Analysis and Simulation of the Bullwhip Phenomenon in Supply Chains

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Abstract

It is well recognized that the need to manage inventories to ensure that customers receive the right products at the right time is a central feature of the operation of many firms. Successful inventory management with the main purpose of keeping safety stocks as low as possible while satisfying demand has become increasingly more difficult as supply chains grow in size, complexity and shift to operating in a global environment. One common phenomenon in almost all forms of supply chain management is that of the bullwhip effect. Bullwhip effect indicates that a small disturbance at the customer end of the supply chain, in the form of a change in amount ordered from its immediate supplier, causes increasingly large disturbances as it works its way back through the many steps of the chain. The end supplier then is faced with producing and shipping wildly varying order amounts back down the chain to the customer end. In this paper we explore these issues via simulations to demonstrate how, under a variety of scenarios, the ease with which the bullwhip effect can occur, its impact on inventory control and to suggest remedies to circumvent resultant effects.

Keywords: supply chain bullwhip effect simulation demand fluctuation

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1 Introduction

1.1 Aim

The aims of the project are: firstly, to analyze the nature of the bullwhip effect in supply chains, identify causes and how these causes contribute to the problem; secondly, since the practice of decision-making is complex and costly, some simulations are constructed to calibrate the effect under a variety of scenarios; thirdly, based on the analysis from the simulations, some recommendations are provided.

1.2 Structure

The structure of the project is shown in Figure 1 as follows:

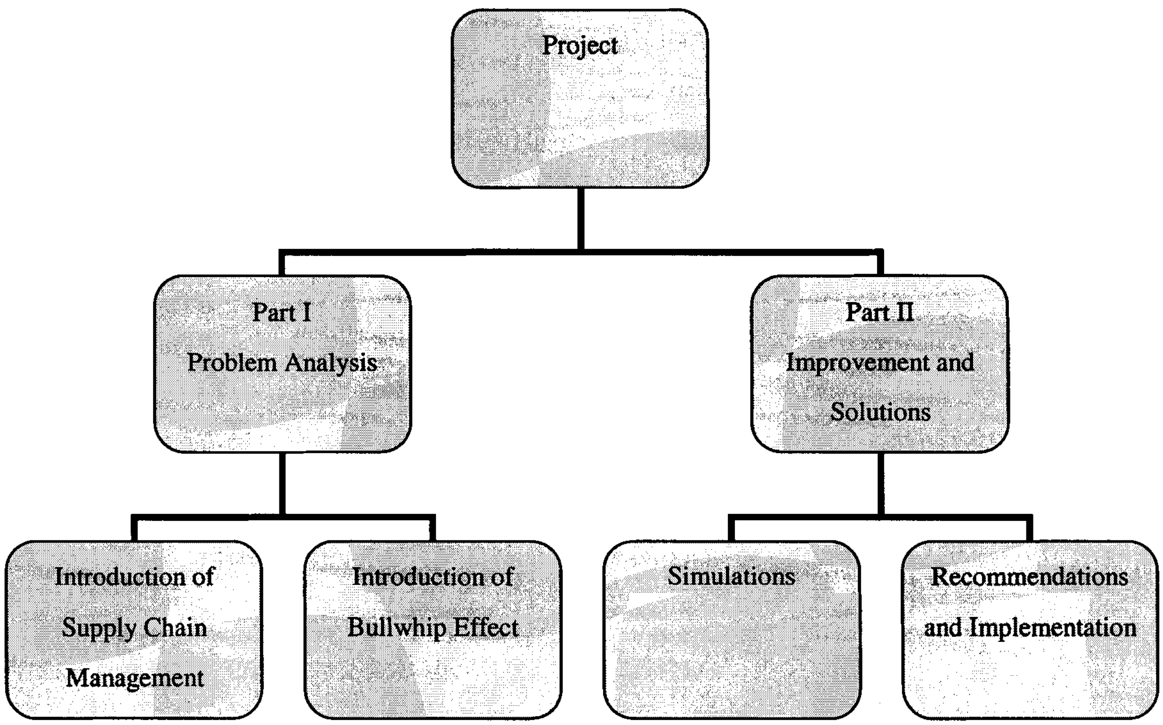

Figure 1 Project structure

1.3 Scope

The scope of the project is as follows:

- Background concepts
    - Supply chain management
    - Bullwhip effect
- Simulations
- Recommendations and implementation

1.4 Importance

Supply chain management is one critical factor for a company's success in today's dynamic business environment. The bullwhip effect is one of the most serious problems in supply chain management. The bullwhip effect happens in (production) systems when information about consumer demand becomes increasingly distorted as it moves upstream in the process. This distortion leads to excessive inventory throughout the system, poor product forecasts, insufficient or excessive capacities, product unavailability, and higher costs generally.[1]

In this project, a series of supply chain simulations are performed, and some recommendations are made to reduce the impact of the bullwhip effect.

An ancillary motivation for this study of bullwhipping is to better understand critical issues in supply chain management. The author is involved in the development of a comprehensive industrial business game described more thoroughly in Appendix 1. The particular industry under study is that of the global automobile industry although the generic nature of the business game can facilitate almost any industry. A better understanding of global supply chain issues permits an improved design for the business game.

2 Supply Chain Management

2.1 Definition of Supply Chain Management

Supply chain management[2] is the management of the interconnection of organizations that relate to each other through up-streams and down-streams linkages between the different processes that produce value in the form of products and services to the ultimate consumers. The "long distance" (or global) view of supply chain responsibility, stretching beyond immediate suppliers and immediate customers is one of the features of modern supply chain management. Improved supply chain management seeks shortened processing times and reduced amount of inventory held. Since most of the time goods spend being processed is in inventories, reducing inventory is an important part of reducing supply chain pipeline time. Figure 2 illustrates the concept of pipeline times in supply chain. One can see that once the supplier receives an order, this initiates a series of processing and waiting delays in getting the goods to the customer. The process is initiated by orders flowing upstream (the opposite direction) from customer to manufacturer and then manufacturer to supplier. Any distortions in the order information flowing upstream magnify the physical inventories being produced and sent into this pipeline.

