Impact of Echelon Ratio for the Bullwhip Effect in a Three-echelon Supply Chain Based on Multi-agent Simulation

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***Abstract*—Many papers have discussed the bullwhip effect in supply chain. However, little research has analyzed the impact of echelon ratio for the bullwhip effect. This paper aims at showing this impact in a three-echelon supply chain using multi-agent simulation. The result indicates that the bullwhip effect exists in not only single-player but also multi-player supply chain. In multi-player supply chain, echelon ratio is more sensitive than player number to affect the bullwhip effect. Order quantity fluctuation remains stable when echelon ratio changes for retailers. But this fluctuation gradually decreases with the increase of echelon ratio for distributors and manufacturers. When echelon ratio is relatively big, the amplification of order quantity fluctuation from distributor to manufacturer is relatively small; and the minimal fluctuation, the maximal fluctuation, the average fluctuation are approximately the same at retailer or distributor echelon. These conclusions offer a macroscopic management view for reducing the bullwhip effect. They can also provide references for estimating the bullwhip effect magnitude of different supply chains.**

***Index Terms*—supply chain, bullwhip effect, echelon ratio, muti-agent simulation, repast**

I. Introduction

Bullwhip effect, proposed by Lee et al. [1], means the variability of order quantity increases when moving upstream in supply chain. The bullwhip effect can cause big efficiency loss in supply chain. It may lead to production misguidance, overstock, sluggish sales, poor customer service, etc. The bullwhip effect is so important that it becomes one of the core problems in supply chain management. Many studies keep on researching in this field. Ref. [2] has built an ordering model of supply chain on Swarm multi-agent workbench and estimated some order procedure policies. Ref. [3] has presented a discrete control theory model to show that the bullwhip effect can be reduced by increasing the average age of forecasts and reducing the inventory and WIP correction rate. Ref. [4] has developed an agent-based system to minimize the total cost and to reduce the bullwhip effect in supply chain, where all demands, lead times, and ordering quantities are fuzzy. Ref. [5] has analyzed the modification ability of distribution centers in Vendor-Managed Inventory (VMI) system. This analysis can provide references for reducing the bullwhip effect. Ref. [6] has compared the proportional order-up-to level policy and the full-state-feedback order-up-to level policy for ARMA(2,2) demand processes. The results show that the full-state-feedback policy is more attractive. Ref. [7] has introduced fuzzy sets and numbers to describe the uncertainty in supply chain. It has presented a fuzzy multi-level programming modeling method to solve the problem. Ref. [8] has analyzed the impact of exponential smoothing and minimum mean squared error forecasting for both the bullwhip effect and inventory variances. Ref. [9] has analyzed the information flow management of VMI system in automobile parts inbound logistics based on the environment of Internet of Things. Ref. [10] has developed a simple set of formulas that describe the traditional bullwhip measure as a combined outcome of several important drivers.

Over the years, studies on supply chain modeling and application have made a great progress. Single-player supply chain and multi-player supply chain are both discussed. Single-player supply chain means a supply chain with only one manufacturer, one distributor and one retailer while multi-player supply chain means a supply chain with multiple manufacturers, multiple distributors and multiple retailers. Few studies, however, have examined the bullwhip effect in multi-echelon and multi-player supply chain from echelon ratio perspective. This study tries to research this topic. The concept “echelon ratio”, also called concentration degree in [11], is defined as the ratio of the number of players in two adjacent tiers. Usually, the number of distributors is bigger than that of manufacturers, and the number of retailers is bigger than that of distributors. Therefore, echelon ratio is bigger than 1. For example, if the manufacturer number is 3 and the echelon ratio equals 2, this supply chain includes 3 manufacturers, $6(3\times2)$ distributors and $12(6\times2)$ retailers. What influences does echelon ratio have on bullwhip effect? What properties do supply chains with different

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echelon ratios have? To answer these questions, a multi-agent model is built. The simulation results show that echelon ratio has different impacts on the order quantity fluctuation of manufacturer, distributor and retailer. On the other hand, supply chains with big echelon ratio have some special properties.

The remainder of this paper is organized as follows. Section 2 builds a three-echelon supply chain model including multiple manufacturers, multiple distributors and multiple retailers. Section 3 simulates the multi-agent model on Repast suite and analyzes the bullwhip effect of different echelon ratios from three aspects. Section 4 concludes.

II. MODEL BUILDING

In traditional supply chain, enterprises always order from the same supplier. This purchase pattern is maintained as a long-term supply relationship. But with the development of informatization and globalization, enterprises could change their suppliers dynamically and flexibly in modern supply chain. Therefore, supply chain in modern society is actually a network. Based on this, the study builds a three-echelon supply chain model including x manufacturers, y distributors and z retailers (x,y,z ∈ N) (See Fig. 1). For example, if distributor-1 orders from manufacturer-1 at current time, it could choose to order from manufacturer-1 again or any other manufacturers at the next time.

