A Simulation Model to Investigate Critical Factors Influencing the Bullwhip Effect in a Supply Chain

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Abstract. In this paper we are simulating a four-stage supply chain that is based on the Stock-to-Demand inventory type. The aim of the simulation is to investigate the well-known phenomenon of the bullwhip effect, and identify the parameters that affect it. To investigate and measure this impact, a simulation model is developed using Arena 12.0 software package for a four-stage supply chain, consisting of a single retailer, wholesaler, distributor and a factory. Since the bullwhip effect is based on an interrelated network of parameters, the model will be changed to reflect the change in these parameters on the variance amplification of orders. The experiments with the developed model are described and the results are analyzed.

1 Introduction

Bullwhip effect is a major problem in supply chains, it means the amplification of orders as you go up along the supply chain. The bullwhip effect is a phenomenon that was first discovered by Forrester (1958) who realized that variations of demand increase up the supply chain from customer to supplier, what was called the Bullwhip Effect and was also known as the Forrester Effect. It became famous as the Bullwhip Effect since the oscillating demand magnification upstream a supply chain looks like a cracking whip. This phenomenon is considered one of the main reasons for inefficiencies in supply chains, and it increases as the lead time increases. Since then and researchers have been busy investigating its causes, listing reasons behind it, and trying to find ways to decrease its effect.

To study the bullwhip effect, a clear understanding of supply chains and their management techniques should be obtained. Thus, in the next section, an overview will be present, it can be considered as an introduction to some basic concepts that should be covered before continuing in investigating the bullwhip effect.

The paper is organized as follows: section 2 explains the problem and gives the background needed to understand supply chains and other related issues. Section 3 views the four main categories of the related work done in the same area. Section 4 is devoted to presenting our model and approach, and the results are displayed and discussed. Finally, section 5 contains a conclusion of the work and the future work.

2 Background

In this section, the reader is given an introduction to the background needed for understanding all the dimensions of the work. Introducing all the five basic building blocks that this research is built on. First, give an introduction to supply chains (Stevenson, 2007), inventory management (Stevenson, 2007; Taha, 2007), and forecasting techniques (Stevenson, 2007), then get into more details explaining what exactly the bullwhip effect means (Wikipedia, 2010), and finally, talk about simulation techniques (Kelton, 2010) and highlight its role in identifying many problems.

2.1 Supply Chain Management

In order to get the chance to know supply chains, you have to know the answer to those two important questions:

1. What is a supply chain?
2. Why do we need supply chain management?

A supply chain is the sequence of organizations –their facilities, functions, and activities– that are involved in producing and delivering a product or service. The sequence begins with basic suppliers of raw materials and extends all the way to the final customer. By mentioning facilities we mean factories, warehouses, offices, outlets and so on, and by mentioning functions and activities we mean purchasing, forecasting, inventory management, scheduling, production, distribution and many other activities.

There are three different types of movement within a single supply chain, the physical movement of material which flows from the higher levels of the chain towards the end customer, the cash flow which moves in the opposite direction starting from customers and ending at suppliers, and finally, information flow which moves in both directions.

2.2 Inventory Management

An inventory is a stock of goods kept by the business, which varies according to the nature of the business itself. These goods might be supplies of raw materials, purchased parts, partially finished items and finished goods, spare parts for machines, tools, and many other supplies.

Inventory management is a core process in the operations management activity. Good management of inventory is very important for the success of most businesses and their supply chains. On the other hand, poor management has its harms to the business, decreases customer satisfaction and might demolishes it, and increase operating costs.

In order to perform good inventory management, a good model has to be followed. Inventory modeling determines the appropriate level of goods that a business must maintain in inventory in order to ensure smooth operation. The basis of such a model is to balance the cost of capital resulting from holding too much inventory against the penalty cost resulting from inventory shortage.

Due to complexity of the inventory problem, it is not the case that there exists one general model that covers all the situations. Instead, different algorithms and techniques are used to model each situation on its own. But what should anyone be aware of is that, regardless of the technique the model used, any inventory model seeks two basic results:

1. *How much* to order?
2. *When* to order?

The basis for answering these questions is the minimization of the following inventory cost function:

$$(TotalCost) = (PurchaseCost) + (SetupCost) + (HoldCost) + (ShortCost) \quad (1)$$

Where:

1. *Purchase cost* is the price per unit of an inventory item
2. *Setup cost* is a fixed amount of money charged when an order is placed regardless of its size
3. *Hold cost* is the cost of maintaining inventory in stock
4. *Short cost* is the penalty incurred when the stock runs out

In order for the reader to be aware of the importance of inventory management, some of the reasons why there exists a huge need for inventories in business are given below:

1. To meet customer demand
2. Smooth production requirements, especially with seasonal inventories
3. Decouple operations, such as using inventory buffers
4. Protect against stockouts
5. Take advantage of order cycles or periodic orders
6. Hedge against price increase
7. Take advantage of quantity discounts

An inventory system may take one of two ordering policies: the first one is based on **periodic review**, in which new orders are placed at the start of each period, the second is based on **continuous review**, where a new order is placed when the inventory level drops to a certain level, called the reorder point.

The inventory model used to study the bullwhip effect in this research is based on the periodic review policy. In all the four stages of the supply chain, the same inventory model is assumed but the parameters might vary from one level of the chain to another. More discussion about the used inventory model will be present in section 5.

2.3 Forecasting

People are forecasting all the time, either in their work or in everyday life. To make a successful forecast, you have to take into consideration two important aspects, or else you will be only guessing. The two aspects are:

1. The current factors or conditions
2. The past experience in similar situations

Sometimes, it is normal to depend on one aspect more that the other, but this greatly depends on the situation and the problem that is dealt with.

In business, forecasting can be found in almost everywhere, in sales, inventory, budgeting, purchasing and many other places. Thus, in business, more cautious should be taken while forecasting, and thus should have more formal approaches to calculate forecasts and to assess forecast accuracy. However, it is not an exact science, successful forecasting often requires a blend of art and science.

There are three approaches to forecasting, the first is **judgmental forecasts** which use subjective inputs such as customer opinions and surveys, managers and experts opinions, etc … The second approach is **time-series forecasts**, it projects past experience into the future. They use historical data assuming that the future will be like the past. The last approach is the **associative model**, it uses explanatory variables that can be used to predict demand. These variables might be the quality of the product, the amount of advertisement, and so on.

In the model developed in this research, forecasting demand is of great concern. An important point that has to be mentioned here is that demand forecast should be based on a time-series of past demand rather than unit sales. Sales would not truly reflect demand if one or more stockouts occurred.