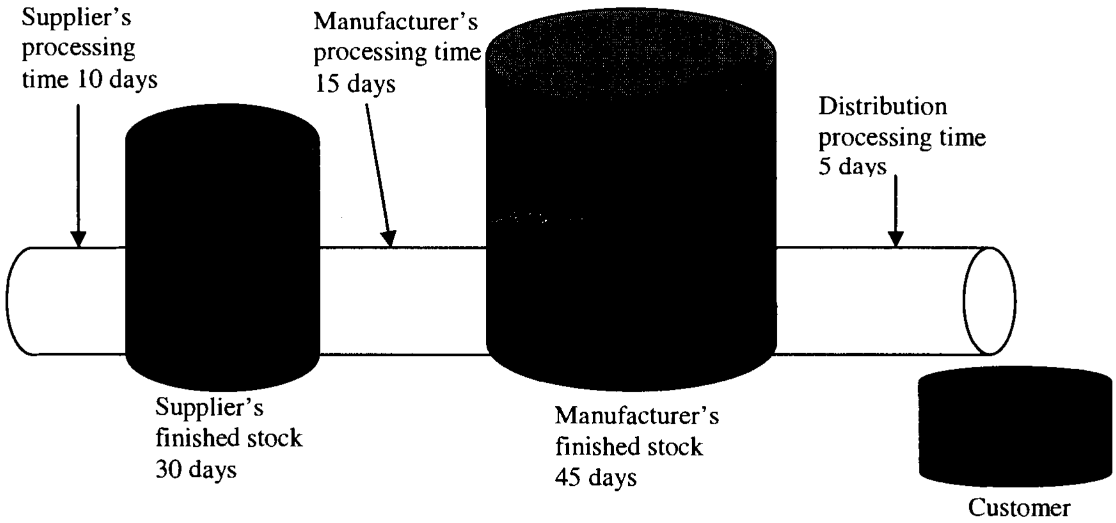

Figure 2 Pipeline time in the supply chain

2.2 Supply Chain Management Objectives

When a supply chain involves multiple stages (e.g., manufacturer to wholesaler to distributor to retailer) it follows that there can be substantial benefits by better management of the whole chain. These benefits focus on the three key objectives of supply chain management: satisfying end customers, doing so efficiently, and responding to change in an agile manner.

2.2.1 Focus on Satisfying End Customers

No matter how long and/or how complex a supply chain is and no matter the specific details included in any particular supply chain, it must eventually include consideration of the final customers. The final customer has the only "real" currency in the supply chain. When a customer decides to make a purchase, he/she triggers all the actions along the complete chain. The order information travels from the customer to the bottom level of the supply chain, while the materials and products move back along the chain to the end users. All the business processes in the supply chain pass on portions of that end-customer's money to each other, each retaining a margin for the value it has added. However, although all the operations in the chain have the immediate objective of satisfying their own immediate customer, the purpose of supply chain management is to make sure that they have a full appreciation of how, together, they can satisfy the end customer. The idea of an efficient consumer response[3] (ECR) has been developed to stress the importance of end customers. Although definitions of ECR vary, many stress the following interrelated factors.

- It is vital to understand the customer behavior and the markets. With the help of information technology, companies can capture or estimate market demand data for deciding safety inventory.
- All parts of the supply chain not only share the customer's money, but also co-operate share the end customer focus. ECR stresses the importance of achieving value for the customer by persuading all operations in the chain to work together to overcome supply problems. The integration includes mutual trust, information sharing and strategic partnership.
- Information technology is central to sharing information along the supply chain and to avoid misperceptions and delays between operations.

2.2.2 Focus on Managing the Chain Efficiently

Supply chain efficiency is regarded as one of the competitive advantages of a business. When information travels upstream the supply chain from market to suppliers and products travel downstream to the market, there are various kinds of delays. The focus on managing the chain efficiency is to reduce delays in the chain. It is important for companies to make sure that production move down the chain quickly rather than building up as inventory. Analyzing the whole supply chain can increase efficiency by allowing inventory only when it is needed[①], identifying bottlenecks, balancing capacity and generally coordinating the smooth flow of materials to reduce inventory costs. Identifying unnecessary inventory along the whole supply chain and reducing it is the basis of supply chain efficiency. Supply chain efficiency includes the following concerns:

- An emphasis on planning and control to ensure that additional supplies are initiated only when required.
- Be aware of costs, quality, delivery schedules and other issues.
- Carefully defined supply level agreements, which dictate exactly what each is expected to do in terms of their relationship, between customers and suppliers.
- Continuous improvement of supplier performance and the elimination of waste to cut the cost of their products or services to the customer.

2.2.3 Focus on Supply Chain Flexibility

Uncertainty is an important facet of most business environments. Some industries (e.g., fashion garments, computer components) exhibit extreme volatility. In such circumstances, supply chains need to be sufficiently flexible to cope with this uncertainty

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[①] One outgrowth of this has been the recent emphasis on JIT and the related Japanese concept of Kanban. See Appendix 2 for a brief discussion of these concepts.

and the disruption it can generate. In supply chain management, the term used to describe responsive flexibility is agility, which is a goal many companies strive to achieve. The concept of agility incorporates an emphasis on market focus, fast movement of goods and services through the supply chain and shared information along the chain. The concept also brings with it an increased emphasis on exploring creative ways of adapting to market changes. Fast movement of goods and service means the reduction of lead time in business processes, placing a premium on accurate and timely information.

2.3 Global Sourcing

Globalization contributes to the expansion of supply chain to places outside companies' home country for materials, products and services in the recent years. This is called global sourcing. Traditionally, companies who exported their goods and services all over the world were international, but only on their demand side, for they still sourced the majority of their suppliers locally. Companies are now increasingly willing to look outside home countries for their suppliers. There are a number of reasons for this:

- Most significantly, far tougher world competition has forced companies to look to reducing their total costs. Given that in many industries bought-in items are the largest single part of operations costs, an obvious strategy is to source from wherever is cheapest. So, for example, much manufacture takes place where labor costs are relatively low.
- The formation of trading blocks in different parts of the world has had the effect of lowering tariff barriers, at least within those blocks.

- Transportation infrastructures are considerably more sophisticated and cheaper than they once were. Super-efficient port operations integrated road-rain systems, jointly developed auto route systems, and cheaper air freight have all reduced some of the cost barriers to international trade.