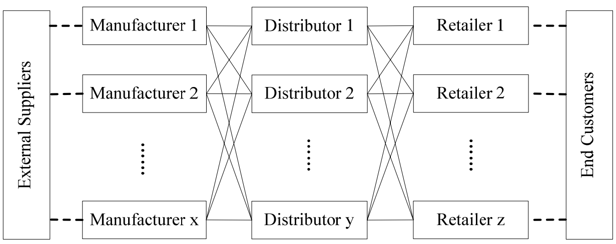

Figure 1. Supply chain

Some hypotheses are made based on the model shown in Fig. 1.

All players sell homogeneous goods. An i.i.d. end customer demand D accords with normal distribution with mean μ and standard deviation σ: D~N(μ,σ2). To enhance the comparability of different player numbers, the model assumes that all retailers' sales volume equals D/z. The initial inventories of every manufacturer, distributor and retailer are μ/x, μ/y, μ/z, respectively.

Players send goods guided by the fixed allocation mechanism [12]. Fixed allocation mechanism means players firstly attach their downstream players with different priorities; then they send goods to downstream players according priority rank until all goods are sent out. This mechanism is proved that players would not exaggerate order quantity to expand the bullwhip effect. This mechanism is also in widespread use. Enterprises could define priority according cooperation time, customer reputation, shipment distance, etc.

The downstream players order from upstream players randomly. Manufacturers send goods entirely, which means distributors' orders could be fulfilled with no gaps. Distributors and retailers' back orders lose immediately. In modern supply chain, enterprises could choose their suppliers dynamically and flexibly. Once an upstream supplier is out of stock, enterprises could get goods conveniently from other upstream suppliers. Therefore, this study assumes that the downstream players order from upstream players randomly and distributors and retailers' back orders lose immediately.

All players use a typical order-up-to level policy to determine order quantity and a moving average method to forecast demand. The order-up-to level policy is commonly used in enterprises. It is the standard algorithm in many MRP and ERP software suites [13]. If the calculated order quantity is bigger than 0, the player would order from upstream players. Otherwise, the player would send no orders. The equations are as follows.

$$q_t = (L + C) \times \bar{\mu}_t + CSL \times \sqrt{L + C} \times \bar{\sigma}_t - cs_t - ps_t \tag{1}$$

$$\bar{\mu}_t = \left(\frac{1}{m}\right) \sum_{i=t+1-m}^{t} d_i \tag{2}$$

$$\bar{\sigma}_t = \sqrt{\left(\frac{1}{m}\right) \sum_{i=t+1-m}^{t} (d_i - \bar{\mu}_t)^2} \tag{3}$$

where:

q_t *order quantity at time t*
L *lead time*
C *cycle counting interval*
$\bar{\mu}_t$ *forecasted mean of demand at time t*
CSL *cycle service level*
$\bar{\sigma}_t$ *forecasted standard deviation of demand at time t*
cs_t *current inventory at time t*
ps_t *pipeline inventory at time t*
t *time step*
d_i *demand quantity at time i*
m *forecasting historical time number*

Since moving average method could not be applied at the first m unit times, all players use a pass-order policy to determine order quantity. The equation is as (4).

$$q_t - d_t \tag{4}$$

where:

q_t *order quantity at time t*
d_t *demand quantity at time t*

Ref. [14] has raised the ratio of upstream enterprises' order quantity variance and end customers' demand variance to quantify the bullwhip effect. If this ratio is bigger than 1, the bullwhip effect exists. The bigger the ratio is, the more notable the bullwhip effect is. In statistics, variance is affected by the mean size. In order to eliminate the influence of mean size, this study uses coefficient of variation (COV) to study the bullwhip effect and the order fluctuation. The equations of average order quantity COV of manufacturer, distributor, retailer and the equation of average end customer demand COV are as follows.

$$\bar{v}_1 = \left(\frac{1}{x}\right)\sum_{j=1}^{x}\frac{\sqrt{\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T}\left(q_{jt}-\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T} q_{jt}\right)^2}}{\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T} q_{jt}} \quad (5)$$

$$\bar{v}_2 = \left(\frac{1}{y}\right)\sum_{j=1}^{y}\frac{\sqrt{\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T}\left(q_{jt}-\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T} q_{jt}\right)^2}}{\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T} q_{jt}} \quad (6)$$

$$\bar{v}_3 = \left(\frac{1}{z}\right)\sum_{j=1}^{z}\frac{\sqrt{\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T}\left(q_{jt}-\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T} q_{jt}\right)^2}}{\left(\frac{1}{n_j}\right)\sum_{q_{jt}\neq 0,t=A}^{T} q_{jt}} \quad (7)$$

$$\bar{v}_4 = \frac{\sqrt{\left(\frac{1}{T-A+1}\right)\sum_{t=A}^{T}\left(D_t-\left(\frac{1}{T-A+1}\right)\sum_{t=A}^{T} D_t\right)^2}}{\left(\frac{1}{T-A+1}\right)\sum_{t=A}^{T} D_t} \quad (8)$$

where:

