Improving the performance of multi-product, multi-stage, and multi-echelon supply chains with an approach to the effectiveness of the bullwhip phenomenon

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Abstract

A supply chain is a network of processes with the ultimate goal of providing goods and services to customers and includes suppliers, manufacturers, distributors, wholesalers, and retailers working together in a coordinated manner to satisfy customers. The present study aims to take an approach to improve the performance of multi-product, multi-stage, and multi-echelon supply chains. For this purpose, first, the effect of the bullwhip phenomenon on the multi-product, multi-stage, and multi-echelon supply chains based on time series is quantified, and a mathematical model is obtained for it. Subsequently, the effect of the order preparation period and net target reserve amount is discussed, and stable and unstable areas of the equations are found. Furthermore, the effect of the bullwhip phenomenon on the multi-product, multi-stage, and multi-echelon supply chains is quantified using simulations with the approach of time series based on appropriate algorithms. The step-by-step and multi-echelon relationships between product demand are compared. Moreover, the impact of the bullwhip phenomenon on the existing case study is optimized with the help of an optimizer software, and as a result, it is discovered that using a time series model as a demand model and updating distributor inventory

inspections, as well as product shipments on a daily basis to supplement their inventory,leads to asuitable decrease in thebullwhip effect.

Keywords: supply chain, bullwhip effect, time series, simulation

Introduction

The bullwhip effect is one of the main reasons responsible for supply chain inefficiency. The main definition of the bullwhip effect becomes meaningful by expanding the concept of "uncertainty". The uncertainty of an activity is defined as follows: "Uncertainty is the difference between the amount of data needed to perform an activity and the amount of information that is currently being processed by the organization." This definition stems from the assumption that uncertainty is the result of a lack of information. From a logistical point of view, uncertainty is divided into four categories: demand uncertainty, supply uncertainty, process uncertainty, and control planning uncertainty. Due to the dependence between each stage on the next demander and its predecessor in the supply chain, through a particular mechanism, raw material suppliers for producers face more severe uncertainties compared to end consumers and downstream members. This particular mechanism in the supply chain is known as the bullwhip effect. Since Forrester found out roughly 45 years ago that changes from customer to the supplier are increasing, researchers have been looking for reasons why. Research indicates that the farther the company is from the end customer in terms of lead time, the demand changes will be proportionately greater. This effect leads to an inefficiency in the supply chain, as it increases the cost of supplying materials and reduces competitiveness. The bullwhip effect has a negative influence on the supply chain in three ways, which are described as follows:

<u>Capacities:</u> A change in demand causes a change in the use of capacities. In this case, the company is faced with a dilemma: if it adjusts its capacity based on the average demand, it will run into problems where demand peaks. However, if it adjusts its capacities based on the demand history, it will result inexcessive and unused capacities.

<u>Changes in inventory levels:</u> Changes in demand lead to changes in inventory levels in each part of the supply chain. If a company stockpilesfewer goods than the next segment needs, the inventory level is decreased. On the other hand, if the company stockpiles more goods than the

next section needs, the inventory level will be increased. High inventory levels create capital expenditures, while low inventory levels jeopardize the reliability of delivery.

High level of prudential reserve: Prudential reserve is necessary to ensure that services are provided at a sufficient level against changes in demand. The stronger the bullwhip effect in the supply chain, the more precautionary storage required.