Since this study focuses on time-series forecasts, the following paragraphs will briefly describe some techniques that are used for averaging:

Naive Forecast: it uses a single previous value of a time-series as the basis of a forecast.

Moving Average: this type of forecasting technique uses the data of a certain number of the most recent actual data values.

Weighted Moving Average: where recent data values are given higher weights in computing the forecast.

Exponential Smoothing: the new forecast is calculated as the previous one plus a percentage of the error in previous demand, which is the percentage of the difference between the actual demand and its forecast for the previous period.

2.4 The Bullwhip Effect

The Bullwhip Effect (or Whiplash Effect) is an observed phenomenon in forecast-driven distribution channels. The concept has its roots in J. Forrester's Industrial Dynamics (Forrester, 1958) and thus, it is also known as the Forrester Effect. Since the oscillating demand magnification upstream a supply chain reminds someone of a cracking whip, it became famous as the Bullwhip Effect.

Causes: Because customer demand is rarely perfectly stable, businesses must forecast demand to properly position inventory and other resources. Forecasts are based on statistics, and they are rarely perfectly accurate. That is why companies often carry an inventory buffer called "Safety Stock". Moving up the supply chain from end-consumer to raw materials supplier, each supply chain participant has greater observed variation in demand and thus greater need for safety stock. In periods of rising demand, down-stream participants increase orders. In periods of falling demand, orders fall or stop to reduce inventory. The effect is that variations are amplified as one moves upstream in the supply chain (further from the customer). This sequence of events is well simulated by the "Beer Distribution Game" which was developed by the MIT Sloan School of Management in the 1960s. The causes can further be divided into behavioral and operational causes:

Behavioral causes

- Misuse of base-stock policies
- Misperceptions of feedback and time delays
- Panic ordering reactions after unmet demand
- Perceived risk of other players' bounded rationality

Operational causes

- Dependent demand processing
  - Forecast Errors
  - Adjustment of inventory control parameters with each demand observation
- Lead time Variability (forecast error during replenishment lead time)
- Lot-sizing/order synchronization
  - Consolidation of demands
  - Transaction motive
  - Quantity discount
- Trade promotion and forward buying
- Anticipation of shortages
  - Allocation rule of suppliers
  - Shortage gaming
  - Lean and JIT style management of inventories and a chase production strategy

Consequences: In addition to greater safety stocks, the described effect can lead to either inefficient production or excessive inventory as the producer needs to fulfill the demand of its predecessor in the supply chain. This also leads to a low utilization of the distribution channel. In spite of having safety stocks, there is still the hazard of stock-outs which result in poor customer service. Furthermore, the bullwhip effect leads to a row of financial costs. Next to the (financially) hard measurable consequences of poor customer services and the damage of public image and loyalty, an organization has to cope with the ramifications of failed fulfillment which can lead to contract penalties. Moreover, the hiring and dismissals of employees to manage the demand variability induce further costs due to training and possible pay-offs.

Countermeasures: Theoretically, the bullwhip effect does not occur if all orders exactly meet the demand of each period. This is consistent with findings of supply chain experts who have recognized that the bullwhip effect is a problem in forecast-driven supply chains, and careful management of the effect is an important goal for Supply Chain Managers. Therefore, it is necessary to extend the visibility of customer demand as far as possible. One way to achieve this, is to establish a demand-driven supply chain which reacts to actual customer orders. In manufacturing, this concept is called Kanban. This model has been most successfully implemented in Wal-Mart's distribution system. Individual Wal-Mart stores transmit point-of-sale (POS) data from the cash register back to corporate headquarters several times a day. This demand information is used to queue shipments from the Wal-Mart distribution center to the store, and from the supplier to the Wal-Mart distribution center. The result is near-perfect visibility of customer demand and inventory movement throughout the supply chain. Better information leads to better inventory positioning and lower costs throughout the supply chain. Barriers to the implementation of a demand-driven supply chain include the necessary investment in information technology and the creation of a corporate culture of flexibility and focus on customer demand. Another prerequisite is that all members of a supply chain recognize that they can gain more if they act as a whole, which requires trustful collaboration and information sharing. Methods intended to reduce uncertainty, variability, and lead time are mentioned in the following:

- Vendor Managed Inventory (VMI)
- Just In Time replenishment (JIT)
- Strategic partnership
- Information sharing
- Smoothed flow of products
  - Coordinate with retailers to spread deliveries evenly
  - Reduce minimum batch sizes
  - Smaller and more frequent replenishments
- Eliminate pathological incentives
  - Every day low price policy
  - Restrict returns and order cancellations

- Order allocation based on past sales instead of current size in case of shortage

2.5 Simulation Techniques

If one is trying to mimic the behavior of a real system, then he is simulating the system. If a computer or software is used, then this is called computer simulation of the system. As long as computers and software development are becoming more and more powerful, simulation becomes more and more powerful and popular that many organizations are now heavily depending on it in taking their decisions. The main reason for simulation's popularity is its ability to deal with very complicated models of complex systems, in addition to the great advances an hardware and in simulation software that makes things easier to be done.

People often study a system to measure its performance, improve its operation, find the cause of a problem or design it if it doesn't exist. Managers of a system might also like to have some help in their daily decisions: "What will happen if I changed this or added that?" That is why simulation now is considered a vital tool in nearly every organization.

Sometimes it is possible to play with the real system itself by trying different scenarios and observe and analyze them, but unfortunately this is not always possible. In many cases, it is just too difficult, costly, or simply impossible to do physical studies on the real system. For example, you cannot study the behavior of a factory that is yet been built, you cannot alter a critical system in a hospital or airport to try some new procedures, and in our case it is impossible to change tens of factors and variables in a real 4-stage supply chain to see their influence on the bullwhip effect! In other words, computer simulation gives you the freedom to try many ideas with the model that could uncover many attractive alternatives that you might not have been able to try with the real system.

In order to view different kinds of simulation, we will use the same classification used in Kelton (2010) which classifies simulation models along the three following dimensions:

- **Static vs. Dynamic:** In dynamic models time plays a significant role, while it doesn't play a role in static models. Most operational models are dynamic.
- **Continuous vs. Discrete:** In a continuous system, the state of the system can change continuously over time. In a discrete model, change can occur only at separated points in time. There are models that combine both elements and they are called mixed continuous-discrete models.
- **Deterministic vs. Stochastic:** Models that have no random input are deterministic, stochastic models, on the other hand, operate with at least some inputs being random.

Finally, if a system has to be simulated, then an important decision is to determine how to carry it out. There are many simulation options that will be briefly discussed here and eventually highlight the type of simulation that is used in this research.