$\bar{v}_1$ *average COV of manufacturer order quantity*
$\bar{v}_2$ *average COV of distributor order quantity*
$\bar{v}_3$ *average COV of retailer order quantity*
$\bar{v}_4$ *average COV of end customer demand*
x *number of manufacturers*
y *number of distributors*
z *number of retailers*
T *total simulation time*
t *time step*
A *the begin time to calculate COV*
q_{jt} *order quantity of manufacturer/distributor/retailer j at time t*
n_j *count of time where the order quantity of manufacturer/distributor/retailer j is bigger than 0 from time A to time T*
D_t *total end customer demand at time t*

In order to eliminate the bias of the initial state, the first A-1 unit times are not used to calculate COV. In this model, when the number of players is big and the echelon ratio is small, an upstream player may receive no orders from downstream players because of randomness. Then the order quantity of the upstream player may also be zero. The mean of order quantity would become not accurate if considering about these zeros. Therefore, this study uses n_j to remove all the times at which a player sends no orders when calculating the COV. This situation also fits the actual order process in modern supply chain. Players may send many or no orders for a period of time. The time interval between one actual order and the next is unstable.

III. Model Simulation

A. Repast Suite

The muti-agent model is realized on Recursive Porous Agent Simulation Toolkit (Repast) suite through programming with Java language. The Repast suite is a family of advanced, free, and open source agent-based modeling and simulation platforms. Repast was firstly created at the University of Chicago and subsequently maintained by organizations such as Argonne National Laboratory. Repast is now managed by the non-profit volunteer Repast Organization for Architecture and Development (ROAD). The Repast system, including the source code, is available directly from the web.

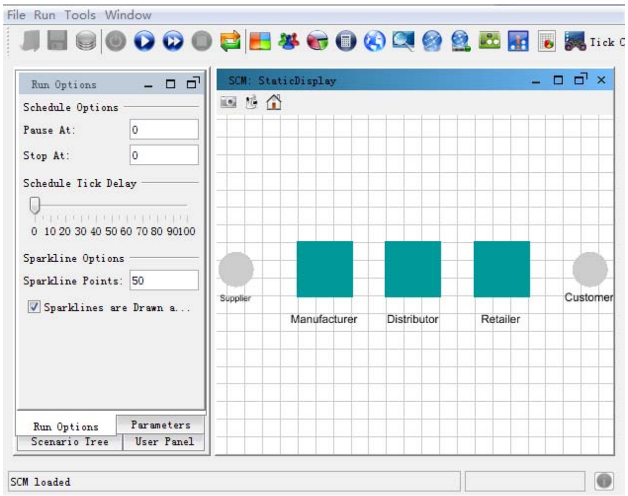

Figure 2. Repast console

Repast borrows many concepts from the Swarm. Swarm is one of the earliest and most famous agent-based modeling toolkits. On the other hand, Repast is differentiated from Swarm since Repast has multiple pure implementations in several languages and built-in adaptive features such as genetic algorithms and regression. More and more researchers use this software as their muti-agent simulation workbench.

In this model, every manufacturer, distributor and retailer is constructed as an agent. Every agent has its attributes including cycle service level, lead time, cycle counting interval, current inventory, pipeline inventory, demand quantity, order quantity. Every agent uses an order-up-to level policy and a moving average method. The order interaction mechanisms between manufacturer agents, distributor agents and retailer agents are established.

Initial parameters are set as follows. μ=10000, σ=2000, L=2, C=1, CSL(90%)=1.2816, m=10, T=500, A=101.

B. Single-player: Average Coefficient of Variation

Assume that this is a single-player supply chain including only one manufacturer, one distributor and one retailer, i.e. number x=y=z=1 and echelon ratio β=1. The order quantities of manufacturer, distributor, retailer and end demand quantity of customer from time 101 to time 500 are collected after running the model. In order to show the patterns clearly, Fig. 3 only describes the order quantities from time 101 to time 200.

