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Li Yan
National University of Singapore

Lie-Wie Yen
National University of Singapore

Tan-Gek Woo
National University of Singapore

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Li Yan
National University of
Singapore
liyan@comp.nus.edu.sg

Lie Wei Yen
National University of
Singapore
lieweiye@comp.nus.edu.sg

Tan Gek Woo
National University of
Singapore
tangw@comp.nus.edu.sg

Abstract

In this paper, we simulate an extendable multi-agent linear supply chain to evaluate the impact of different lead-time distributions on bullwhip effect and supply chain performance under centralized and decentralized information sharing strategies. Given a fixed total lead-time across the supply chain, centralized information sharing and disintermediation improve the supply chain performance. A skewed lead-time distribution also reduces the bullwhip effect under decentralized information sharing strategy. Although the bullwhip effect remains unchanged, different lead-time distributions will lead to different supply chain performance. These insights can help practitioners in the re-configuration of the supply chain.

Keywords: Lead-time distribution, bullwhip effect, supply chain performance, simulation, information sharing

Introduction

Today's global market has become more and more time-sensitive and time competitive. Shortening product life cycles, heightened expectation from customers, dangers of being dependent on a long forecast horizon in a volatile marketplace etc. have led both enterprises' and academic researchers' attention to the study of lead-time (Martin, 1998). Lead-time refers to the time lag between placing an order and receiving it (Li, 2000). It is one of the most important causes of bullwhip effect.

Reasons to reduce lead-time have been grouped as: (1) improvement of the ability to quickly fill customer orders that cannot be filled from stock; (2) reduction in the bullwhip effect; (3) more accurate forecasts due to a decreased forecast horizon; (4) reduction in finished goods inventory levels (Simchi-Levi and Kaminsky, 2000). Fisher and Raman (1996) model a Quick Response System to shorten the lead-time. Chen (2000) quantifies the impact of lead-time on bullwhip effect. His model is closely related to our paper.

In industrial practice, many strategies have been introduced to reduce lead-time. Wal-Mart uses cross-docking with most of its suppliers and shares its retail sales data (POS data) with Proctor and Gamble (P&G) to reduce lead-time. EDI and other advanced web technology have been used to shorten the order processing and communication time. To the suppliers who fail to recognize time as a competitive variable or whose systems cannot meet the needs for fast-changing market, the cost can be considerable. Compaq estimated that it had lost $500-$1bin in sales in 1994 because of stock-outs on its laptop and desktop computers (Martin, 1998)

Although lead-time reduction is well studied, there is relatively little research on lead-time distribution. We define *lead-time distribution* as varying the lead-time between each tier while keeping the total lead-time of the whole supply chain constant. There are two limitations in the previous research on the lead-time reduction: first, it only focuses on one or two tiers and does not have an overall view of the whole supply chain; and second, it does not include other performance metrics such as fill rate, total cost and inventory cost etc. into consideration. Our motivation for this research is to gain a deeper understanding of the behavior of supply chain network (SCN) under different lead-time distributions. In particular, given a fixed total lead-time, how the different distributions of this lead-time will affect the bullwhip effect and supply chain performance under both centralized and decentralized information sharing strategies. We also evaluate the effect of the number of tiers. The insights from our simulation results can help improving supply chain performance and point out direction for further optimization research.

We have organized this paper as follows: Section 2 describes the bullwhip effect and information sharing strategies in the supply chain context; then introduces Chen's quantification model of lead-time's impact on bullwhip effect. Section 3 describes the simulation model and performance measures used in this model. Section 4 reports and analyses the simulation results. Section 5 summarizes our findings and suggests future research directions.

Background

Literature Review

Bullwhip effect refers to the amplification of demand variability resulted from the information distortion in a supply chain where companies upstream do not have information on the actual consumer demand (Lee et al. 1997).