- **Hand Simulation:** The oldest and most traditional way is simulation by hand. Engineers, physicists, and mathematicians have used it for many years on a variety of problems. We do not need to mention how tough this method could be with large models!
- **General-Purpose Programming Languages:** When digital computers appeared, people started writing computer programs using general-purpose procedural languages like FORTRAN to do simulations of more complicated systems. Although it was a customizable way of simulation, but it was very tedious and error prone as each model had to be coded from scratch. Along with this use of computer languages, spreadsheet software were sometimes used for some kinds of simulation. But spreadsheet simulation has a lot of limitations that prevent it from simulating large, realistic, dynamic models.
- **Simulation Languages:** Special purpose simulation languages like GPSS, SLAM and SIMAN appeared sometime later and provided a better environment for many kinds of simulation and they are still in use.
- **High-Level Simulators:** Simulation products appeared that are characterized by their ease of use. However, the domains of many simulators are not as flexible as it might look like in order to build valid models of the system. Arena simulation software is used in this research, it combines the ease of use found in high-level simulators with the flexibility of simulation language and even all the way down to general-purpose procedural languages like Microsoft Visual Basic or C. So, the model built here is embedded with Visual Basic code which facilitates the process of having more complicated procedures and details for the simulation model.

3 Literature Review

Since the discovery of the bullwhip effect phenomenon by Forrester (1958), many research studies have been done in this area. Starting with investigating the bullwhip effect, finding its causes, and finally finding ways and techniques to minimize or even overcome it. Great work have been done in this field. In order to give a quick survey on the major researches in this field, the work will be divided into four main research categories. Each category will take one of the next few subsections. This research will fall into the last category to be explained, will relate it to previous work, and will show how it differs from what have been done already.

3.1 Analyzing the causes of the Bullwhip Effect

Lee et al. (997a), in their paper they claim that the information transferred in the form of "orders" tends to be distorted and can misguide upstream members in their inventory and production decisions. Thus, the variance of orders may be larger than that of sales, and the distortion tends to increase as one move upstream, which describes the phenomenon of the "bullwhip effect". They analyzed four sources of the bullwhip effect:

1. Demand signal processing
2. The rationing game
3. Order batching
4. Price variations

They considered a multiperiod inventory system that is operated under a periodic review policy. The four conditions of the system are:

1. Past demand are not used for forecasting
2. Resupply is infinite with a fixed lead time
3. There is no fixed order cost
4. Purchase cost of the product is stationary over time

Having those conditions leads to the optimal order-up-to policy, and the order quantity in each period equals the demand of the previous period. By relaxing all the four conditions one at a time, the four causes of the bullwhip effect arises. Thus, they discussed actions that can be taken to mitigate the impact of this distortion. Again, Lee et al. (997b) investigated the four causes of the Bullwhip Effect in their new paper "The Bullwhip Effect in Supply Chains". In their research, they explained each cause and suggested actions that could be done to decrease the bullwhip effect.

According to Buchmeister et al. (2008), the factors contributing to the bullwhip effect are:

1. Forecast errors
2. Overreaction to backlogs
3. Lead-time variability
4. No communication and no coordination up and down the supply chain
5. Delay times for information and material flow
6. Batch ordering (larger orders result in more variance)
7. Rationing and shortage gaming
8. price fluctuations
9. Product promotions
10. Free return policies
11. Inflated orders

They declare that the phenomenon in itself is not harmful, but its consequences are. The following are some of the consequences of the bullwhip effect according to their study:

1. Excessive inventory investments
2. Poor customer service levels
3. Lost revenues
4. Reduced productivity
5. More difficult decision making
6. Sub-optimal transportation
7. Sub-optimal production

Geary et al. (2006) also contributed to the problem. In their paper, they have identified ten published causes of bullwhip, all of which are capable of elimination by re-engineering the supply chain.

Not only operational reasons can cause the bullwhip effect, but also researchers have discovered that human behavior has its role too. Nienhaus et al. (2006) have conducted a study based on the beer distribution game online. After reviewing the classical reasons of the bullwhip effect including lead time and forecasting, they identified two types of extreme behavior for humans that deviates them from the best strategy, namely "safe harbor" and "Panic". In the safe harbor behavior, humans order more than actually necessary so as to increase their safety stock, they cause not only high costs in their level, but they also force the next level (their supplier) either to increase his orders or to pay for out of stock. So, this behavior has a negative impact that propagates along the chain. The second extreme strategy is panic, which is to empty the stock before the end customers demand increases. At first, this does not affect other co-makers negatively. But as soon as end customers orders increase, a co-maker following this strategy has to order more than a co-maker, who has safety stock left. Then, this strategy has the same negative impact on the whole supply chain like the safe harbor strategy.

Oliva and Gonalves (2007) used again the beer distribution game to add a new behavioral cause to the causes of the bullwhip effect, which is "overreaction to backlogs". They found that players of the beer game treated backlog and inventory differently. Also, Croson and Donohue (2006) have studied this phenomenon from a behavioral perspective in the context of a simple, serial supply chain subject to information lags and stochastic demand. Their paper reports the results of two experimental studies on the behavioral causes of the bullwhip effect. They found that participants continue to exhibit the bullwhip effect (the amplification of oscillation of orders higher in the supply chain) even under conditions where it should not occur. This suggests that cognitive limitations contribute to the bullwhip effect, even in ideal and controlled settings like the lab. They also observed that transmitting dynamic inventory information lessens the bullwhip effect, particularly at higher echelon levels. They argued that this information allows upstream members to better interpret orders on the part of their customers and prevents them from overreacting to fluctuations when placing their own orders.

3.2 Quantifying and Reducing the Bullwhip Effect

In this category, a lot of researches have been done trying to quantify the bullwhip effect and suggest solutions and methods to reduce it. Starting with Metters (1997), his purpose was to assist in the justification of both practitioner and research interest in the bullwhip effect by determining the significance of the detrimental effect that the bullwhip effect can have on profitability. His results indicate that the importance of the bullwhip effect to a firm differs greatly depending on the specific business environment. Given appropriate conditions, however, eliminating the bullwhip effect can increase product profitability by 10-30%.

Carlsson and Fullér (2002) worked on a series of companies in a supply chain and showed that if the members of the supply chain share information and agree on better fuzzy estimates (as time advances) on future sales for the upcoming period, then the bullwhip effect can be significantly reduced. One year earlier, they had published a paper about reducing the bullwhip effect by means of intelligent, soft computing methods (Carlsson and Fullér, 2001).