There are of course problems with global sourcing. The risks of increased complexity and increased distance need managing carefully. In particular, the following issues are important:

- Suppliers who are a significant distance away need to transport their products across long distances. The increasing of lead time, risks of delays and hold-ups can be far greater than when sourcing locally.
- Negotiating and information sharing with suppliers whose native language is different from one's own makes communication more difficult and can lead to misunderstandings over contract terms.
- Global sourcing is more subject to supply chain risks caused by issues such as political disputes, wars, natural disasters, strikes and so on.
- It may not always be possible to investigate suppliers' performance and quality control at long distance.

2.4 Supply Chain Strategy

Supply chain strategy[4] focuses on identifying and quantifying supply chain improvements and assisting clients in transforming their operations, from suppliers to the ultimate customer, to enable real strategic change and competitive advantage.[5]

Some uncertainty characteristics require supply chain strategies with initiatives and innovations that can provide a competitive edge to companies. These strategies can be classified into four types. Information technology has played an important role in shaping such strategies. Figure 3 illustrates the relationships of the four types of strategies.

Supply Uncertainty	Demand Uncertainty: Low (Functional Products)	Demand Uncertainty: High (Innovative Products)
Low (Stable Process)	Efficient supply chains	Responsive supply chains
High (Evolving Process)	Risk-hedging supply chains	Agile supply chains

Figure 3 Four types of supply chain strategy

2.4.1 Efficient Supply Chains

These supply chains utilize strategies aimed at creating the highest cost efficiencies. In order to achieve this kind of efficiencies, non-value-added activities should be eliminated, scale economies should be pursued, optimization techniques should be deployed to get the best capacity utilization in production and distribution, and information linkages should be established to ensure the most efficient, accurate, and cost-effective transmission of information across the supply chain. The role of the Internet in this case is that it enables the supply chain to have tight and effortless information integration, as well as enabling production and distribution schedules to be optimized once the demand, inventory, and capacity information throughout the supply chain are made transparent.

2.4.2 Risk-hedging Supply Chains

Risk-hedging supply chains utilize strategies aimed at pooling and sharing resources in a supply chain so that the risks in supply disruption can also be shared. A single entity in a supply chain can be vulnerable to supply disruptions, but if there is more than one supply source or if alternative supply resources are available, then the risk of disruption would be reduced. A company may want to increase the safety stock of its key component to hedge against the risk of supply disruption, and by sharing the safety stock with other companies who also need this key component, the cost of maintaining this safety stock can be shared. Such inventory pooling strategies are quite common in retailing, where different retail stores or dealerships share inventory. The Internet plays a key role in providing information transparency among the members of the supply chain that are sharing inventory. Having real time information on inventory and demand allows the most cost-effective transshipment of goods from one site (with excess inventory) to another site.

2.4.3 Responsive Supply Chains

Responsive supply chains utilize strategies aimed at being responsive and flexible to the changing and diverse needs of the customers. To be responsive, companies use build-to-order and mass customization processes as a means to meet the specific requirements of customers. The customization processes are designed to be flexible. Order accuracy (i.e., accurate specification of customer requirements) is the key to the success of mass customization. Again, the Internet has enabled very accurate and timely capturing of highly personalized requirements of customers as well as fast transfer of order information to the factory or customization centers for the final configuration of the product.[6]

2.4.4 Agile Supply Chains

Agile supply chains utilize strategies aimed at being responsive and flexible to customer needs, while the risks of supply shortages or disruptions are hedged by pooling inventory or other capacity resources. These supply chains essentially have strategies in place that combine the strengths of "hedged" and "responsive" supply chains. They are agile because they have the capability to be responsive to the changing, diverse, and unpredictable demands of customers on the front end, while minimizing the back-end risks of supply disruptions.

3 Bullwhip Effect

3.1 Supply Chain Dynamics—Bullwhip Effect

Fundamental to any form of supply chain management system is a forecast of customer demand for a product or service. Since typically, forecasts are based on statistics and history records, they are rarely perfectly accurate. To mitigate the resultant forecast errors, companies often maintain an inventory buffer (or 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 will increase their orders. In periods of falling demand, orders will fall or stop in order to reduce inventory. The effect that variations are amplified as they move upstream in the supply chain (further from the customer) is called the bullwhip effect.[7, 8, 9]

The bullwhip effect, rooted in J Forrester's *Industrial Dynamics*[10] (1961), is an observed phenomenon in forecast-driven distribution channels. It denotes the variability, or gap, in amounts ordered compared to that of actual sales. A small disturbance at market end of the chain causes increasingly large disturbances as it works its way upstream towards the supplier end. Furthermore, the more extensive and complex the supply chain, the more the bullwhip is hard to counter.[11]

Supply chain experts 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.The primary cause of bullwhip effect is a perfectly understandable and rational desire by the different links in the supply chain to manage their production rates and inventory levels sensibly.

3.2 The Impact of Bullwhipping

Bullwhipping is a very pervasive problem in many supply chains situations giving rise to a host of undesirable effects and costs. These include:[12]

- Poor plan of the supply: Consistent with the bullwhip effect, each level of the supply chain over-react the demand fluctuation. If demand increases, there will be greater increase in suppliers' inventory and greater need for human resources in the manufacturing processes. However, when demand decreases, there will be greater decrease in the suppliers' demand. The great fluctuation in demand for lower level suppliers will severely influence the strategic decision-making and the manufacturing plan of the suppliers.

- Increase inventory costs: Even a small increase in the market demand will result in larger increase in the suppliers' demand. So, the call for inventory will be greater, resulting in either surplus inventory or insufficient capacity to produce what is needed.

- Increase business risk: Given the expense of carrying excessive inventories, it follows that poorly managed inventories in general exposes any firm to increase business risk. Monies directed to managing a poor inventory system are monies that could well be better utilized in other parts of the firm.

3.3 Causes of the Bullwhip Effect

Generally, it is accepted in industry that there are five most common causes of the bullwhip effect. In this section, we provide a general explanation of these causes. In section 5.2, we explore these causes via a series of simulation experiments and posit approaches to mitigate the impact of these causes.

3.3.1 Demand Signal Processing

Companies cannot, and usually do not, expect demand for their products or services to be stationary over time. Typically in making forecasts, these forecasts are updated based on observed demand and often there is over-reaction. This fluctuation of market demand is amplified through the supply chain.

There are many contributing factors for this cause, which includes ignorance of end user demand, multiple forecasts by different levels along the chain and long lead-times.