Any factor that shifts the links in a supply chain toward local optimization, or leads to delays or distortions of information exacerbates the changes between supply chain steps, therefore being an obstacle to coordination and acontributing factor in the bullwhip effect. If the managers of a chain can identify key barriers, they can take appropriate steps to eliminate them and achieve coordination in the supply chain. The problem of measuring the bullwhip effect is of great importance both theoretically and practically. Of course, the source of the measurement debate can be traced to practical systems (François et al., 2000). The rate of variance has been the most important and widespread measure in assessing thebullwhip effect over the years (Miragliotta, 2006). The rate of variance is defined as the ratio between the variances in the upstream and downstream streams, and if this ratio increases at each stage compared to the previous stage, then a bullwhip effect will occur in the chain. In addition to this rate, a modified variance rate method has been proposed to demonstrate the impact of product classification(Bahari, 2004). It can be said that for each of the causes of the bullwhip effect, different measurement methods have been developed. These include François (2000) and Dejonckheere et al. (2003).In general, overall methods such as variance or standard deviation are commonly used because of their ability to scale the phenomena. In addition to the causal methods,Warburton(2004) used the ratio between the number of orders within chain components,and Disney, (2003) calculated the amount of order peak increase (Riddalls, Bennett, 2001, 159-168) and the rate of peak deviation for orders. These methods are effective in calculating the peak points of the demand and its influence on the bullwhip effect. However, these methods are rather troublesome for practical applications (Zhang, 2004: 88, 15-27).For this purpose, a measure is employed instead that calculates the number of times the variance of demand increases as orders move. Considering the criterion of variance and its importance, it indicated the following three different criteria that work based on the ratio of variance and standard deviation:

- Standard deviation of the number of orders in each part of the chain.

- The variance ratio of demand at point ***k*** in the chain to the variance of the customer order.

- The variance ratio of demand at point **k** in the chain to the variance at point ***k-1***.

Therefore, several main goals have been considered throughout this study. The first issue is proposing and presenting two mathematical and simulation solutions to obtain the bullwhip effect with a time series approach for multi-product, multi-stage,and multi-echelonsupply chains.The second problem will be determining an approach to improve the bullwhip effect based on multi-product, multi-stage, and multi-echelonsupply chains.

Main goals

1- Determining the mathematical relationship based on time series to measure the bullwhip effect and discussing the impact of the order preparation period as well as the magnitude of target net stock on the equations.

2- Determining the simulation method based on time series to assess the bullwhip effect and present the relevant algorithms.

3- Selecting the appropriate and common prediction method to foresee the demand during the order preparation period.

4- Providing solutions for limiting the bullwhip effect, while expressing limitations and suggestions for future studies.

Tools and methods

The bullwhip effect occurs not only between members of the supply chain (retailer, wholesaler, distributor, manufacturer, and supplier) but also between the areas of the organizations responsible for ordering. Figure 1 (a) represents a multi-stage, multi-echelon, and multi-product supply chain network. Due to the importance of supply chain management and the bullwhipphenomenon in the aforementioned supply chains, measures have been taken to quantify the influence of this phenomenon, which can be classified into two groups:

• Quantifying the impact of the bullwhip phenomenon mathematically.

• Simulating the impact of the bullwhip phenomenon.

In the present study, the method of quantifying the impact of the bullwhip phenomenon is presented in both forms, and the two methods are then compared with oneanother.

Figure 1: (a) Multi-stage, multi-echelon, and multi-product supply chain network

Figure 2: (b) Distribution process of product A in the supply chain network

Suggested Model

A two-layer simulation and three general models are used to measure the bullwhip effect for supply chain units (areas). These three models include the inventory model, the linkage model, and the contribution model shown in Figure 2.

Figure 3: A two-tier model for the general inventory, linkage, and contribution models

As indicated in Figure 3, the supply chain network layer (layer 1) consists of two contribution models and an inventory model. The inventory model is used for modeling the supply chain between its units. The contribution model (Layer 2) is used for modeling the ordering process and resetting the supply chain. Selecting such a structure allows the user to simulate their supply chain and reduce the bullwhip effect. This structure allows the study of complex multi-stage and multi-product supply chains.