Again, the concept of quantifying the bullwhip effect was investigated by Chen et al. (2000), this time the work was on a simple two-stage supply chain consisting of a single retailer and a single manufacturer. Their model includes two of the factors commonly assumed to cause the bullwhip effect: demand forecasting and order lead times. They extended these results to multiple-stage supply chains with and without centralized customer demand information and demonstrated that the bullwhip effect can be reduced, but not completely eliminated, by centralizing demand information.

In a search for other forms of supply chains that are more immune to the bullwhip effect, Ouyang and Li (2003) compared the bullwhip properties of a vendor managed inventory (VMI) supply chain with those of a traditional "serially-linked" supply chain. The emphasis of this investigation is the comparative impact the two structures have on the "bullwhip effect" generated. They concluded that a balanced VMI offers a significant opportunity to reduce the bullwhip effect in real-world supply chains. Actually, their analysis shows that, with VMI implementation, two sources of the bullwhip effect may be completely eliminated: rationing and gaming.

Sucky (2009) focused on measuring the bullwhip effect taking into consideration the network structure of supply chains. They showed that the bullwhip effect is overestimated if just a simple supply chain is assumed and risk pooling effects are present. Another paper has presented a system control framework for analyzing order stability and the bullwhip effect in complex supply networks (Ouyang and Li, 2010).

Papers from any of the three other categories can also fall in this category. They might combine between analysis and quantification, or between simulation and reducing the effect. An example on that is the studies of Lee et al. (997a,b) as they combine between identifying the causes and quantifying the bullwhip effect.

3.3 Observing the Bullwhip Effect in Business

Numerous studies focused on identifying the bullwhip effect in some industries, and in numerous examples from individual products and companies. In the supply chain for diapers, Procter and Gamble (P&G) noticed that the volatility of the diaper orders issued by the distributors was quite high even though end consumer demand was reasonably stable (Lee et al., 997b). In another paper, the same authors, Lee et al. (997a), observed the bullwhip effect in a soup supply chain as well as in the supply chain for printers of Hewlett–Packard (HP).

Barilla also found that phenomenon in the supply chain for pasta (Hammond, 1994). Furthermore, Blanchard (1983) concluded: “In the automobile industry, inventory behavior is destabilizing: the variance of production is larger than the variance of sales”. Additionally, the bullwhip effect has been experienced by many subjects playing the beer game (Sterman, 1989).

In the research done by P. Cachon et al. (2007), the objective of their study was to document the existence of the bullwhip effect in industry level U.S. data. They concluded that the bullwhip effect is not widespread in the U.S. economy.

3.4 Simulating the Bullwhip Effect

Here comes the category that this work will be listed under it. Simulation, as we discussed earlier, is a very important tool to mimic a real system. What most people have done in this category is to simulate the supply chain in order to find turning points where the behavior of the bullwhip effect can change, they can study the bullwhip phenomenon and the effect of the system attributes on it, and also try different scenarios and techniques to decrease its effect on the supply chain.

Kleijnen (2003) has conducted a survey of simulation in supply chain management. It reviews four types of simulation, namely:

1. Spreadsheet simulation
2. System dynamics
3. Discrete event simulation
4. Business games

He also highlighted the importance of performing a sensitivity analysis on any given model as it serves several goals: it provides insight into the behavior of the supply chain, and gives a shortlist of critical factors.

Manyem and Santos (1999) made a simulation analysis of a simple two-stage serial supply chain. Their objective was to study the propagation of the bullwhip effect, the profitability impact caused by bullwhip effect and the effect of lead-times on this phenomenon. They have observed that both demand variability and supply chain costs increase with an increase in replenishment lead-time. The consequences of the bullwhip effect have been quantified in monetary terms in this study through a simulation study that compares the costs incurred in a supply chain where bullwhip effect occurs with the cost incurred in a supply chain where bullwhip effect does not occur. They have also showed through simulation that not only in capacitated systems that the bullwhip effect will have serious cost implications, but also in uncapacitated systems, the bullwhip effect leads to higher supply chain costs.

Boute and Lambrecht (2009) have presented a spreadsheet application to gain a clear insight into the use or abuse of inventory control policies in relation to the bullwhip effect and customer service. They explored a series of replenishment policies and forecasting techniques under different demand processes, and illustrated how tuning the parameters of the replenishment policy and the forecasting technique result in the bullwhip effect. Moreover, they demonstrated how bullwhip can be reduced, with an increase in inventory fluctuations and reduced customer service as a result. The spreadsheet models presented in their paper should guide the decision maker through a fairly complicated interplay between order fluctuations, inventory fluctuations and customer service in a variety of demand process scenarios and forecasting techniques.

This study follows the work of Merkuryev et al. (2002) and moves on nearly the same direction. In their study they described the impact of two different information sharing strategies – decentralized and centralized information – combined with two inventory control policies – min-max and stock-to-demand inventory control – on the bullwhip effect. To investigate and measure this impact, they used simulation models that are developed using the Arena 5.0 software package for a four-stage supply chain, consisting of a single retailer, wholesaler, distributor and manufacturer. As a conclusion of their work, they found that the bullwhip effect is present in all the four models, but the models with centralized information structure give better results. Models using a stock-to-demand inventory control revealed better results than those with min-max inventory control from the point of view of the bullwhip effect. And again, in Merkuryev and Petuhova (2004), a simulation study was used on the same four-stage supply chain. But this time, a statistical analysis of the demand distortion phenomenon in inventory systems with a stochastic demand has been performed.

Some researchers have concentrated in comparing different simulation techniques like what Banks and Malavé (1984) did. They made a survey of simulation techniques used in the modeling of inventory systems. Six categories of use were formed and research published in each of the categories was described.

Many others have done work using simulation with different tools and techniques, Schmitt and Singh (2009) have used Monte Carlo and Discrete-Event simulation to quantify disruption risk in supply chains.

This work follows some principles in Merkuryev et al. (2002), and is similar to it in:

1. Working on the stock-to-demand inventory control model
2. Using Arena in simulation (although advanced version was used here)

but is different from it in:

1. Reducing the bullwhip effect by changing the parameters of the model and creating many variations of the original model, while what they did is compare two information sharing strategies in terms of their effect on the bullwhip, using two inventory models
2. Choosing a different simulation technique to implement the inventory model Stock-to-Demand
3. Focusing on one inventory control policy and make many variations of it, while they compared two policies

4 Contribution

The objective of this paper is to simulate supply chains in order to illustrate and discuss the impacts of changing inventory control parameters at different stages of the supply chain on the strength of the bullwhip effect. The results, which are the changes in the order variance and amplification, are viewed and discussed for all stages. For this purpose, four variations of the original supply chain model will be viewed, and will discuss the consequences of these variations on the bullwhip effect.