Counter measures for this cause include information sharing, such as access end customer Point of Sale data, single control of replenishment and lead time reduction. Another method is to reduce the length of the supply chain and form a flat chain with fewer levels, thus to limit the fluctuation of bullwhip.

3.3.2 Order Batching

Due to the economies of scale in ordering, most customers would like to place orders with their suppliers in batches. Often batching also includes possibilities such as quantity discounts or short term discounting (e.g., trade promotions).

Inventory management typically utilizes on of two forms of order batching, one is fixed quantity/variable cycle and the other is fixed cycle/variable quantity. Both of them need estimation of the market demand. Without going into the specific details of these two batching approaches, it is not uncommon to see firms using combinations of the two approaches in dealing with their various suppliers.

High order cost, low carrying costs of inventory, random or correlated ordering all contribute to order batching, and often results in bigger inventory turns.

Some measures to counter order batching include:

- EDI (Electronic Data Interchange) & Computer Assisted Ordering (CAO)
- Discounted on assorted truckload, consolidated by third party logistics
- Regular delivery appointment
- Rapid ordering and manufacturing changeovers to reduce setup costs

3.3.3 Price Variations

Price is one of the most critical factors when placing an order. Short term discounting and trade promotions are the typical forms of price variations. However, raw material price fluctuations can cause over/under contracting for materials. In global sourcing, exchange rate is regarded as a contribution to price variation.

Discounts, specials and other forms of short-term pricing and the lack of synchronization through to end user both contribute to the price variations. Every-day low pricing and special purchase contract could smooth price fluctuations.

3.3.4 Rationing Game

Suppose, limited production capacity, say during peak season, supplier / manufacturer will ration the supply to satisfy retailers' orders. Retailers' know this and will often exaggerate orders in order to secure a larger share of the limited capacity. During off-peak, there will be no capacity limits. So orders are back to normal.

Proportional rationing schemes, ignorance of supply conditions and unrestricted orders & free return policy all contribute to the rationing gaming found in inventory systems. Companies can reduce the impact of such gaming by, among other things, relying on historical figures to guide how they ration to their customers. They can also insist on greater information sharing as well as developing production capacity that permits greater flexibility in meeting demands.

3.3.5 Behavioral Issues

Misperceptions of feedback, in many cases, can give rise to bullwhip effect. Usually, in the supply chain, customers can get feedback from suppliers as orders travel along. However, sometimes, customers fail to see, or just ignore the impact of their behavior on their suppliers. When something is wrong with the supply chain due to customer behaviors, customers do not notice the problem, or blame others and continue their way to make situation worse. After the problem is solved at high cost, customers do not take any lessons from the experience and get the same problem elsewhere.

The causes of behavior issues include:

- Players in the chain don't see or care about the effect of their actions

- Myopic reward systems
- Accentuated when blame can be shifted

Some measure that can limit the effect of behavior issues include:

- Align reward systems
- Shared rewards through chain
- Limit myopic decision making

4 Feed-forward Model

Based on the discussion on the nature of supply chain and the concept of bullwhip effect, we introduce an information sharing model named "Feed-forward" to counter bullwhip effect.

4.1 Typical Information Flow in Supply Chain

Traditionally, the market demand from customers will only directly influence the production of OEM companies, then, the supplier only get the demand or market information from OEM (the immediate customer of suppliers). Figure 4 illustrates the traditional information flow in supply chain. The demand signal processing, order batching, price variance and other causes all contribute to the bullwhip effect. Therefore, in traditional supply chain, the small fluctuation of demand is amplified as it travels through the supply chain.

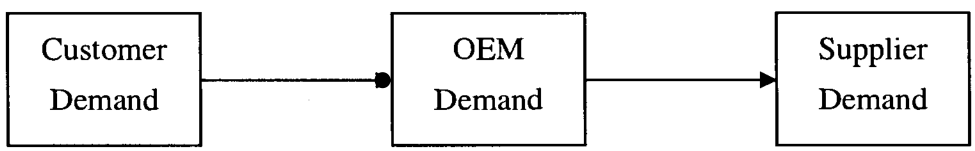


Figure 4 Traditional information flow in supply chain

4.2 Basic Concept about Feed-forward Model

Feed-forward[13] is a term originates in the field of control systems. It describes a form of system control by reacting to changes in its environment, usually to maintain some desired state of the system. A system which exhibits feed-forward behavior responds to a measured disturbance in a pre-defined way — contrast with a feedback system which attempts only to keep a system on course by correcting for deviations from setpoints. For example, a feed-forward-controlled car with the aim to maintain a predefined speed in all kinds of road conditions measure the slope of the road and, upon encountering a hill, would open up the throttle by a certain amount to counter the anticipated extra load.

Feed-forward is utilized in neural networks and control systems, but it does not appear to specifically address the issue of bullwhipping in supply chains.

Since the problem of traditional supply chains is that the supplier gets market information only from its immediate customer, we provide a model in which demand information of a company in the supply chain can be obtained by up-stream suppliers other than its immediate suppliers. Since the information is fed forward to that part of the supply chain where, traditionally, it has not yet arrived, this model is called feed-forward model. Information flow of feed-forward model is shown in Figure 5.

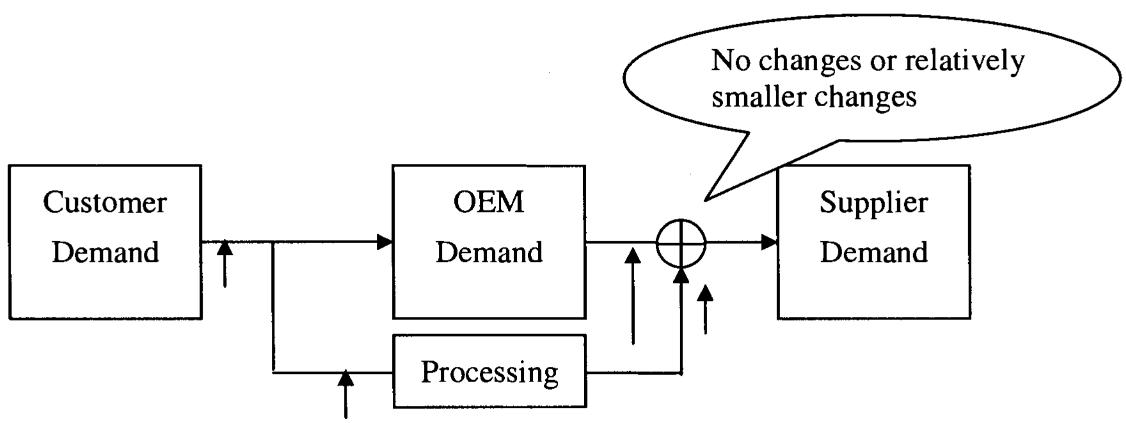


Figure 5 Feed-forward model

In the feed-forward model, there is a processing channel (feed-forward channel) beside the traditional chain. The processing channel gets the customer demand trend information, performs some processing, and combines the output with OEM demand to determine the real demand for the supplier.

