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Counteracting the bullwhip effect with decentralized negotiations and advance demand information

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Abstract

This paper shows how to reduce the bullwhip effect by introducing advance demand information (ADI) into the ordering schemes of supply chains. It quantifies the potential costs and benefits of ADI, and demonstrates that they are not evenly distributed across the chain. Therefore, market-based strategies to re-distribute wealth without penalizing any supplier are presented. The paper shows that if a centralized operation can eliminate the bullwhip effect and reduce total cost, then some of this reduction can also be achieved with decentralized negotiation schemes. Their performance is evaluated under different modes of probabilistic supplier behavior. For some forms of behavior the optimum is reached. But if suppliers are greedy and impatient the expected gain in wealth is relatively small. This is a case of economic "market failure".

Keywords: Bullwhip effect; Advance demand information; Market-based strategy; Probabilistic supplier behavior

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1. Background and definitions

In the supply chain literature, the term "bullwhip effect" refers to a phenomenon where the fluctuations in order sequence are usually greater upstream than downstream of a chain. This phenomenon is repeatedly shown in industry operations [1–4], macroeconomic data [5–10], and simulations such as "beer games" [11–13]. The bullwhip effect results in huge extra operation costs for suppliers; in some cases reported to be as much as 25% [14–16]. The rest of this section explains advance demand information (ADI) and its effect on, both, the bullwhip effect and the cost of operation; the key ideas are taken from Ref. [17].

1.1. Supply chain operation with ADI

Consider a multi-echelon chain with $i = 1, 2, \ldots, I+1$ suppliers and one final customer (treated as supplier $i = 0$), as shown in Fig. 1. Every supplier ($i = 0, 1, 2, \ldots, I$) orders $u_i(t)$ items from its upstream neighbor at

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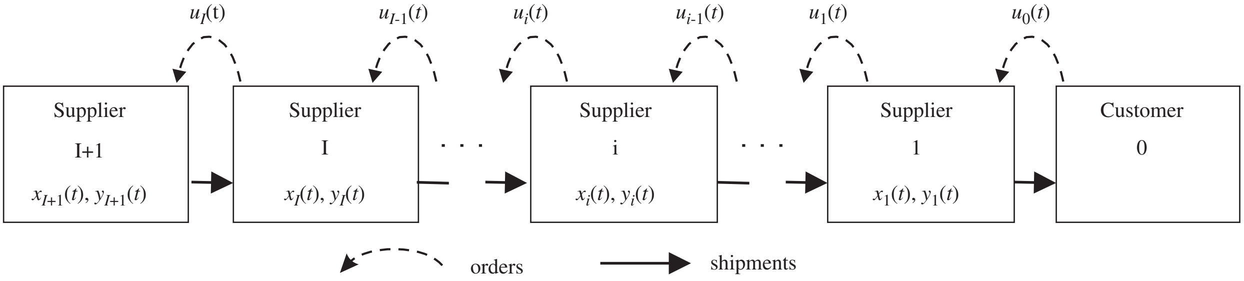

Fig. 1. A representation of a supply chain.

discrete times $t = \ldots, -2, -1, 0, 1, 2, \ldots$, and receives the items after a constant lead time $l_i = 0, 1, 2, \ldots$. The conservation equations for the supplier's *inventory position* at time t (cumulative orders placed minus orders received, $x_i(t)$) and for the *in-stock inventory* at time t (cumulative items received minus orders received, $y_i(t)$) are

$$x_i(t+1) = x_i(t) + u_i(t) - u_{i-1}(t) \quad \forall i = 1, 2, \ldots \tag{1}$$

and

$$y_i(t+1) = y_i(t) + u_i(t - l_i) - u_{i-1}(t) \quad \forall i = 1, 2, \ldots . \tag{2}$$

The supply chain is decentralized if suppliers act independently, placing orders based on private information; i.e., on all the inventory records and the histories of orders received and placed. Since it turns out that the history of orders placed is redundant information [17], all the information available to supplier i at time t is encapsulated in the following information set:

$$\mathscr{I}_i(t) := \{x_i(t), x_i(t-1), \ldots, x_i(-\infty); y_i(t), y_i(t-1), \ldots, y_i(-\infty); \\ u_{i-1}(t-1), u_{i-1}(t-2), \ldots, u_{i-1}(-\infty)\}.$$

Therefore, the most general linear and time-invariant (LTI) ordering policy only uses elements of this set as inputs, and can be written as follows:

$$u_i(t) = \gamma_i + A_i(P)x_i(t) + B_i(P)y_i(t) + C_i(P)u_{i-1}(t-1), \quad i = 1, 2, \ldots, \tag{3}$$

where parameter γ_i is a real number, and $A_i(\cdot), B_i(\cdot), C_i(\cdot)$ are polynomials with real coefficients. The symbol P is a backward lag operator; i.e., $P^k x(t) = x(t-k), \forall k = 0, 1, 2, \ldots$. The polynomials $A_i(P)$ and $B_i(P)$ indicate the influence of inventory history, and $C_i(P)$ the history of orders received. We shall abbreviate the policy of supplier i by $\mathscr{F}_i := \{\gamma_i, A_i, B_i, C_i\}, \forall i$.

We can also allow suppliers to incorporate ADI into their policies [17–21]. We say that ADI is available to supplier $i+1$ if its downstream neighbor (i) announces at every t the orders it will place in $\bar{h}_{i,i+1} = 0, 1, \ldots$ future periods, and commits to these orders with a contract. We call $\bar{h}_{i,i+1}$ the commitment index between i and $i+1$, and the difference $h_i := \bar{h}_{i-1,i} - \bar{h}_{i,i+1}, i = 1, \ldots, I$ the ADI level of i; see Fig. 2.[1]

If the ADI level of a supplier is positive ($h_i > 0$), the supplier (i) is a net consumer of ADI and can incorporate extra information into its policies. Its order $u_i(t)$ is determined and committed at time $t - \bar{h}_{i,i+1}$ based on the following information set:

$$\mathscr{I}'_i(t - \bar{h}_{i,i+1}) := \mathscr{I}_i(t) \cup \{u_{i-1}(t), u_{i-1}(t+1), \ldots, u_{i-1}(t + h_i - 1)\} \quad \text{if } h_i > 0.$$

A general LTI policy based on this information set has the following form [17]:

$$u_i(t) = \gamma_i + A_i(P)x_i(t) + B_i(P)y_i(t) + C_i(P)u_{i-1}(t + h_i - 1) \quad \forall i, t, \ \text{if } h_i > 0. \tag{4}$$

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[1] We assume that the customer and supplier $I+1$ do not make commitments; i.e., we let $\bar{h}_{0,1} = \bar{h}_{I+1,I+2} = 0$.