As mentioned earlier in the background section, inventory control plays an important role in supply chain management. It determines how much and when to order from the supplier. When forecasting enters in the order determination process, the bullwhip effect will appear in the supply chain, and this is simply because forecasts are based on statistics that are rarely perfectly accurate. That is why the concern in this simulation study is to choose one of the best well known inventory control policies that relies on forecasting in determining the amount to be ordered in each stage, so that we can spot out and investigate the bullwhip effect.

According to Merkuryev et al. (2002) the stock-to-demand inventory control policy was proved to have better results regarding the bullwhip effect than the min-max inventory policy. Regardless of whether the customer demand information is shared or not, the stock-to-demand model always behaves better. That is why the best choice was to let all the inventory management in the core model be based on the stock-to-demand policy, which is a variant of the periodic review model, where:

- The inventory level will be reviewed at predetermined time intervals (every one week in the present model).
- At each review time, an order will be placed to get the inventory back up to a target level.

4.1 Conceptual Model

In this section, the general formation of the core model is discussed. Since many variations to our supply chain model were created, the original model will be referred to as the core model, and the variations will take names and numbers to be identified.

The simulation model is a four-stage supply chain model, a structure that corresponds to the well known beer distribution game. Consisting of a single retailer, wholesaler, distributer, and factory, as it can be seen in figure 1. This structure is widely used in the literature, and it is in the mid-way between simple two stage supply chains, and complex supply networks.

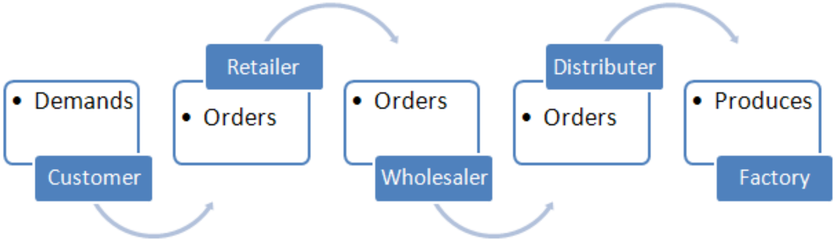

Fig. 1. A Four-Stage Supply Chain

All the inventories in the four stages are operated under the same control policy (Stock-to-demand). Under this inventory control policy, each stage will place its order to its supplier in a predetermined review period. The order size is the difference between the target level and the effective inventory level at the review time, where the effective level is the quantity on hand plus the quantity on order (if an order is on its way to the inventory), minus the unshipped backorders to customers or the quantity allocated to production. Thus,

$$Order = Target - (OnHand + OnOrder - Backorder) \tag{2}$$

According to Ballou (1999), the target level can be calculated as:

$$Target = Forecast * (LeadTime + ReviewPeriod + SafetyTime) \tag{3}$$

Where lead time is the time taken by the order to be received, review period is the number of weeks between each two reviews, and safety time represents the safety stock, and is expressed as a number of weeks of average demand.

The forecast is calculated using the moving average technique. This way, future demand forecasts are continuously updated in face of new demand realizations. In the core model, a moving average of the last ten weeks is used.

The bullwhip effect will be measured using the following equation:

$$Bullwhip = OrderVariance/DemandVariance \tag{4}$$

If the bullwhip value equals to one, then the order variance is equal to the demand variance, or in other words, there is no variance amplification. A bullwhip value larger than one indicates that the bullwhip effect is present. Whereas a bullwhip value smaller than one is referred to as a smoothing scenario, meaning that the orders are less variable compared to the demand pattern.

4.2 Simulation Model

Using Arena in simulating the model gives us the advantage of combining the high-level simulation tool Arena and the procedural programming language Visual Basic for Applications (VBA). The model logic can be represented comprehensibly in Arena, while the more complex calculation algorithms can be programmed in VBA.

The following is a description and some assumptions of the presented simulation model:

1. Assuming that customers are infinitely loyal and patient. This means that they will wait for the order even if it is not available at the present time, in other words they will not go to another store, they will wait for the product without complaining, and they will receive the products when available at any order
2. The four-stage supply chain is working on a decentralized information sharing policy, where each stage calculates its demand forecast based on the orders it gets from the downstream stage, and not on the actual user demand
3. No capacity constraints for inventories are assumed
4. The customer orders from the retailer follow the normal distribution with mean 100 and variance 30
5. Orders in each stage, in order to be fulfilled, must take a certain amount of time (lead time), so orders are not fulfilled instantaneously
6. Backorders are allowed, thus if one of the inventories cannot fulfill the whole order, it will keep the shortage amount as a backorder to be fulfilled as soon as it gets new replenishment
7. The review period is set as one week
8. The lead-time is considered to be deterministic at two days
9. The safety time is set to one and a half weeks
10. Weeks are the basic time unit in the model
11. The simulation starts with 300 items initialized in each inventory
12. On calculating the order, if the inventory stock exceeds the target, then the order equals zero. This means that no order is performed that week
13. The simulation model is run for a period of 100 weeks and a warm-up period of 20 weeks is specified so that the first few transient values are not considered while calculating average statistics
14. All important statistics along with some formulas and graphs, are written directly from Arena into Microsoft Excel to be further analyzed

In algorithm 1, it can be seen how the interaction between the customer and the retailer is done. In this algorithm, the customer demand takes place every one week, where the number of simulation weeks is predetermined. The retailer tries to fulfill all the orders, otherwise a backorder will occur. Figure 2 shows the Arena submodel for this part.

Algorithm 1: Customer Demand Algorithm

```
CustomerDemand
begin
    foreach Week do
        Customer makes Demand

        if RetailerInventory greater than or equal Demand then
            RetailerInventory = RetailerInventory - Demand
        else
            RetailerBackorder += (Demand - RetailerInventory) Set
            RetailerInventory = 0

        Save statistics into Excel file
        Week += 1
```

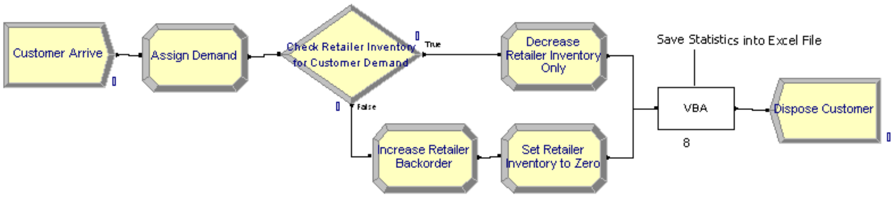

Fig. 2. Customer Demand Submodel

The communication procedure between the retailer and wholesaler stages of the supply chain is described in algorithm 2. Such communication occurs in the form of sending an order to the wholesaler based on a weekly review done on the retailer's inventory. The wholesaler tries to fulfill all the order, otherwise backorder will occur. Replenishments are received by the retailer after a predetermined lead time, which can be considered as the order preparation and transportation time. When the retailer receives the ordered amount (or part of it), it starts with fulfilling the backorders first then it adds into its inventory the rest if any. Figure 3 shows the Arena submodel of the retailer to wholesaler communication phase, starting from creating a retailer's inventory review, making an order and sending it to the wholesaler, and then receiving the order and fulfilling retailer's backorders or increasing its inventory.