The input of the processing channel is the market demand trend of all lower levels of the supply chain (customer end). It is the market demand trend that fluctuates at the customer end and gets amplified throughout the supply chain. Therefore, it is the source of the bullwhip effect.

Our basic feed-forward model is parameterized such that it can be tailored to particular situations. The parameterization takes the form of coefficients (or weights) for various information stages utilized to construct an overall situation-specific model. Obviously for such a feed-forward model to work, suppliers need to have a transparent relationship with customers (and possibly form strategic partnerships to access product needs), such that information sharing can be utilized.

The output of the processing channel is adjustment to the demand for suppliers. It is related to the market trend of the customer, but it is applied negatively (notice that there is a negative sign near the arrow from processing module) to counter the amplification caused by bullwhip effect. With the processing channel output combined negatively with the real demand, the supplier can adjust its production to limit the impact of fluctuation. For example, if the customer demand is increasing, the OEM demand will increase more greatly. But with the combination of the output from processing module, the real demand for supplier may be stable or relatively stable.

Based on feed-forward model, the demand for the supplier in Figure 5 is:

$$Ds = Do + \Delta Dc \times P$$

Ds: Demand of supplier

Do: Demand of OEM

ΔDc: Change in the demand from customer

P: Processing coefficient

In this formula, the process can be quite complex since often it is hard to determine the influence of customer demand on suppliers. For ease of implementation, we assume that the processing function is linear, and we thus can use a constant coefficient to represent it. More sophisticated structures could be implemented if found necessary.

In our simulations in later sections, we set pre-defined values to the parameters of Direct and P to simplify our simulation. However, in real situations, different parameter values could result in different system performances. For example, if we set Direct to 1 and all the P to 0, then Ds = Do, i.e., the demand for supplier is solely determined by the demand from OEM, thus, there would be no feed-forward. However, other coefficients would result in a more responsive system.

According to bullwhip effect, the small fluctuation of the market demand will be amplified along the supply chain. The feed-forward model is to detect the fluctuation from lower levels (near the customer) and use negative coefficient to counter the original fluctuation.

4.3 Feed-forward in Multi-level Supply Chain

In a multi-level supply chain, information flow is relatively complicated. From the customer's view, the market demand information is shared by all the higher levels of the supply chain. From the supplier's view, the demand for one level of the supply chain is not determined by that from its immediate customer, but influenced by that from all the lower levels (customer side).

As it is illustrated in Figure 6, there are different processing modules influencing the demand of the same level of supply chain. For example: The customer (company 1) demand information is shared by the OEM, first-tier supplier, second-tier supplier and third-tier supplier. On the other hand, the demand for third-tier supplier (company 5) is influenced by the demand from customers, OEM, first-tier supplier and second-tier supplier.

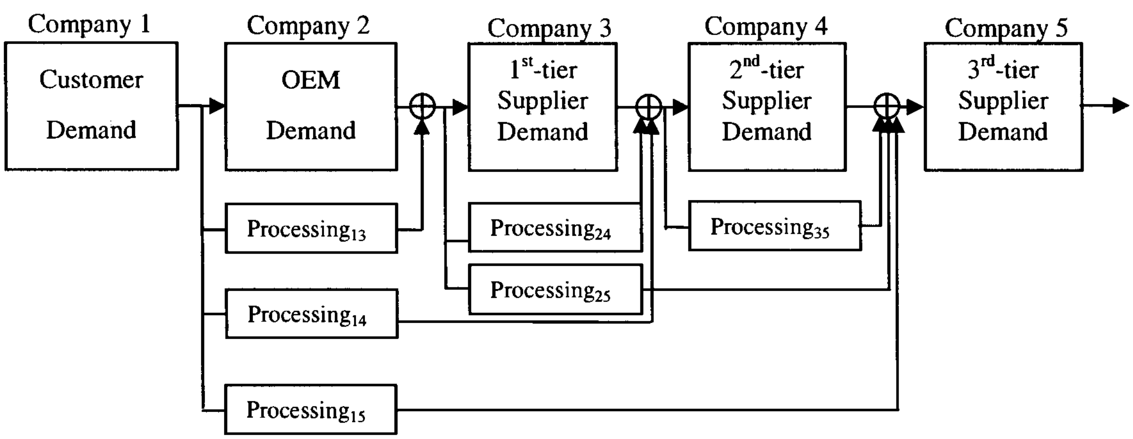


Figure 6 Improved multi-level supply chain

Table 1 shows the influence relationship among all the levels. In this table, there are three kinds of coefficients:

- "×" means that there is no relationship between the two levels.
- "Direct" is the coefficient between two consecutive levels. Its subscript indicates the two participants of the relationship. For example, $Direce_{12}$ is the coefficient between company 1 (customer) and company 2 (OEM).

- "Processing" is the coefficient between two inconsecutive levels. Its subscript indicates the two participants of the relationship. For example, Processing $_{13}$ is the coefficient between company 1 (customer) and company 3 (first-tier supplier).