Large amount of work has been done on the quantification of bullwhip effect. They can be classified into three categories: (1) To quantify the magnitude of the bullwhip effect mathematically (Chen et al. 2000); (2) To examine how the bullwhip effect causes such as demand forecasting, lead-time etc. affect the increase in the demand variability (Chen et al. 2000); and (3) To measure the impact of some of the counteractions for bullwhip effect, such as the effect of consumer demand and supplier capacity information sharing. (Bourland, 1996; Chen et al. 1998; Gavirneni, 1998; Lee et al. 1999; Gavirneni et al. 1999;).

In decentralized information sharing, each tier only knows the order information from its immediate downstream tier and bases its forecast only on this information. This can cause the bullwhip effect. A famous example of bullwhip effect is Beer Game (Senge, 1994). The most well-known simulations of this game are MIT Beer Game (Simchi-Levi et al. 2000; Kimbrough et al. 2001), and Columbia Beer Game (or Stationary Beer Game) (Kimbrough et al. 2001).

Centralized information sharing has been a frequent suggestion for reducing the bullwhip effect. Each tier in the supply chain is provided with the real customer demand information and can create more accurate forecast based on this information rather than relying on the orders received from its immediate downstream tier. This is the idea behind CRP/VMI implementation. Tan (1999), Li et al. (1999) and Lin et al. (1999) use a multi-agent simulation model to explore the impact of inventory, order and shipment information sharing on the supply chain performance.

Quantification Model of the Impact of Lead-time on Bullwhip Effect

In Chen (2000)'s effort to quantify the bullwhip effect, there are two famous and widely accepted inequalities which quantify the impact of lead-time on bullwhip effect. In this model, customer's demands in each observation period are i.i.d.

D refers to the customer demand to the retailer
k is the number of tiers.
q^k refers to the *(k-1)*th tier's order to the *k*th tier
L_i is the lead-time between stage *i* and *i+1*.
p is the number of observations of the demand, because each tier here is supposed to use the simplest forecasting method to forecast demand from the immediate downstream tier: the moving average.

$$\frac{Var(q^k)}{Var(D)} \geq 1 + \left(\frac{2(\sum_{i=1}^{k-1} L_i)}{p} + \frac{2(\sum_{i=1}^{k-1} L_i)^2}{p^2} \right) \qquad (2)$$

$$\frac{Var(q^k)}{Var(D)} \geq \prod_{i=1}^{k-1} \left(1 + \frac{2L_i}{p} + \frac{2L_i^2}{p^2} \right) \qquad (3)$$

Var(D) refers to the variance of the customer demand seen by the retailer.
Var (q^k) represents the variance of the demand seen by the *k*th tier, in another words, that is also the variance of the order placed by the *(k-1)*th tier the *k*th tier.

For convenience of expression, we define: $B_c = \left(\frac{2(\sum_{i=1}^{k-1} L_i)}{p} + \frac{2(\sum_{i=1}^{k-1} L_i)^2}{p^2} \right)$, $B_d = \prod_{i=1}^{k-1} \left(1 + \frac{2L_i}{p} + \frac{2L_i^2}{p^2} \right)$