Algorithm 2: Retailer – Wholesaler Communication

```
Retailer To Wholesaler
begin
    Review Retailer Inventory
    Order = CalculateOrder()

    if WholesalerInventory greater than or equal RetailerOrder then
        WholesalerInventory -= RetailerOrder
    else
        WholesalerBackorder += RetailerOrder - WholesalerInventory
        RetailerActualOrder = WholesalerInventory
        Set WholesalerInventory = 0

    Wait for LeadTime

    if RetailerBackorder greater than or equal RetailerActualOrder
    then
        RetailerBackorder -= RetailerActualOrder
    else
        RetailerInventory += RetailerActualOrder - RetailerBackorder
        Set RetailerBackorder = 0
        Set WholesalerInventory = 0

    Save statistics into Excel file
```

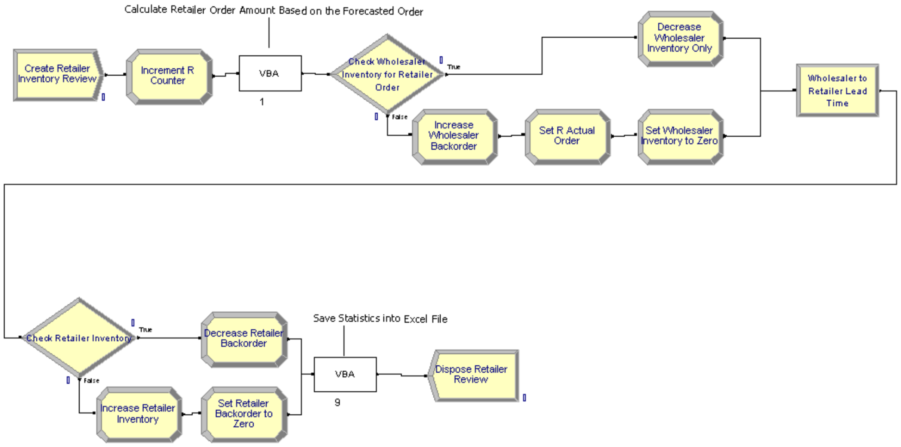

Fig. 3. Communication between Retailer and Wholesaler

The same procedure happens between each two consecutive stages on the supply chain, (i.e: between wholesaler and distributer, then between distributer and factory). At the last stage, the factory will behave a little different, since it is the end of the chain and thus has to rely on production other than ordering from the next stage.

The CalculateOrder function is written in Visual Basic. Due to the importance of this function, a simplified algorithm for it is displayed in algorithm 3 to enable the reader understand how the order of each week is calculated.

Algorithm 3: Order Calculation

```
CalculateOrder()
Input: LeadTime, ReviewPeriod, SafetyTime, OnHand, OnOrder,
Backorder
Output: Order
begin
    Forecast = CalculateForecast(last 10 orders)

    Target = Forecast * (LeadTime + ReviewPeriod + SafetyTime)

    Order = Target - (OnHand + OnOrder - Backorder)
```

The core model is run for one replication and the demand variance, retailer, wholesaler, distributer and factory order variances are obtained. These values are given in table 1. From this table, it can be observed that the variance of demand increases as one moves up the supply chain (with the exception of the factory production). This phenomenon is the bullwhip effect. The magnitude of increase in variability from one stage to another has been shown to be dependent on many factors such as the lead time, safety time, review period and forecasting window.

Table 1. Variation Increase in the Supply Chain

Source	**Variance**
Customer Demand	32.22
Retailer Order	95.66
Wholesaler Order	297.99
Distributer Order	605.64
Factory Production	577.24

Orders are amplified as we go up the supply chain. That is exactly what figure 4 shows. This figure is a chart that is created with Excel using VBA orders, the data is taken from the simulation statistics saved at each stage in an Excel file. The chart compares together customer demands, retailer's orders, wholesaler's orders, distributer's orders and factory productions. Notice that orders might take zero value, which means that no order is performed this week. For visual purposes, the zero orders are eliminated from the chart and plot only orders with positive values.

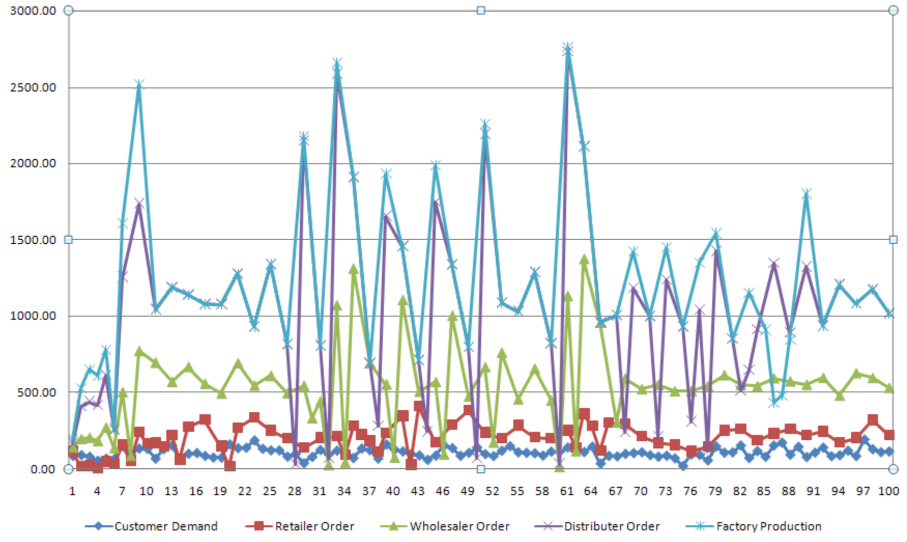

Fig. 4. Order Amplification in the Supply Chain: Core Model

4.3 Validation and Verification

Importing data on an Excel file enables for a good review of the model behavior. This helps the verification of the outputs of the model that was done by tracing the numbers and values produced by the system and verifying them by hand using the mathematical formulas used in constructing the model.