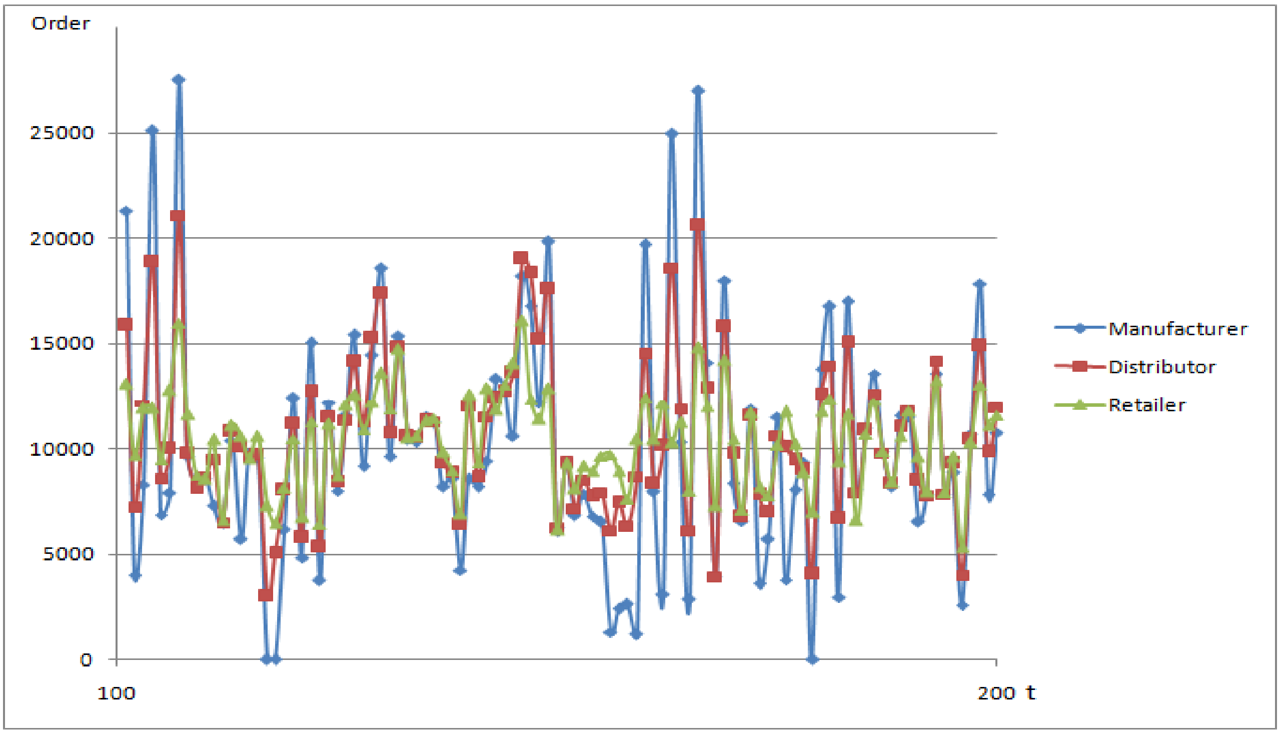

Figure 3. Order quantity

As indicated in Fig. 3, the order quantity fluctuation is relatively stable in this period. From downstream to upstream, i.e. from retailer, distributor to manufacturer, variance of order quantity is amplified. The bullwhip effect is notable. This conclusion tallies with many studies [15][16][17]. In order to compare the magnitude of fluctuation, the average COV is calculated in Tbl. 1. It clearly shows $\bar{\mathbf{v}}_1 > \bar{\mathbf{v}}_2 > \bar{\mathbf{v}}_3 > \bar{\mathbf{v}}_4$. The fluctuation is amplified more than three times (0.6480/0.2081=3.1139) from end customer to manufacturer.

TABLE 1.
AVERAGE COV

β	$\bar{\mathbf{v}}_1$	$\bar{\mathbf{v}}_2$	$\bar{\mathbf{v}}_3$	$\bar{\mathbf{v}}_4$
1	0.6480	0.4249	0.2703	0.2081

C. Multi-player: Average Coefficient of Variation

Assume that this is a multi-player supply chain including multiple manufacturers, multiple distributors and multiple retailers.

Firstly, the number of retailers is fixed at 900. Echelon ratios are set to 1.5, 2, 4, 6, 10, 15, respectively. The echelon ratios are not arithmetical series or geometric series. The reason for using these values is that the simulation result will show clear patterns under these values. Tbl. 2 summarizes the detailed number of manufacturers, distributors and retailers. The order quantity of manufacturer, distributor, retailer and the demand quantity of end customer from time 101 to time 500 are collected after running the model. The collected data are many high dimension matrices. Tbl. 3 shows the calculated average COV using the collected data. Fig. 4 gives the scatter diagram of the average COV.

TABLE 2.
PLAYER NUMBER WITH FIXED RETAILER

β	Manufacturer	Distributor	Retailer
1.5	400	600	900
2	225	450	900
4	56	225	900
6	25	150	900
10	9	90	900
15	4	60	900

TABLE 3.
AVERAGE COV WITH FIXED RETAILER

β	$\bar{\mathbf{v}}_1$	$\bar{\mathbf{v}}_2$	$\bar{\mathbf{v}}_3$	$\bar{\mathbf{v}}_4$
1.5	0.9481	0.8333	0.4333	0.2023
2	0.9418	0.8256	0.4195	0.1943
4	0.8114	0.7470	0.4032	0.1987
6	0.7315	0.6893	0.3885	0.1923
10	0.6328	0.6240	0.3883	0.2011
15	0.5801	0.5520	0.3668	0.2002