Chen quantifies bullwhip effect as $Var(q^k)/Var(D)$. Inequalities (2) and (3) give the lower bound of bullwhip effect under centralized and decentralized information sharing strategies respectively. Seen from this model, it seems that under the centralized information sharing strategy, given the same number of observations p, only the total lead-time will affect the bullwhip effect. As long as the sum of the lead-times at each tier is the same, the different distributions of lead-time will not affect the bullwhip effect. For example, we have two different distributions of lead-time as shown in Figure 1, one is [6 6 6 6], the other is [2 2 2 18]. Since the total lead-times are both 24, their bullwhip effects will be the same under centralized information sharing strategy. Under decentralized information sharing strategy, the distributions of lead-time [2 2 2 18], [2 2 18 2], [2 18 2 2] and [18 2 2 2] should give the same bullwhip effect since B_d is the same for these 4 distributions. Although the distribution of [6 6 6 6] also has the same total lead-time, it should display a different bullwhip effect since it has a much larger B_d. Although we can quantify the bullwhip effect by this model, it does not tie to the supply chain performance directly. We run the simulation model of an extendable supply chain to investigate this phenomenon and observe the supply chain performance under different lead-time distributions and different information sharing strategies.
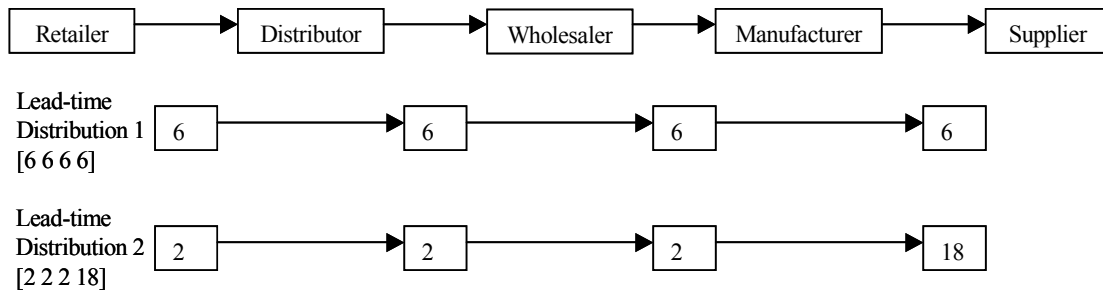

Figure 1. Lead-Time Distribution

Simulation Model

Based on the multi-agent simulation platform Swarm, we simulate an extendable multi-agent supply chain with a single entity at each tier. We verified that the entities, activities included in the system are those that are typically described in the supply chain management literature. This model is valid because it encompasses all of the major components of a real-world supply chain and it involves a detailed review of the inner-workings that is not seen in high-level analytical models.

Calculation

Calculation of target stock level uses the same formula for both centralized and decentralized information sharing strategies as shown below (Tan, 1999):

$$StockLevel = AVG * AVGL + z * STD * sqrt(AVGL)$$

For the decentralized strategy, AVG is the average demands of the immediate customer and AVGL is the average lead-time of this tier. On the other hand, AVG for the centralized case is the average consumer demand and AVGL is the sum of current lead-time and downstream lead-time. In this formula, z is a constant associated with service level.
The inventory position for decentralized strategy is

$$InvPos = current\ inv + outstanding\ order - backlog.$$

For centralized strategy, in contrast, it is calculated as below:

$$InvPos = current\ inv + outstanding\ order + downstream\ InvPos - retailer\ backlog$$

The reorder quantity for both policies is calculated as below:

$$Reorder\ Quantity = max\ \{StockLevel - InvPos,\ 0\}$$

Performance Measurements

The following performance measures are used to evaluate the simulation results:

Fill rate — the percentage of order that the entity is able to ship to its downstream customer.

Inventory Cost — calculated as current inventory times inventory holding cost per unit. In this simulation the inventory holding cost increases towards the downstream.

Backorder Cost — incurred when order cannot be met and this is calculated as unit of backlog times the backorder penalty rate. The backorder penalty rate, similar to inventory holding cost, increases towards the downstream.

Total Cost — the sum of the inventory cost and the backorder cost.

Result Analysis

Experimental Design

Table 1. Backorder Cost and Inventory Holding Cost Structure (Tan, 1999)

	Retailer	Distributor	Wholesaler	Manufacturer	Supplier
Unit Inventory Cost ($)	4	4	3	2	1
Unit Backorder Cost ($)	5	5	3	2	1