Demand\ Supply	1 Customer	2 OEM	3 1st-tier supplier	4 2nd-tier supplier	5 3rd-tier supplier
1 Customer	×	$Direct_{12}$	$Processing_{13}$	$Processing_{14}$	$Processing_{15}$
2 OEM	×	×	$Direct_{23}$	$Processing_{24}$	$Processing_{25}$
3 1st-tier supplier	×	×	×	$Direct_{34}$	$Processing_{35}$
4 2nd-tier supplier	×	×	×	×	$Direct_{45}$
5 3rd-tier supplier	×	×	×	×	×

Table 1 Improved multi-level supply chain

To simplify the estimation, we assume that all the relationships are linear. The simplified demand formulas are:

$Demand_1 = Demand_1$

$Demand_2 = Demand_1 \times Direct_{12}$

$Demand_3 = \Delta Demand_1 \times P_{13} + Demand_2 \times Direct_{23}$

$Demand_4 = \Delta Demand_1 \times P_{14} + \Delta Demand_2 \times P_{24} + Demand_3 \times Direct_{34}$

$Demand_5 = \Delta Demand_1 \times P_{15} + \Delta Demand_2 \times P_{25} + \Delta Demand_3 \times P_{35} + Demand_4 \times Direct_{45}$

Notes:

- $Demand_1$ is the demand from customers, which is the real demand from market.
- $Demand_2$ is the demand for OEM. $Direct_{12}$ is the coefficient representing the relationship of market demand to OEM's demand. To simplify the formula, we set it to 1. But in real situation, this coefficient may be different than 1. For example, if customer ordered 100 units, OEM may produce 110 units to allow some possible damaged or returned units.
- $Demand_3$ is the demand for level 3 (the first-tier supplier), which is determined by both the demand from OEM and the market demand from customers. P_{13} is the

coefficient represents the influence from level 1 of the supply chain (the customers) on level 3 of the supply chain (the first-tier supplier).

5 Bullwhip Simulation

5.1 Simulation Data Table

To perform our simulations in section 5.2, we create a data table denoted below as Table2. This table illustrates a four-stage supply chain where an original equipment manufacturer is served by three tiers of suppliers. The demand from the OEM's market has been running at a rate of 100 units per period, but in period 2, demand reduces to 95 units per period. All stages in the supply chain work on the principle that they will keep in stock one period's demand. This is a simplification but not a gross one. Many operations gear their inventory levels to their demand rate. The column labeled "stock" for each level of supply shows the starting stock at the beginning of the period and the finish stock at the end of the period. At the beginning of period 2, the OEM has 100 units in stock (that being the rate of demand up to period 2).

The demand in period 2 is 95 units and so the OEM knows that it would need to produce sufficient units to finish up at the end of the period with 95 units in stock (this being the new demand rate). To do this, it need only manufacture 90 units; these, together with 5 units taken out of the starting stock, will supply demand and leave a finished stock of 95 units. The beginning of period 3 finds the OEM with 95 units in stock. Demand is also 95 units and therefore its production rate to maintain a stock level of 95 units will be 95 units per period. The original equipment manufacturer now operates at a steady rate of producing 95 units per period.

Period	Third-tier supplier		Second-tier supplier		Firs-tier supplier		OEM		Demand
	Production	Stock	Production	Stock	Production	Stock	Production	Stock	
1	100	100	100	100	100	100	100	100	100
		100		100		100		100	
2	20	100	60	100	80	100	90	100	95
		60		80		90		95	
3	180	60	120	80	100	90	95	95	95
		120		100		95		95	
4	60	120	90	100	95	95	95	95	95
		90		95		95		95	
5	100	90	95	95	95	95	95	95	95
		95		95		95		95	
6	95	95	95	95	95	95	95	95	95
		95		95		95		95	

Note: All companies keep one period's inventory.

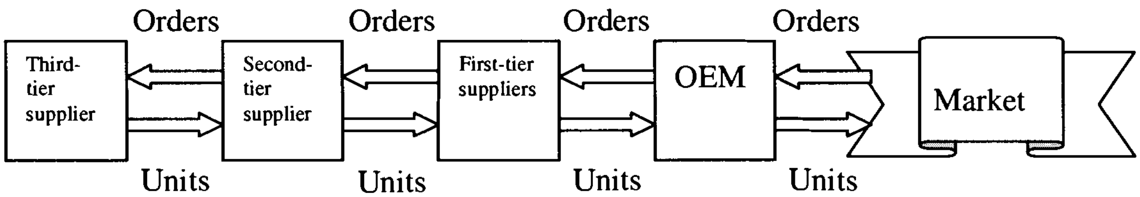


Table 2 Demand signal processing example

Now carry this same logic through to the first–tier supplier. At the beginning of period 2, the second-tier supplier has 100 units in stock. The demand that it has to supply in period 2 is derived from the OEM production rate. In Table 2, it has been dropped down to 90 in the second period. The first-tier supplier therefore, has to produce sufficient to supply the demand of 90 units (or the equivalent) and leave one month's demand (now 90 units) as its finish stock. A production rate of 80 units per month will achieve this. It will therefore start period 3 with an opening stock of 90 units, but the demand from the OEM has now risen to 95 units. It therefore has to product sufficient to fulfill this demand of 95 units and leave 95 units in stock. To do this, it must product 100 units in period 3. After period 3, the first-tier supplier then resumes a steady state, producing 95 units per month. Note again, however, that the fluctuation has been even greater than that in the OEM's production rate, decreasing to 80 units a period, increasing to 100 units a period, and then achieving a steady rate of 95 units a period.

Table 2 shows the data of this logic if it is extended right back to the third-tier supplier. From the data, we can notice that the further back up the supply chain an operation is placed, the more drastic are the fluctuations caused by the relatively small change in demand from the final customer. In this simple case, the decision of how much to product each month was governed by the following relationship:

- Total available for sales in any period = total required in the same period
- Starting stock + production rate = demand + closing stock
- Starting stock + production rate = 2 × demand (because closing stock must be equal to demand)
- Production rate = 2 × demand – starting stock

5.2 Simulation and Analysis

5.2.1 Decrease and Stay

In this scenario, the market demand decreases by 5 units, then becomes stable again. This relatively simple scenario only demonstrates the demand signal processing cause of bullwhip effect. In the scenario, the fluctuation of 5 units in market caused a 10 units fluctuation in OEM, a 20 units change in first-tier supplier, a 60 units change in the second-tier supplier and a fluctuation of 160 units in third-tier supplier.

The key reason for this problem is that each level of supplier only focuses attention on the market demand of its immediate customers, and ignores the end user demand. Thus, when planning for production to satisfy the customer, the supplier fails to have an overview of the entire supply chain, and does not estimate end user's demand. In this way, when the customer's demand decreases, the company over-reacts to the trend and places much fewer orders to its supplier due to the existing surplus inventory, which causes the fluctuation in the entire supply chain.