Findings

In the previous section, quantifying the impact of the bullwhip phenomenonwas proposed in both mathematical and simulation models based on the system dynamics approach to properly evaluateits effect in a multi-stage, multi-echelon, and multi-product supply chain. To assess these methods, it is necessary to have a proper case study and a comparison between the real and theoretical results. Since a suitable case study was not available to determine the bullwhip effect in such a supply chain, we decided to use external sources for this purpose.As the basis of the simulation section was based on astudyundertaken by Dr. Wang Panich [1], a suitable example of determining the bullwhip effect in a multi-echelon supply chain, multi-product was therefore available. Under the supervision of the supervisor, correspondence was made and as a result, the supply chain data used in the aforementioned research was obtained. Based on this information, the current chapter has been laid out.

The main problem in this case study was the use of an adaptive network-based fuzzy inference system to predict future sales.

This section of the research is divided into multiple categories. First, a case study is obtained, and then an introduction is given to the adaptive network-based fuzzy inference system to approximate the functions of the system dynamics model. Afterward, this case study is resolved based on mathematical quantification and simulations, Finally, suggestions are made to improve the bullwhip effect.

In the existing model for the supply chain of the beverage factory, the bullwhip effect is calculated during a period of 90 days (real) and compared with the simulated model (based on the reference article). This comparison is shown separately based on two products, A and B. The error rate for the whipping effect varies between zero and 9%. The average error rate is 0.94% for the distribution sector, and 6.35% for the production sector.

Table 1: Estimation of bullwhip error for products A and B, and calculation derived from reference article simulation [1]

Factor	Item	Actual calculation	Calculation by simulation (base article)	Error (percentage)	Average error (percentage)
Distributor 1	Product A	30.74	30.74	0.00	0.94
	Product B	21.62	21.82	0.93	
Distributor 2	Product A	36.21	36.21	0.00	
	Product B	28.59	28.59	0.00	
Distributor 3	Product A	43.27	45.06	4.14	
	Product B	29.58	29.41	0.57	
Producer	Product A	10.82	11.48	6.10	6.35
	Product B	4.33	4.72	9.01	
	Raw material	6.58	6.32	3.95	

The bullwhip effect for the supply chain of the beverage factory throughout the calculated period of 90 days is then compared with the time series model (based on the present study). This comparison is presented in Table 2 for two products, A and B. The error rate for the bullwhip effect varies between 0.57 and 13.16%. The average error rate is 1.41% for the distribution sector and 8.45% for the production sector.

Table 2: Estimation of bullwhip errors for products A and B, and calculation based on time series

Factor	Item	Actual calculation	Calculation based on time series	Error (percentage)	Average error (percentage)
Distributor 1	Product A	30.74	30.55	0.62	1.41
	Product B	21.62	21.04	2.70	
Distributor 2	Product A	36.21	35.56	1.79	
	Product B	28.59	28.43	0.57	
Distributor 3	Product A	43.27	44.14	2.01	
	Product B	29.58	29.36	0.75	
Producer	Product A	10.82	11.23	3.82	8.45
	Product B	4.33	4.69	8.38	
	Raw material	6.58	5.71	13.16	

In the next step, the model is designed for the supply chain of the beverage factory, where the bullwhip effect for each supply chain unit for a period of 90 days is calculated and compared with the simulation model (based on the present study). This comparison is shown in Table 3 based on products, A and B. The error rate for the whipping effect varies between 0.17 and 11.40%. The average error rate is 1.83% for the distribution sector and 7.34% for the production sector.

Table 3: Estimation of bullwhip errors for products A and B, and calculation based on the simulation model of the present study

Factor	Item	Actual calculation	Calculation based on time series	Error (percentage)	Average error (percentage)
Distributor 1	Product A	30.74	30.05	2.23	1.83
	Product B	21.62	21.72	0.46	

Distributor 2	Product A	36.21	35.36	2.34	
	Product B	28.59	27.83	2.67	
Distributor 3	Product A	43.27	44.26	2.30	
	Product B	29.58	29.29	0.98	
Producer	Product A	10.82	10.84	0.17	7.34
	Product B	4.33	3.88	10.44	
	Raw material	6.58	5.83	11.40	

Finally, comparative tables for evaluating the bullwhip effect throughout the supply chain of the beverage factory and for a period of 90 days, calculated separately for products A and B, and the simulated model are presented based on the reference article,as well as the time series and simulation model from the current study.