We run the simulations with normally distributed customer demand of mean 10,000 and standard deviation 1000. The cost structure we have used is shown in Table 1. Each simulation run consists of 360 cycles and a cycle is a fixed unit of time in which items transported one step down the channel, new orders arrive, inventory level reviewed and orders placed upstream. In our simulation, we look into three independent variables for supply chains of 24 cycles total lead-time. They are information sharing policies, number of tiers and lead-time distribution as shown in Figure 2.
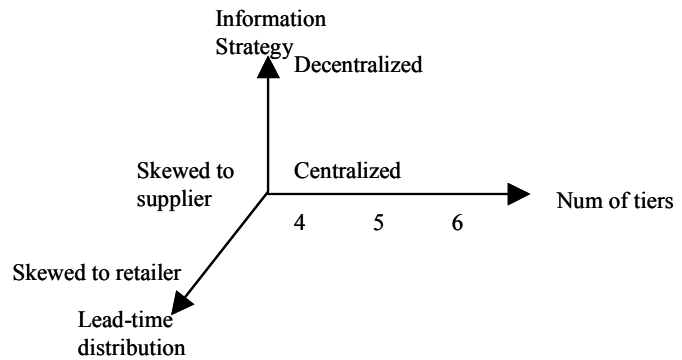
There are more than 8000 different lead-time distributions for a 5-tier supply chain with 24 cycles total lead-time alone. We will examine the two extreme distributions: even distributions and the most skewed distributions. For

Figure 2. Three Dimensions For Performance Measurement

example, the even distribution for a 5-tier supply chain is [6 6 6 6] and the skewed distributions for a 5-tier supply chain are [18 2 2 2], [2 2 2 18], [2 18 2 2] and [2 2 18 2].[1] To ensure that even distributions and skewed distributions are indeed extreme, we randomly select other distributions like [12 3 5 4] and [3 6 10 5] and find that these results fall between the two extreme distributions.

Supply Chains with Same Number of Tiers, Same Total Lead-time, Different Lead-time Distributions

Centralized Information Sharing
Our simulation shows that centralized information sharing yields very good performances with average fill rate 97.5%. The total cost is averaged at $189.4K consisting of 97.3% inventory holding cost and 2.7% backorder cost. The overall performances are similar across distributions yet performance improvement is visible when longer lead-time is distributed at upstream than downstream. The distributions [2 2 20], [2 2 2 18] and [2 2 2 2 16] all have the lowest inventory cost, backorder cost and total cost and the highest fill rate among distributions of the same number of tiers.

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[1] To allow enough time for each tier to response and to make the simulation more realistic, we set 2 as the smallest lead-time in our simulation.

There are larger deviations at individual tier level performances. Upstream lead-time relates positively with inventory cost, backorder cost and total cost. This is not surprising because long lead-time is known to produce poor performance. However, we observe that despite the large deviation seen at the tier level across different distributions, the overall performances are still similar when the total lead-time is fixed.
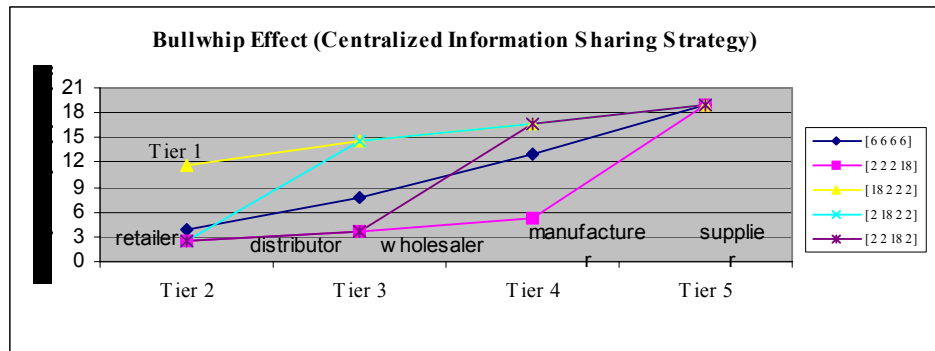

Figure 3. Bullwhip Effect under Centralized Information Sharing Strategy

Figure 3 shows the bullwhip effects for 5–tier supply chains. The bullwhip effects contributed by different lead-times are distinct and increase upstream in proportion to the lead-time at that tier. Despite taking different paths, the total bullwhip effect for all distributions are the same. We observe that under centralized information sharing strategy with constant total lead-time, all different distributions with fixed number of tiers have the same total bullwhip effect. This agrees with our discussion in Section 2.

Decentralized Information Sharing
Compared with centralized policy, decentralized information sharing yields relatively poor performances with average fill rate 82.1%. The total cost is averaged at $200.7K, consisting of 73.1% inventory holding cost and 26.9% backorder cost. Even though decentralized policy gives a lower inventory cost, the backorder cost is much higher. Highly skewed distributions perform better in all the four performance measures compared to even distribution.

