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Understanding supply chain dynamics: A chaos perspective

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Abstract

Variability in orders or inventories in supply chain systems is generally thought to be caused by exogenous random factors such as uncertainties in customer demand or lead time. Studies have shown, however, that orders or inventories may exhibit significant variability even if customer demand and lead time are deterministic. In this paper, we investigate how this class of variability, chaos, may occur in a multi-level supply chain and offer insights into how to manage relevant supply chain factors to eliminate or reduce system chaos. The supply chain is characterized by the classical beer distribution model with some modifications. We observe the supply chain dynamics under the influence of various factors: demand pattern, ordering policy, demand-information sharing, and lead time. Through proper decision-region formation, the effect of various factors on system chaos is investigated using a factorial design. The degree of system chaos is quantified using the Lyapunov exponent across all levels of the supply chain. This study shows that, to reduce the degree of chaos in the supply chain system, the adjustment parameters for both inventory and supply line discrepancies should be more comparable in magnitude. Counter-intuitively, in certain decision regions, sharing demand information can do more harm than good. Similar to the bullwhip effect observed previously in demand, we discover the phenomenon of "chaos-amplification" in inventory across supply chain levels.

Keywords: Supply chain management; Chaos theory; Beer distribution game; System dynamics

1. Introduction

A supply chain is a complex system which involves multiple entities encompassing activities of moving goods and adding value from the raw material stage to the final delivery stage. Along the chain, there exist various types of uncertainties, e.g., demand uncertainty, production uncertainty, and delivery uncertainty. Making decisions as to how much and when to replenish, often involves a feedback process triggering interaction between system entities, which may result in system nonlinearity. A time delay is observed when there is a lag between when a decision is made and when its effect is felt, which often further complicates the interaction between entities. Feedback, interaction, and time delay are inherent to many processes in a supply chain, making it a dynamic system.

For instance, the two widely used inventory replenishment policies, i.e., the continuous-review

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policy and the periodic-review policy, involve a negative feedback mechanism. For the continuous-review policy, the inventory is reviewed continuously and when the inventory drops to the reorder point, Q units are ordered to restore the inventory level. The replenishment process creates a negative feedback loop. A similar feedback process is observed in the periodic-review policy. Feedback demands actions which must involve interactions between entities in a system or between the effects of these actions or decisions made. This is seen in a typical automobile supply chain such as Toyota's wherein a dealer's (with a local view) pre-set inventory level and the automaker's (with a global view) allocation policy will affect the velocity of parts going to the dealers. Besides feedback and interaction, time delays between cause and effect often further complicate the interaction between system entities. For example, ideally, the safety stock levels at a centralized hub such as Dell's should be kept as low as possible. However, time delays in the form of long and uncertain lead time coupled with build-to-order practice and decision making behaviors adversely contribute to the variability of the safety stock. Indeed, feedback, interaction, and time delay induce variability, instability, and complex behaviors that make supply chain management even more challenging.

The above-mentioned dynamics and complex behaviors in a supply chain can be appropriately modeled by adopting the system dynamics approach, particularly from a chaos perspective. Chaos is disorderly looking long-term evolution occurring in a deterministic nonlinear system (Williams, 1997). Chaos theory is concerned with chaotic behavior/chaos in nonlinear dynamical systems from a number of aspects, e.g., the principles and mathematical operations underlying chaos, chaos characteristics, and the methods to identify chaos. The origin of chaos theory dates back to Lorenz's (1963) study in weather forecasting systems. The work of Feigenbaum (1978) and Mandelbrot (1982) has contributed to greater interest in studying and applying chaos theory.

A system of chaos is often characterized by a number of distinct features (Williams, 1997; Wilding, 1998), such as: (1) non-randomness and nonlinearity; (2) apparent disorder: the motion of the variables looks disorganized and irregular; (3) strange attractor: order, structure, or pattern can be found in phase space; (4) bounds: the ranges of the variables have finite bounds, hence, the attractor is bounded; and (5) sensitivity to initial conditions: a small change in initial conditions can have a large effect on the evolution of the system.

To investigate the existence and formation of chaotic behaviors, it is necessary to constrain parameters to deterministic. Mosekilde and Larsen (1988), Thomsen et al. (1992), Sosnovtseva and Mosekilde (1997), and Larsen et al. (1999) adopted such an approach to studying various nonlinear chaotic behaviors in a distribution system. Their foci, nevertheless, remain on showing the existence and categorization of chaotic behaviors in the system. The cause-and-effect and dynamic nature of various system factors contributing to the chaotic behavior remains an interesting topic for further research.

In this paper, we intend to investigate how various supply chain factors contribute to the complex dynamics and chaotic behaviors. We are interested in a general class of multi-level supply chains that can be represented by the well-known beer distribution model (Jarmain, 1963). Various supply chain factors are considered, such as demand pattern, ordering policy, demand-information sharing, and lead time, with different options or levels. A simulation model is developed to observe system dynamics, particularly the inventory across all levels of the supply chain. Using the Lyapunov exponent (LE), we quantify the degree of system chaos in terms of inventory across all supply chain levels.

The objectives of this paper are: (1) to understand, from a chaos perspective, how the different levels of a multi-level supply chain behave under the influence of factors such as demand pattern, lead time, demand-information sharing, and ordering policy; (2) to investigate how these factors act or interact to affect the system dynamics which in many cases lead to chaos; and (3) to offer some insights into more effective management of supply chains.

2. Related past studies

It is well studied and recognized that demand pattern, ordering policy, lead time, and information sharing have direct impact on the performance of supply chains. Lead time reduction is found to be very beneficial and can reduce inventory and demand variability, and improve customer service and responsiveness (see for example, Chen et al., 2000; Karmarkar, 1987; Lee et al., 1997a,b; Oke and Szwejczewski, 2005; Ryu and Lee, 2003; Steckel