Results and Discussion

One of the main advantages of the proposed models is the possibility of performing various computer-based experiments in such a way that it can describe and predict the behavior of the entire supply chain. Once the entire supply chain is defined by an appropriate combination of inventory, linkage, and contribution models, it is then possible to evaluate the bullwhip effect. This stage is called the baseline. To improve the bull effect, a certain approach is implemented the steps of which are shown in Figure 4.

Figure 4: The proposed approach to improve the bullwhip effect

As shown in Figure 4, this approach consists of two steps. In the first step, an initial solution is carried out to improve the bullwhip effect.In the second step, after matching the supply chain unit participation along the entire simulated supply chain, the improved bullwhip effect is calculated.

Initial solution design for improving bullwhip effect

Improving the structure of the supply chain network

By trying to eliminate several supply chain units in the network structure defined for it, we attempted to improve the bullwhip effect. This should be applied to the minimum supply chain units and done so appropriately, so as not to interfere with the main objectives of the network. Deleting the appropriate unit or units reduces time delays (or procurement time) thus reduces the complexity of the information during the update process. The bullwhip effect is improved by reducingthe magnitude of the shocks caused by non-zero supply time and updating the demand process.

Improving the information sharing level

By changing the information level of a traditional supply chain to an information-sharing chain, the level of information sharing can be improved. Enhancing the information sharing levelresults in better coordination throughout the chain,therefore improving the bullwhip effect (Boute, 2007).

Improving the operational efficiency of the supply chain unit

By increasing the quality of the supply chain unit process, operational efficiency can be improved. Increasing the quality of the process means enhancing the reliability of the process and the machine, and lowering the number of their defects. This shortens the processing time due to the reduced preparation time (Taylor, 2000). Process quality is among the causes of the bullwhip effect (Miragliotta, 2006). This method usually involves process reengineering with the implementation of the total quality management program (Cachon Fisher, 2000).

Improving supply chain unit contribution

In this study, supply chain unit contributionimplies the controllable procedures in the face of order process shocks that have already been introduced in previous sections. By increasing the accuracy of the predicting procedure and selecting the appropriate ordering procedure, it is possible to improve the bullwhip effect.

Adaptation of supply chain unit contribution throughout the chain

After designing the initial solution for improving the bullwhip effect, it can be re-measured. However, what is not seen in the initial solution design is the issue of contribution matching between production chain units. Discrepancies in contributions between production chain units may make the issue of the whipping effect more important. For example, customer demand depends on the balance of retailers' orders. Whenever the order of retailers is simultaneous, the variance of customer demand (bullwhip effect) is at a maximum owing to the order of retailers happening simultaneously, and to overcome the aforementionedphenomenon, the order of retailers needs to be balanced (Lee et al., 1997).

To adapt the supply chain unit partnerships throughout the chain, it is sufficient to manually adjust the parameters of each stage of the partnership model to achieve a proper improvement in the bullwhip effect. This can be done using optimization software. With this method, it will be possible to predict the extent of the bullwhip effect.

Improving the bullwhip effect

To improve the bullwhip effect in the mentioned factory, we first receive the current data of the factory and introduce it to the model, and based on that, we obtain the bullwhip effect for each supply chain unit to have a baseline. Then,the bullwhip effect improvement procedure is carried out in two steps. First, the initial solution for improving the bullwhip effect and is performed, then the matching contributions are applied to the supply chain units throughout the supply chain.

<u>Designing the solution for improvingthe bullwhip effect in the factory (first step)</u>

After a thorough study of the factory supply chain factors, it can be concluded that:

• To improve the structure of the supply chain network, there isn’t much to be achieved by removing the appropriate supply chain unit or units, since these chains are limited and the factory is unable to eliminate or lose any of its distributors.