The results at individual tiers for decentralized policy show similarity with those of centralized policy in the positive relationship between lead-time and performance. The difference is that supply chain with even distribution of total lead-time performs much worse than that with the four skewed distributions for all the performance measures.
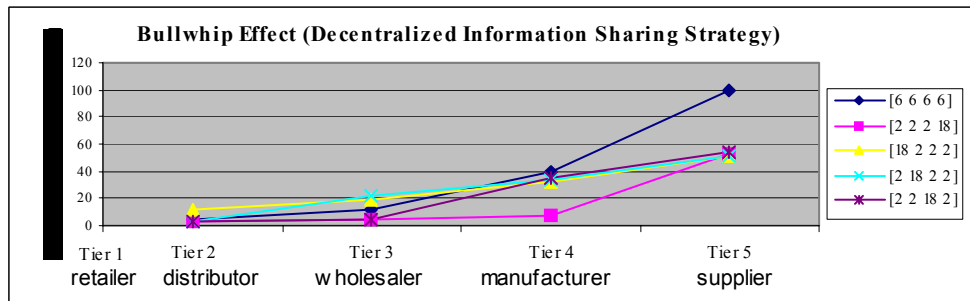

Figure 4. Bullwhip Effect under Decentralized Information Sharing Strategy

Figure 4 shows the bullwhip effects using decentralized policy on 5-tier supply chains. The total bullwhip effects are always higher than those adopting centralized policy. We also see different total bullwhip effects arising from different distributions of total lead-time 24. The four skewed distributions all have total bullwhip effect of about 52 but the even distribution gives a distinctly high total bullwhip effect of 98.9. This also agrees with what we expect in Section 2 that when B_d are the same, the bullwhip effects are similar. The even distribution [6 6 6 6] has a much larger bullwhip effect as it has a much larger B_d.

Performances in constant bullwhip effects
Even with the very similar bullwhip effects as observed among lead-time distributions like [2 2 2 18], [2 2 18 2], [2 18 2 2] and [18 2 2 2], there are still slight differences in supply chain performance. We observe that the SCN performs better when we have longer lead-time upstream and shorter lead-time downstream (i.e. skewed towards upstream). This is consistent with our other observation that skewing the distribution upstream transfers more inventory upstream and hence this reduces overall inventory cost.

Supply Chains with Different Number of Tiers, Same Total Lead-time, Different Lead-time Distributions

The performances worsen when the number of tiers increases regardless of which policy is adopted. As tier number increases from 4 to 5, total cost increases by an average of 10.7% and inventory cost increases by 8.2% while fill rate remains about the same. Backorder cost for centralized case increases by 33.3%. As tier number increases from 5 to 6, total cost increases by 4.7% and

inventory cost increases by 2.8% on average. Backorder cost for centralized policy increases by 16.9%.

Figure 5 shows that under both information-sharing strategies, the bullwhip effect increases with increasing number of tiers. The change under decentralized information sharing is more drastic than that under centralized case. This is because under decentralized information sharing strategy, adding a tier in the supply chain while keeping the same total lead-time changes B_d much. But with centralized information sharing, increasing the number of tiers keeping total lead-time constant do not increase B_c. Number of tiers indeed contributes to performance even when total lead-time is constant.
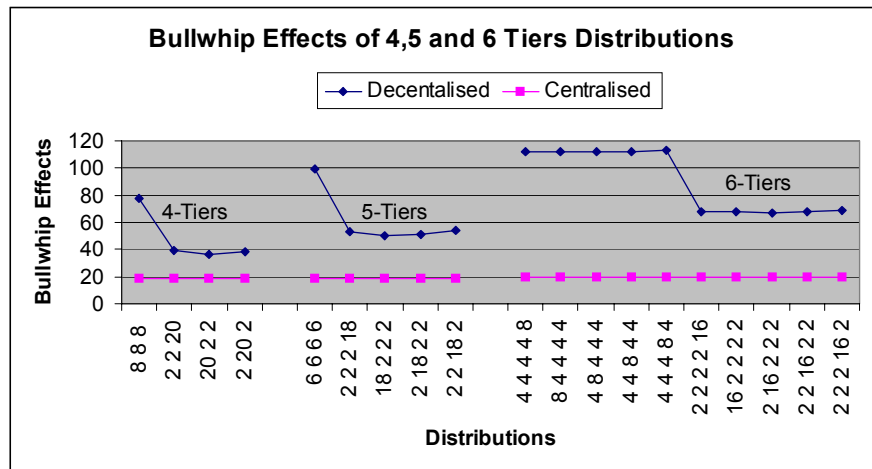