4.4 The Impacts of Changing Parameters

Supply chains are controlled by many factors and parameters, some of them have a direct impact on the bullwhip effect. This subsection is dedicated to spot the lights on these parameters and monitor the behavior of the system and the reaction of the bullwhip effect when they are changed. The goal is to decrease or minimize the bullwhip, and thus finding parameters that could be used to accomplish this task.

Lead Time: This is the first variation to the core model. Although it has been proved in many of the literature before that increasing the lead time directly affects and increases the bullwhip effect, but it is included here for completeness and as a way of proving that the present simulation model behaves normally on aspects that were previously proven to be true.

By doubling the lead time – from two to four days – and taking a look at the variance of orders in the different stages (see table 2), it is obvious that the variance increases than what it was in the core model. This refers to an increase in the bullwhip effect. Figure 5 refers to the amplification of orders when the lead time was increased. The maximum order now almost reaches 6000 items, previously the maximum order was about 2700. This can be explained by the fact that the lead time is a component of the equation that calculates the target. Thus increasing it increases the target and so the order may be done less frequently but with high quantities. Having less frequent orders might mean shutting down a facility. If we take the factory as an example, less frequent production with high quantities means that the factory has times where it has to produce huge amounts of items, while other times the factory is idle and produces nothing and just rely on the stock in the inventory. This also may lead to increased costs due to large amounts of items in stock.

Table 2. Variation Changes on Increasing Lead Time

Source	**Variance**
Customer Demand	32.32
Retailer Order	95.20
Wholesaler Order	483.73
Distributer Order	1314.93
Factory Production	1477.49

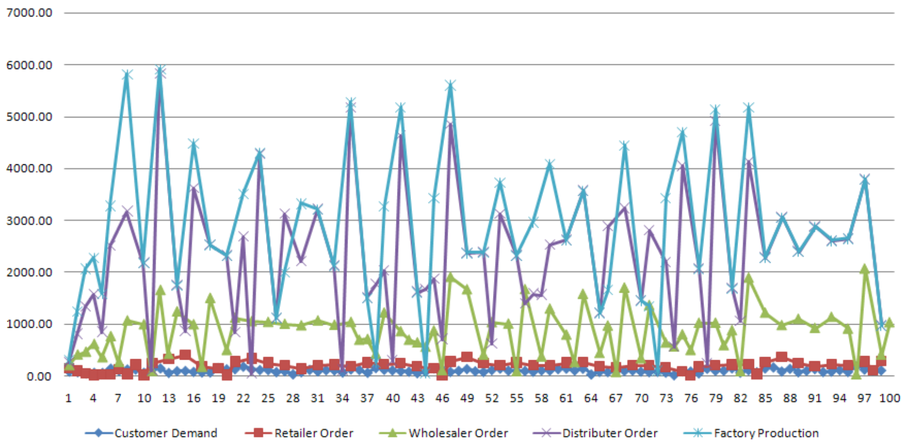

Fig. 5. Increased Order Amplification on Increasing Lead Time

Review Period and Safety Time: The same thing that happened with increasing the lead time are expected to happen with review period and safety time parameters. All three parameters share the same property that the three of them are components of the equation that calculates the target, and the increase in any of them increases the target level and thus results in less frequent orders with large amounts of items. The important thing here is to measure this increase in order to be able to compare the effect of the change in each parameter with the others.

In the following, this observation will be proved by means of simulation. In variation 2, the review period is increased from one to two weeks. In variation 3, the safety time is also changed from one and a half week to three weeks. Let us see what will happen with the order variance (tables 3 and 4) and the order amplification (figures 6 and 7). It is very obvious that the variance increases tremendously, especially with variation 3 when we increased the safety time. Keeping in mind that demand distribution is kept the same in the core model and in all variations. A normal distribution with mean 100 and variance 30.

Table 3. Variation Changes on Increasing Review Period

Source	**Variance**
Customer Demand	32.50
Retailer Order	94.32
Wholesaler Order	674.69
Distributer Order	2011.32
Factory Production	2351.66

Table 4. Variation Changes on Increasing Safety Time

Source	**Variance**
Customer Demand	32.32
Retailer Order	63.00
Wholesaler Order	6387.63
Distributer Order	16308.92
Factory Production	17765.90

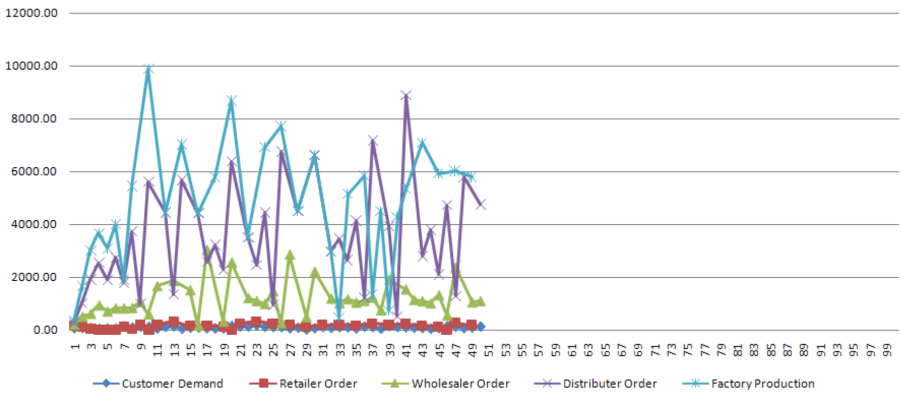

Fig. 6. Increased Order Amplification on Increasing Review Period

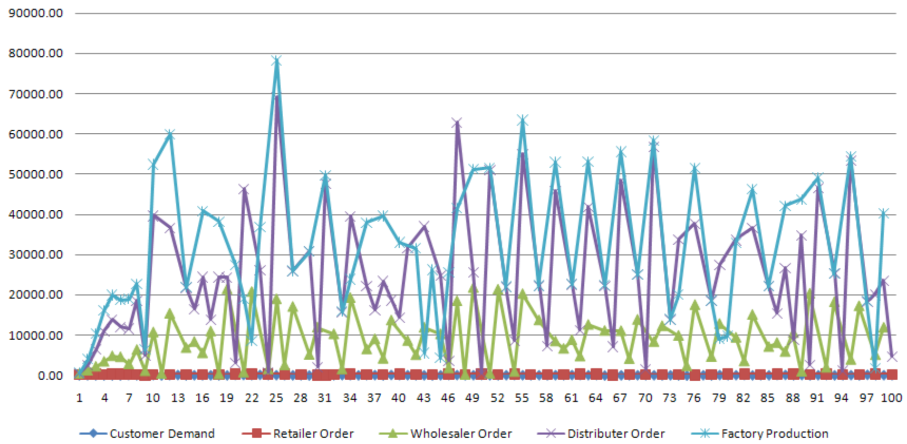

Fig. 7. Increased Order Amplification on Increasing Safety Time

Forecast Window: The moving window average was used as the forecasting technique in this model. Thus, this enables for another parameter to change: the forecasting window. In the core model, a window of the last 10 orders has been used. In this variation model – variation 4 – we will represent an increase in the forecasting window to be the last twenty orders. As a result, the variation has improved especially in the last three stages, see table 5. As seen in figure 8, and by comparing it to figure 4, a less variation in the orders can be visually detected. This behavior leads to a decrease in the bullwhip effect. Thus increasing the moving average forecasting window enhances the bullwhip effect due to creating more reliable forecasts.