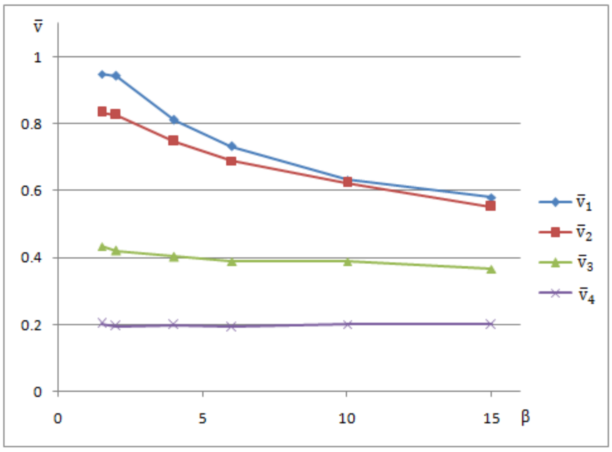

Figure 4. Average COV with fixed retailer

A couple of patterns can be identified from Tbl. 3 and Fig. 4.

From vertical aspect, no matter what the echelon ratio is, average COV increases from downstream to upstream. This reflects that order quantity fluctuation is amplified from retailer, distributor to manufacturer. The bullwhip effect exists. For example, when echelon ratio is 4, the average COV of order quantity is 0.1987, 0.4032, 0.7470, 0.8114, respectively. When echelon ratio is relatively small, say 1.5, the average COV has much difference between upstream and downstream. The amplification from retailer to distributor is bigger than that from end customer to retailer or that from distributor to manufacturer. When echelon ratio is relatively big, the amplification from retailer to distributor is also notable. But the average COV of manufacturers is just a little bigger than that of distributors, which means big echelon ratio reduces the order quantity fluctuation or the bullwhip effect. For example, when echelon ratio is 10, the average COV of distributor is 0.6240 and the average COV of manufacturer is 0.6328. The former is closed to the latter.

From horizontal aspect, the average COV of retailers remains stable when echelon ratio increases. All retailers sell the same volume of goods, then the average COV is only affected by end customer demand. End customer demand accords with normal distribution, and the average COV is σ/μ at every unit time. Then the average COV of retailers changes as the average COV of end customer demand and remains stable. But to distributors and manufacturers, the average COV decreases, and the decrease speed slows down. Distributors and manufacturers receive orders from downstream randomly. A distributor or a manufacturer could expect to receive orders from more downstream players when echelon ratio increases from a small value. This would counteract some of the randomness impacts and bring the order quantity fluctuation down. The counteraction fades when the echelon ratio keeps increasing.

Secondly, the number of distributors is fixed at 60. Echelon ratios are set to 1.5, 2, 4, 6, 10, 15, respectively. Tbl. 4 summarizes the detailed number of manufacturers, distributors and retailers. The order quantity of manufacturer, distributor, retailer and the demand quantity of end customer from time 101 to time 500 are collected after running the model. Tbl. 5 shows the calculated average COV using the collected data. Fig. 5 gives the scatter diagram of the average COV.

TABLE 4.
PLAYER NUMBER WITH FIXED DISTRIBUTOR

β	Manufacturer	Distributor	Retailer
1.5	40	60	90
2	30	60	120
4	15	60	240
6	10	60	360
10	6	60	600
15	4	60	900

TABLE 5.
AVERAGE COV WITH FIXED DISTRIBUTOR

β	$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$
1.5	0.9334	0.8369	0.4370	0.2024
2	0.9110	0.8091	0.4114	0.1862
4	0.8202	0.7647	0.4089	0.1954
6	0.7251	0.6994	0.4175	0.1968
10	0.6370	0.6183	0.3886	0.1927
15	0.5801	0.5520	0.3668	0.2002

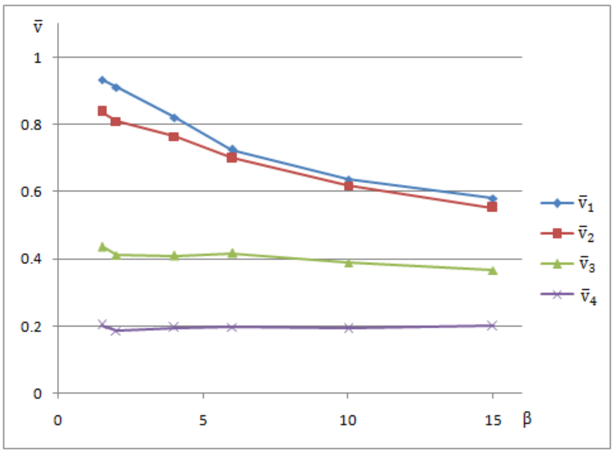

Figure 5. Average COV with fixed distributor

Finally, the number of manufacturers is fixed at 4. Echelon ratios are set to 1.5, 2, 4, 6, 10, 15, respectively. Tbl. 6 summarizes the detailed number of manufacturers, distributors and retailers. The order quantity of manufacturer, distributor, retailer and the demand quantity of end customer from time 101 to time 500 are collected after running the model. Tbl. 7 shows the calculated average COV using the collected data. Fig. 6 gives the scatter diagram of the average COV.