• No furtherstepsexistedforenhancing the level of information sharing due to the type of factory work.

• To improve performance, supply chain units could not do anything due to the factory resistance towards changing the quality of the process, increasing the reliability of the process and the machine as well as reducing the number of defects because ofthe investment restrictions.

Ultimately, the only possible task at the plant was to improve the supply chain unit's participation. In this case, two steps were implemented:

• The quality level of information in this factory was of type one, meaning that no new information was used to predict and update the parameters of the order procedure, and the parameters of the order point and the target level and reliability storage were set manually.

• The manufacturer was required to complete the distributorinventory daily. As stated at the beginning of the case study, the order request for the distributor inventory was completed by the factory itself and passed through the factory decision center, which was set without change. The mentioned action should be carried out dailyby the factory.

Adaptation of supply chain unit contribution throughout the entire supply chain (second step)

It is sufficient to alter the parameters of each stage of the partnership model to fit the supply chain unit'scontribution throughout the entire supply chain. For this purpose, the optimization software VENSIM was utilized,which features an optimization engine based on Powell hill-climbing algorithm. This algorithm is used to find the best answer for a problem, or to find a solutionfor an issue that is sufficiently appropriate and optimal. This software was configured to improve the bullwhip effect with minor changes to the contribution model. The results of the optimization process are presented in Figures 2 and 3 and Table 4.

Table 4: Estimate of the reduction of bullwhipfollowing the improvement

Factor	Item	Baseline	Reduction	Reduction (percentage)	Average reduction (percentage)
Distributor 1	Product A	30.740	2.591	91.57	92.17
	Product B	37.170	3.580	90.37	
Distributor 2	Product A	45.060	2.222	95.07	
	Product B	21.820	2.079	90.47	
Distributor 3	Product A	28.590	2.021	92.93	
	Product B	29.410	2.182	92.58	
Producer	Product A	11.480	7.654	33.33	22.31
	Product B	4.718	4.625	1.97	
	Raw material	6.323	4.323	31.63	

Conclusion

Two specificalterations, including changing the level of information quality from mode one to type seven using the time series model as a demand model, as well as updating distributor inventory inspections and shipping the product daily to supplement the inventory have resulted in a noticeable improvement of the bullwhip effect. The outcome of the implementation of the supply chain unit contribution throughout the entire supply chain demonstrates that the size of the units of the product sent to the distributors does not need to be changed if their inventory is decreased, and should remain the same 840 units for product A and 700 units for product B. On the other hand, in the production sector, the batch size does not need to be changed remains the same at 12,000 units for product A and 10,500 units for product B.However, it is preferred to lower the order of raw materials from 21,600 units to 7,200 units.

The results shown in Tables 1-4 indicate an appropriate reduction in the level of the bullwhip effect. For distributors, there is an average drop of 92.17%, the main reason being the daily transportation of the product for replenishing inventory. In fact, by replenishing the inventory of each distributor alternatively, the extent of the bullwhip effect was reduced by about 90%.

For producers, the magnitude of the bullwhip effect was decreased by an average of 22.31%, which is 33.33% for product A and 1.97% for product B. Although the reduction of the bullwhip effect for product B was not as significant, by referring to the baseline section, it can be observed that since the start, the bullwhip effect for product B was 4.718, which in comparisonto the amount of bullwhip effect for product A in the baseline at 11.48, is much better asit can be ascribed to thebetter compatibility of this product with customers (distribution factor).Therefore, there is a smaller level of reduction in the bullwhip effect (1.97%) in this case. On the other hand, a 33.33% reduction in the level of bullwhip effect of product A implies that the adaptation of the contributions for this product has improved its adaptability throughout the production chain. Finally, a 31.63% reduction in the level of bullwhip effect in raw materials is due to the reduction in the size of the custom batch and its adaptation to the demands of the production sector.

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