen & Samroengraja, 2009) have been studied since the beer distribution game was first developed at MIT in the 1960s. Researches have mainly focused on the supply chain system dynamics and its complexity. Analytical studies tend to focus on the inventory level or order quantity decisions. Though based on random demand processes (Cachon, 1999; Chen et al., 2000; Kim, Chatfield, Harrison, & Hayya, 2006), they are not related to chaos dynamics. One typical phenomenon observed in the beer distribution model is the bullwhip effect manifested in the amplification of demand or inventory (Lee et al., 1997a, 1997b; Sterman, 1989). In this research, however, we focus on using the beer distribution model to investigate the applicability of the chaos theory in understanding inventory dynamics in a complex multi-echelon supply chain system from a chaos perspective. The supply chain system, shown in Fig. 1, is based on the beer distribution model which represents a multi-level supply chain consisting of retailer, wholesaler, distributor and factory.

In this supply chain system, orders propagate from customers to the factory; while goods are shipped from factory to customers. Specifically, the retailer estimates customers' demands and places an order with the wholesaler; the wholesaler decides how much to order from the distributor; the distributor places an order with the factory and the factory makes production decisions. Conversely, products flow from the factory to the retailer. The factory ships the goods to the distributor; the distributor transports the goods to the wholesaler; the wholesaler allocates the goods to the retailer; and customers' orders are satisfied from the retailer.

The only decision made at each supply chain level is the order quantity (or the production quantity for the factory). Each supply chain level may adopt a specific ordering policy to replenish its inventory, with the objective to minimize the holding costs while attempting to avoid out of stock situations. Adapted from Sterman (1989), in the simulation model, the ordering policy is an anchoring and adjustment heuristic designed to manage the inventory level. The characteristics of the ordering heuristic include replenishment of expected orders, correction of differences between the desired inventory and the actual one, and an evaluation of the supply line inventory, which comprises of the orders placed but not yet received. To facilitate the model description, relevant notations for model variables and parameters are listed in Table 1.

At each supply chain level, the adjustment for the inventory level and the adjustment for the supply line at time t are expressed as follows:

$$AS_t = \alpha_S(S^* - S_t) \tag{1}$$

$$ASL_t = \alpha_{SL}(SL^* - SL_t) \tag{2}$$

The actual inventory level and supply line level at time t are expressed as follows:

$$S_t = \sum_{t=t_0}^{t_n}(A_t - L_t) + S_{t_0} \tag{3}$$

$$SL_t = \sum_{t=t_0}^{t_n}(O_t - A_t) + SL_{t_0} \tag{4}$$

So the order at time t can be described as below:

$$O_t = \max(0, \widehat{L}_t + AS_t + ASL_t) \tag{5}$$

The expected demand is based on the adaptive expectation on demand as follows:

$$\widehat{L}_t = \theta L_t + (1-\theta)\widehat{L}_{t-1}, \quad 0 \leqslant \theta \leqslant 1 \tag{6}$$

As exhibited in Fig. 1, various types of delays, $t - p_d$ namely, order delay, production delay, and shipment delay, exist in the supply chain system. The expected demand dynamics at supply chain level i is captured by the following:

$$\widehat{L}_{i,t} = \theta O_{i-1,t-o_d} + (1-\theta)\widehat{L}_{i,t-o_d}, \quad 0 \leqslant \theta \leqslant 1 \tag{7}$$

where o_d is the order delay. Similarly, the goods received at time t at supply chain level i (retailer, wholesaler and distributor) is the actual outgoing shipment at the successive upstream level $i - 1$ at

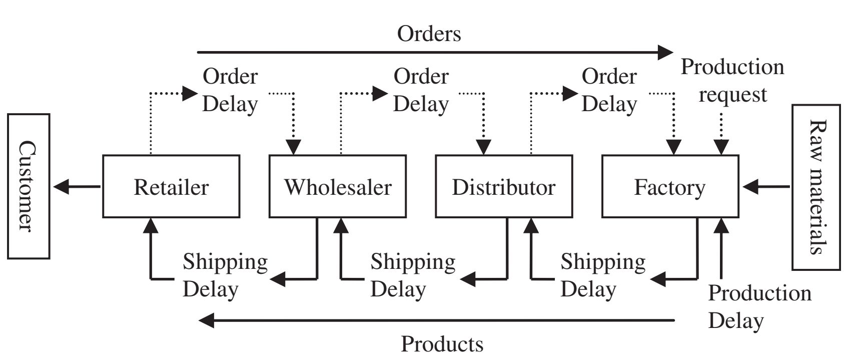

Fig. 1. The beer distribution model.