TABLE 6.
PLAYER NUMBER WITH FIXED MANUFACTURER

β	Manufacturer	Distributor	Retailer
1.5	4	6	9
2	4	8	16
4	4	16	64
6	4	24	144
10	4	40	400
15	4	60	900

TABLE 7.
AVERAGE COV WITH FIXED MANUFACTURER

β	$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$
1.5	0.9267	0.8013	0.4109	0.1994
2	0.9057	0.8114	0.4174	0.2053
4	0.7785	0.7571	0.3981	0.1890
6	0.6939	0.6801	0.3982	0.1966
10	0.6335	0.6285	0.4013	0.2060
15	0.5801	0.5520	0.3668	0.2002

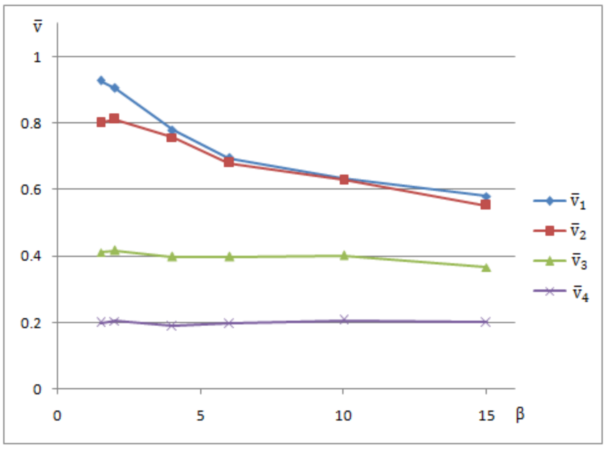

Figure 6. Average COV with fixed manufacturer

As shown in the tables and figures above, the bullwhip effect exists no matter what the echelon ratio is. When fixing the number of distributors or the number manufacturers, the conclusions are nearly the same as that of fixing the number of retailers. No matter what the fixing number is, the calculated average COV values almost equal. These phenomena indicate that echelon ratio is more sensitive than player number to affect the bullwhip effect.

D. Multi-player: Detailed Coefficient of Variation

The former part has analyzed the average COV of order quantity. This part will unfold the average COV to find some detailed laws. The echelon ratio is focused on a relative big number: 10. At this echelon ratio, the average COV values of distributor or retailer almost equal no matter what the fixing number is. Since the number of manufacturers is small, it could not show patterns clearly. The follow analysis will mainly talk about the detailed COV of distributor and retailer. Fig. 7 shows the detailed COV of 90 distributors and 900 retailers ranked by attached priority when fixing the number of retailers. Fig. 8 shows the detailed COV of 60 distributors and 600 retailers ranked by attached priority when fixing the number of distributors. Fig. 9 shows the detailed COV of 40 distributors and 400 retailers ranked by attached priority when fixing the number of manufacturers.