Figure 5. Bullwhip Effect with Different Tiers

Discussions

Table 2. Summary of Findings

Increase in:	Bullwhip Effect	Inventory Cost	Backorder Cost	Total Cost	Fill rate
Information shared	Significantly decreases	Increases	Significantly decreases	Slightly decreases	Increases
Skewness of Lead-time Distribution (Decentralized)	Decreases	Decreases	Decreases	Decreases	Increases
Skewness of Lead-time Distribution(Centralized)	Exactly the same	About the same	About the same	About the same	About the same
Skewness toward upstream with the same division	About the same	Slightly decreases	Slightly decreases	Slightly decreases	Slightly increases
Number of Tiers	Increases	Increases	Increases	Increases	About the same

Table 2 summarizes the relationship among lead-time distribution, bullwhip effect and supply chain performance for supply chains with constant lead-time. The results suggest that highly skewed supply chains with less number of tiers reduce the bullwhip effect and improve the supply chain performance. By negotiating among business partners to increase lead-time in the upstream and reduce lead-time in the downstream, practitioners may reap the benefits of skewed SCN. This can be achieved using other sets of transportation methods or relocations of facilities. The individual performance at the supplier may worsen but redistributing the overall gain across tiers can solve this problem. However, one needs to note that there is a limit to lead-time reduction between two particular tiers and there is a trade-off between lead-time reduction and transportation cost.

Our simulation results show that centralized information sharing gives the greatest improvement in SCN performance. Both reducing number of tiers (i.e. disintermediation) and increasing the skewness of lead-time distribution will lead to improved supply chain performance. Which gives a better performance? Having centralized information sharing significantly reduces the bullwhip effect and its negative effects on performance. In addition, the performance is stable across distributions with centralized information sharing strategy. However, sharing information involves much investment in IT as well as trust and long term relationship among business partners and sometimes information sharing is very limited. What then can we do if there is no information sharing to improve performance? Our simulation results show that with decentralized information sharing, [3 3 6 6 6] is more skewed than [6 6 6 6] while the latter has one less tier. Results from simulation shows that when we change the lead-

time distribution from [3 3 6 6 6] to [6 6 6 6], the total cost decreases by 28.5% and the fill rate increases by 1.8%. The results obtained from these two cases agree with the general consensus that disintermediation yields benefits. However, if in the process of disintermediation the supply chain changes from an even more skewed [7 6 5 3 3] to the even distribution [6 6 6 6], disintermediation may not give so much benefit. This warrants a need for a more in-depth study of the interaction between tiers numbers and lead-time distribution.

Conclusion

In this paper, we evaluate the impact of different lead-time distributions on the bullwhip effect and the supply chain network (SCN) performance while keeping the total lead-time across the SCN fixed. We explore along three dimensions: centralized vs. decentralized information sharing, the skewness of lead-time distribution, and disintermediation. Our results show that centralized information sharing gives the greatest improvement in SCN performance and reduction in bullwhip effect, with disintermediation coming in second. A more skewed lead-time distribution also reduces the bullwhip effect in decentralized information sharing. Even when the bullwhip effect remains constant, SCN performance could still be improved through a skewed lead-time distribution. Future research studying the calculation of the cost and savings of supply chain configuration with different degree of skewing would clarify the feasibility of performance improvement via having a more skewed lead time distribution.

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