Table 5. Variation Changes on Increasing Forecasting Window

Source	**Variance**
Customer Demand	32.32
Retailer Order	95.06
Wholesaler Order	217.54
Distributer Order	422.71
Factory Production	470.73

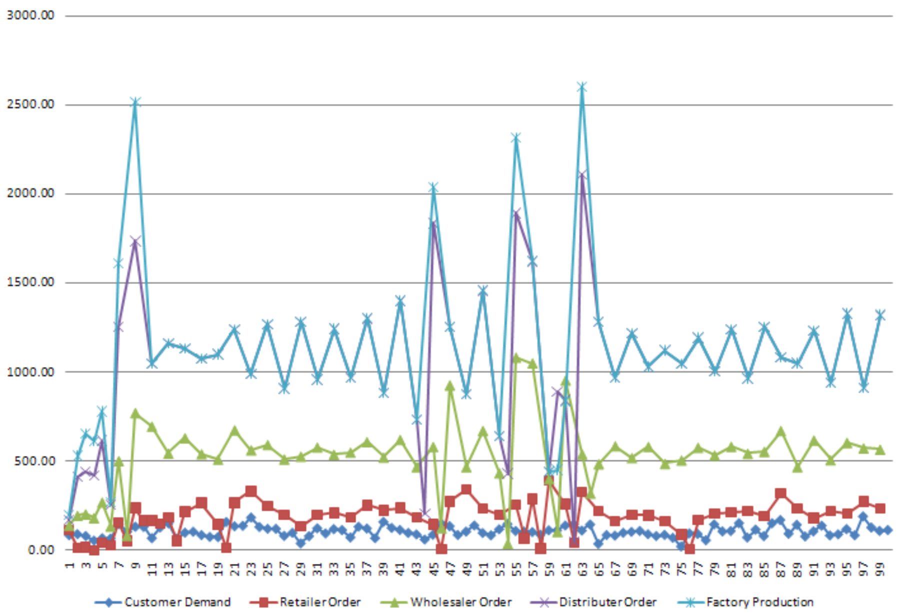

Fig. 8. Decreased Order Amplification on Increasing the Forecasting Window

4.5 Experimental Results

Working on a simulation model of a four-stage supply chain, where all the stages are using the stock-to-demand control policy. The results of changing the model parameters, in terms of order variation between subsequent stages, are grouped in table 6.

Table 6. Results

Variation **Source**	**Core**	**Lead Time**	**Review Period**	**Safety Time**	**Forecasting Window**
Customer Demand	32.22	32.32	32.50	32.32	32.32
Retailer Order	95.66	95.20	94.32	63.00	95.06
Wholesaler Order	297.99	483.73	674.69	6387.63	217.54
Distributer Order	605.64	1314.93	2011.32	16308.92	422.71
Factory Production	577.24	1277.49	2351.66	17765.90	470.73

As shown in the previous table, this is a summary of the investigation done by changing some system parameters and monitoring the effect in order variation over the different stages of the supply chain. The standard deviation of the orders after changing lead time, review period, safety time, and forecasting window is shown.

In table 7 the results are displayed as the percentage of increase of the bullwhip effect compared to the amount of change in the parameter, the percentages are measured relative to the core model. All the four parameters have been doubled, so we have the same unit of measurement for increase in the parameters. Thus we will focus on measuring the percentage of increase in the variation of orders and will measure an average increase for the whole supply chain.

Table 7. Percentages of Increase in the Bullwhip Effect

Variation **Source**	**Lead Time**	**Review Period**	**Safety Time**	**Forecasting Window**
Customer Demand	0.31%	0.87%	0.31%	0.31%
Retailer Order	-0.48%	-1.40%	-34.14%	-0.63%
Wholesaler Order	62.33%	126.41%	2043.57%	-27.00%
Distributer Order	117.11%	232.10%	2592.84%	-30.20%
Factory Production	121.31%	307.40%	2977.73%	-18.45%
Average Increase	**60.12%**	**133.07%**	**1516.06%**	**-15.19%**

From this table, it is clear that the bullwhip effect increased on doubling the lead time, review period and safety time. However, on doubling the forecasting window the bullwhip effect was reduced. Another observation to make is that sometimes the bullwhip effect decreases at the beginning of the supply chain, but it increases in subsequent stages. This observation highlights the fact that global analysis on the supply chain is very important. If each stage makes its decisions based on a local analysis, this might result in very bad management of the whole supply chain and this bad management will eventually affect all the stages in the chain.

5 Conclusion and Future Work

Factors affecting the bullwhip effect are complex and interfering together which poses more challenge to studying them. What have been done in this research is a focused investigation of the reaction of the bullwhip effect in respond to changing system parameters. Most of the parameters we have focused on rely directly on the type of inventory control policy in each stage of the supply chain. So, this study can be considered an illustration of the effects of using the Stock-to-Demand inventory policy on the bullwhip effect, and how can the parameters be tuned in this policy to minimize the bullwhip effect.

Simulation of the core model and its variations shows that changing the model parameters directly affects the bullwhip effect in the whole supply chain. It was observed that doubling the lead time increased this phenomenon by 60.12%, doubling the review period increased it by 133.07%, and doubling the safety time increased it by 1516.06%. The only variation where a decrease of the bullwhip was observed is doubling the forecasting window, this had a good impact on the bullwhip effect and actually decreases the variation by 15.19%. Tuning these parameters could lead to very promising results concerning the bullwhip effect, and could lead to identifying the best combination of parameter values that could lead to the least variation in orders.

Future work could include other inventory control policies, so that for each policy, a guide of which parameters should affect the bullwhip effect could be obtained. Moreover, in this study, we concentrated on measuring the variance in orders (comparing standard deviations) and how orders are amplified from one stage to another, in future studies the cost factor could enter in the comparison in a way that the analyzer relates the increase in the bullwhip effect with the increase in revenue costs.

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