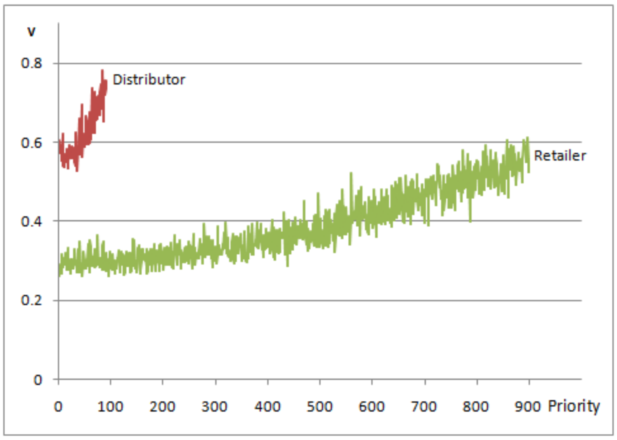

Figure 7. Detailed COV with fixed retailer

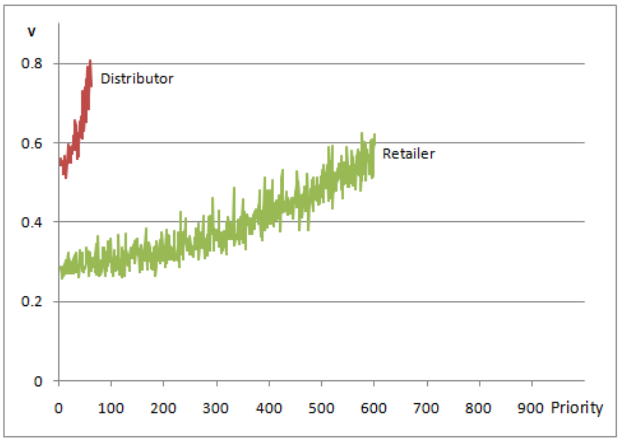

Figure 8. Detailed COV with fixed distributor

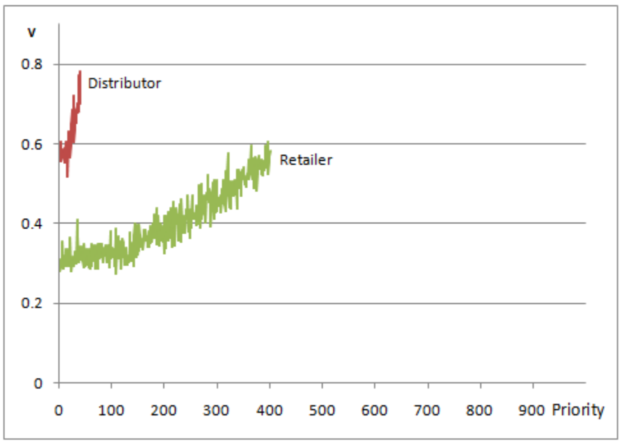

Figure 9. Detailed COV with fixed manufacturer

Some properties can be recognized by comparing of the three figures above. To distributors and retailers, the detailed COV increases with the decrease of priority when echelon ratio is 10. The increase speed of distributors is bigger than that of retailers. This phenomenon is caused by fixed allocation mechanism. If a distributor or retailer has low priority, it is likely that it could not get sufficient goods at some unit times. Then it would raise the order quantity the next unit time. This behavior would amplify the fluctuation of order quantity. On the other hand, when the number of distributors is 90, 60 or 40, the detailed COV generally increases from about 0.52 to about 0.80. The maximal value, the minimal value and the average value are approximately the same. When the number of retailers is 900, 600 or 400, the detailed COV generally increases from about 0.26 to about 0.61. The maximal value, the minimal value and the average value are also approximately the same. This is decided by the supply chain structure and has nothing to do with the player number in a certain range.

Fig. 10 and Fig. 11 are the histograms of the detailed COV of 90 distributors and 900 retailers when fixing the number of retailers. Fig. 12 and Fig. 13 are the histograms of the detailed COV of 60 distributors and 600 retailers when fixing the number of distributors. Fig. 14 and Fig. 15 are the histograms of the detailed COV of 40 distributors and 400 retailers when fixing the number of manufacturers. They are all right skewed distributions.