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[illegible]			OEM			[illegible]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	[illegible]	[illegible]	[illegible]	Prod-uction	Start Stock	End Stock	[illegible]
1	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	100	100	100	[illegible]
2	20	100	60	60	100	80	[illegible]	[illegible]	[illegible]	90	100	95	[illegible]
3	180	60	120	120	80	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
4	60	120	90	90	100	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
5	100	90	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
6	95	95	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]

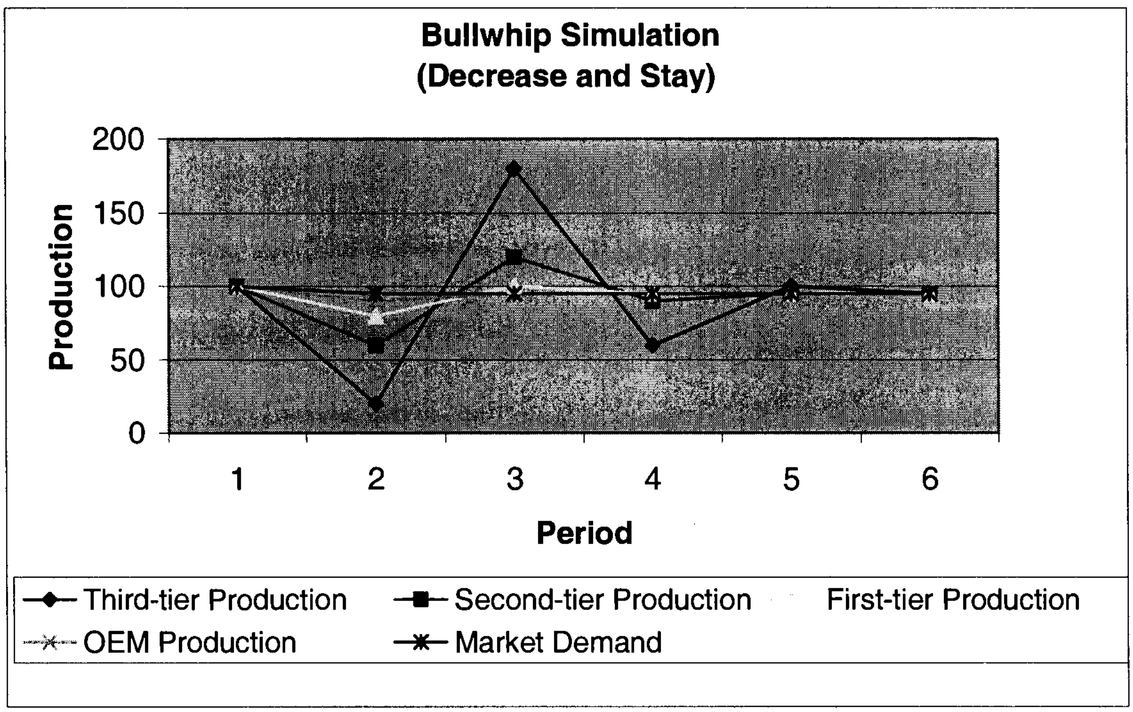


Figure 7 Decrease and stay simulation

5.2.2 Decrease and Stay with Feed-forward

This scenario is the simulation of bullwhipping due to signal processing countered by feed-forward model. We use the data in Table 2 as an example to illustrate the effect of feed-forward model on multiple-level supply chain. To simplify our calculation, we set:

- $Direct_{n\ n+1} = 1$ (No margins for returned units)
- $P_{n\ n+2} = -0.5$ (The demand is also influenced by the demand changes from its customer's customer, -0.5 is a random selected value)
- All the other P coefficients are 0 (The demand is not influenced by demands from any levels that are more than two levels away in the supply chain)

So, the simplified formulas are:

$Demand_1 = Demand_1$

$Demand_2 = Demand_1$

$Demand_3 = Demand_2 + (-0.5) \times \Delta Demand_1$

$Demand_4 = Demand_3 + (-0.5) \times \Delta Demand_2$

$Demand_5 = Demand_4 + (-0.5) \times \Delta Demand_3$

Based on the formulas above, we calculate the demand and stock data for the multi-level supply chain scenario. The result is shown in the table below. In the table, the data headed with "Production" are the demand for its supplier.

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			First-tier supplier			OEM			Market
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	Demand
1	100	100	100	100	100	100	[illegible]	100	100	100	100	100	100
2	75	100	83	83	100	89	89	100	[illegible]	93	100	95	[illegible]
3	108	83	100	100	89	96	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
4	92	100	94	94	96	95	[illegible]	95	95	95	95	95	[illegible]
5	95	94	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
6	95	95	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]