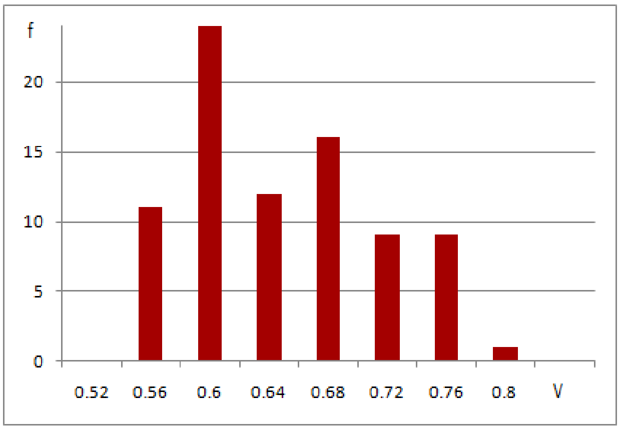

Figure 10. Detailed COV of distributor with fixed retailer

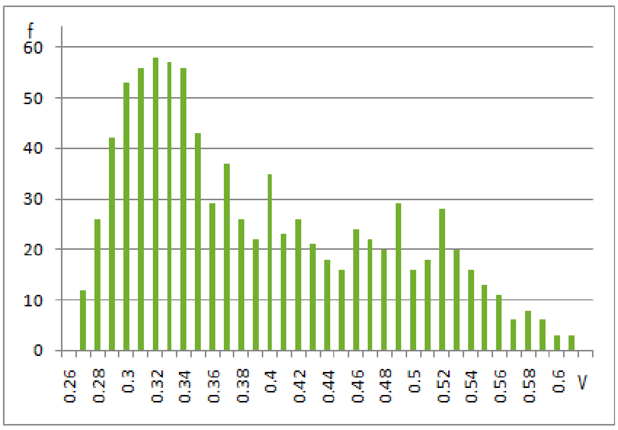

Figure 11. Detailed COV of retailer with fixed retailer

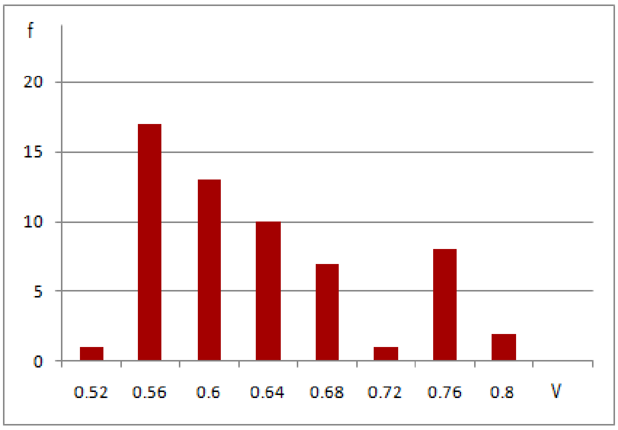

Figure 12. Detailed COV of distributor with fixed distributor

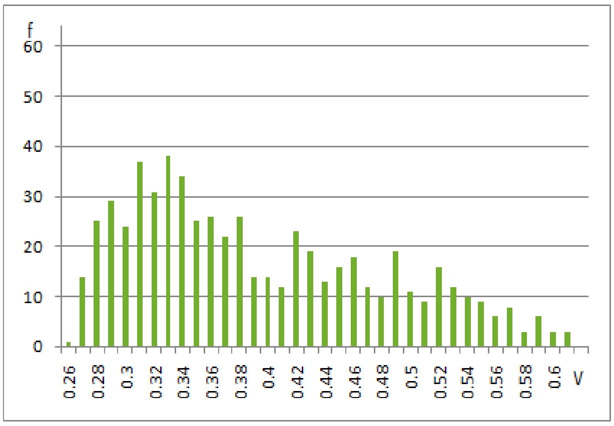

Figure 13. Detailed COV of retailer with fixed distributor

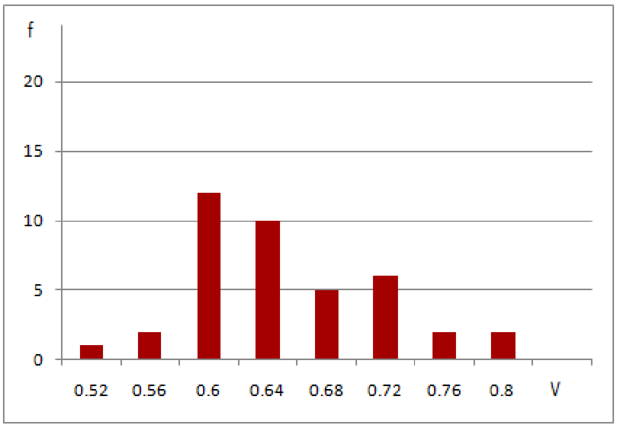

Figure 14. Detailed COV of distributor with fixed manufacturer

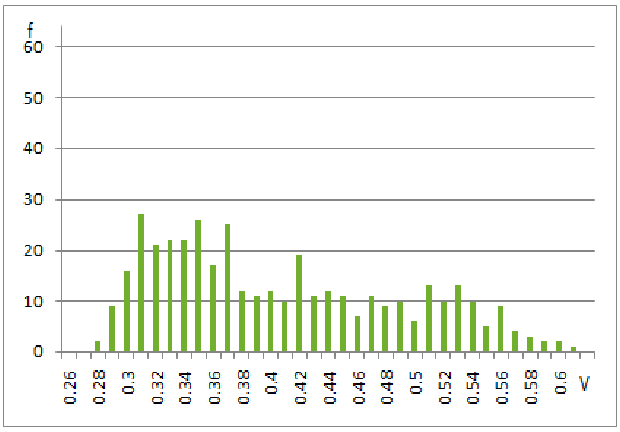

Figure 15. Detailed COV of retailer with fixed manufacturer

The conclusions are the same when echelon ratio is 6 or 15. Because of the limitation of length, there is no more tautology here.

IV. CONCLUSION

This study researches a three-echelon supply chain including manufacturers, distributors and retailers. When players use a typical order-up-to level policy to determine order quantity and a moving average method to forecast demand, the order quantity fluctuation is amplified from downstream to upstream. The bullwhip effect exists. Through simulation experiments and subsequent analysis of the results, it has been found that:

1) In single-player supply chain, order quantity fluctuation increases from downstream to upstream. The bullwhip effect is notable.

2) In multi-player supply chain, echelon ratio is more sensitive than player number to affect the bullwhip effect. The order quantity fluctuation of retailer is significantly amplified compared with that of end customer demand. But the fluctuation remains stable when the echelon ratio changes, because the order quantity of retailer is only affected by end customer demand. But to distributors and manufacturers, order quantity fluctuation gradually decreases with the increase of echelon ratio, and the decrease speed slows down. This is also a kind of emergency in Complex Adaptive Systems (CAS).

3) In multi-player supply chain, when echelon ratio is relatively big, although there is an amplification of order quantity fluctuation from distributor to manufacturer, the amplification is not notable compared to supply chain with small echelon ratio. On the other hand, the minimal fluctuation, the maximal fluctuation and the average fluctuation are approximately the same at retailer or distributor echelon. These three fluctuations have nothing to do with the player number in a certain range.

These conclusions offer a macroscopic management view for reducing the bullwhip effect. These conclusions can also provide references for estimating the bullwhip effect magnitude of different supply chains. In the future, we plan to improve this model to do some coordination analysis.

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