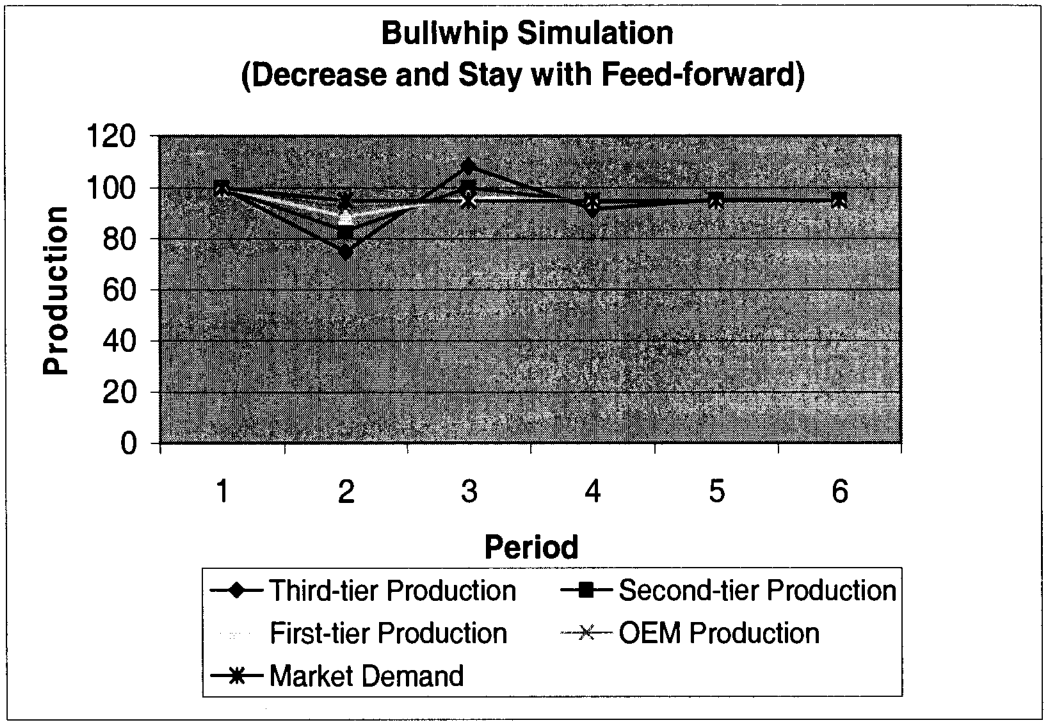


Figure 8 Decrease and stay simulation with feed-forward

In this simulation, the market demand decreases by 5 units, then stays at the decreased volume. This simulation uses the same scenario as the simulation in section 5.2.1 except the feed-forward model. Compared with the data and chart in section 5.2.1, we can see that the fluctuation with feed-forward is 33 units in the third-tier supplier production compared with the fluctuation of 160 units without feed-forward. Besides, in this simulation, the supply chain regains stability in period 5.

Based on the data in the table and figure above, we can see that the feed-forward model counter the bullwhip effect in two ways:

- Decrease the fluctuation: According to the original data in section 5.2.1, the fluctuation in third-tier supplier's production is 160 (from 20 to 180). But with the feed-forward model, the fluctuation is 33 (from 75 to 108).
- Terminate the fluctuation faster: According to the original data in Table 2, it takes 5 periods time for the production of all levels of the supply chain to be the same as market demand, which means that the supply chain is stable. But with the feed-forward model, the fluctuation only takes 4 periods to stop.

5.2.3 Step Pulse Up

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[redacted]	OEM			[redacted]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock		Prod-uction	Start Stock	End Stock	
1	100	100	100	100	100	100		100	100	100	
2	180	100	140	140	100	120		110	100	105	
3	-60	140	40	40	120	80		95	105	100	
4	220	40	130	130	80	105		100	100	100	
5	60	130	95	95	105	100		100	100	100	
6	105	95	100	100	100	100		100	100	100	
7	100	100	100	100	100	100		100	100	100	
8	100	100	100	100	100	100		100	100	100	

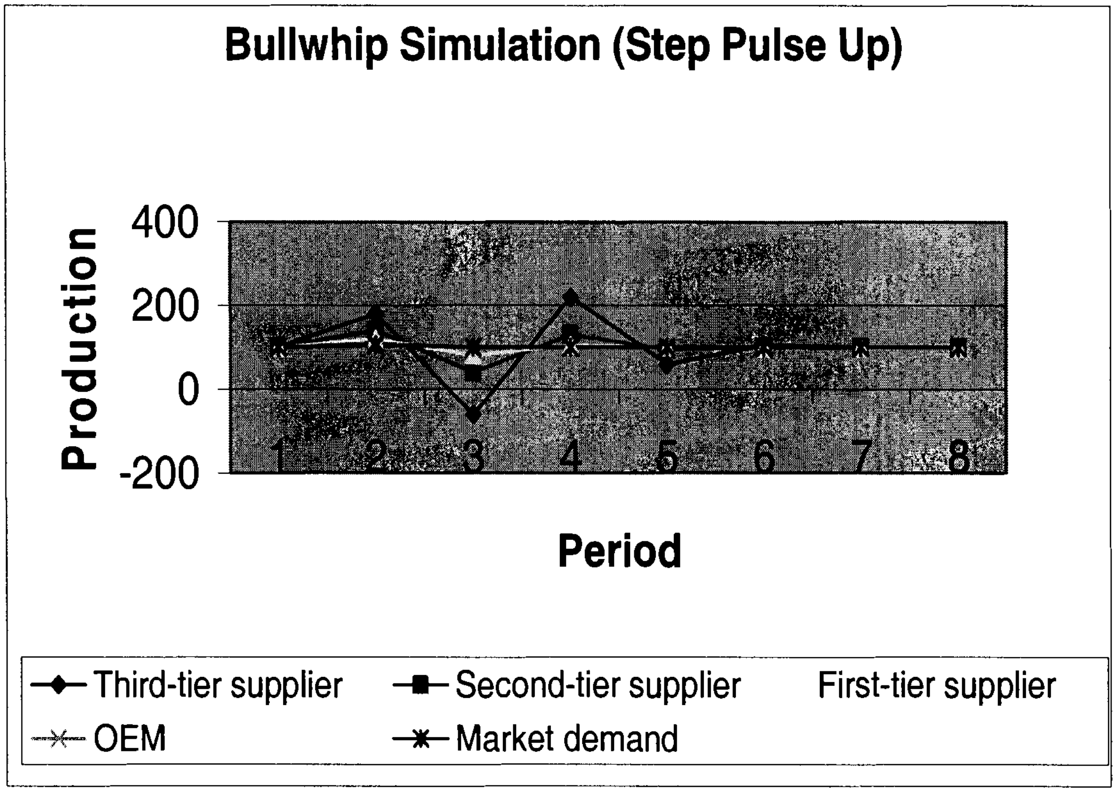


Figure 9 Step pulse up simulation

In this scenario, the market demand increased by 5 units for one period, then comes back to and stays at the original volume. There may be various causes for the step pulse up, such as price variation, behavior error, rationing game, estimated supply limit, estimated shipping problem, or favorite exchange rate in global sourcing.

From the table and chart, we can see that the 5 units step pulse up in market demand is amplified to fluctuation of 280 units (from -60 to 220) in the third-tier supplier, and it takes 6 periods for the supply chain to regain stability.

5.2.4 Step Pulse Up with Feed-forward

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[illegible]	OEM			[illegible]
	Produ-ction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock		Prod-uction	Start Stock	End Stock	
1	100	100	100	100	100	100	[illegible]	100	100	100	[illegible]
2	125	100	117	117	100	111	[illegible]	[illegible]	100	105	[illegible]
3	66	117	83	83	111	93	[illegible]	[illegible]	[illegible]	100	[illegible]
4	117	83	106	106	93	101	[illegible]	100	100	[illegible]	[illegible]
5	96	106	99	99	101	100	[illegible]	100	100	100	[illegible]
6	100	99	100	100	100	100	[illegible]	100	100	100	[illegible]

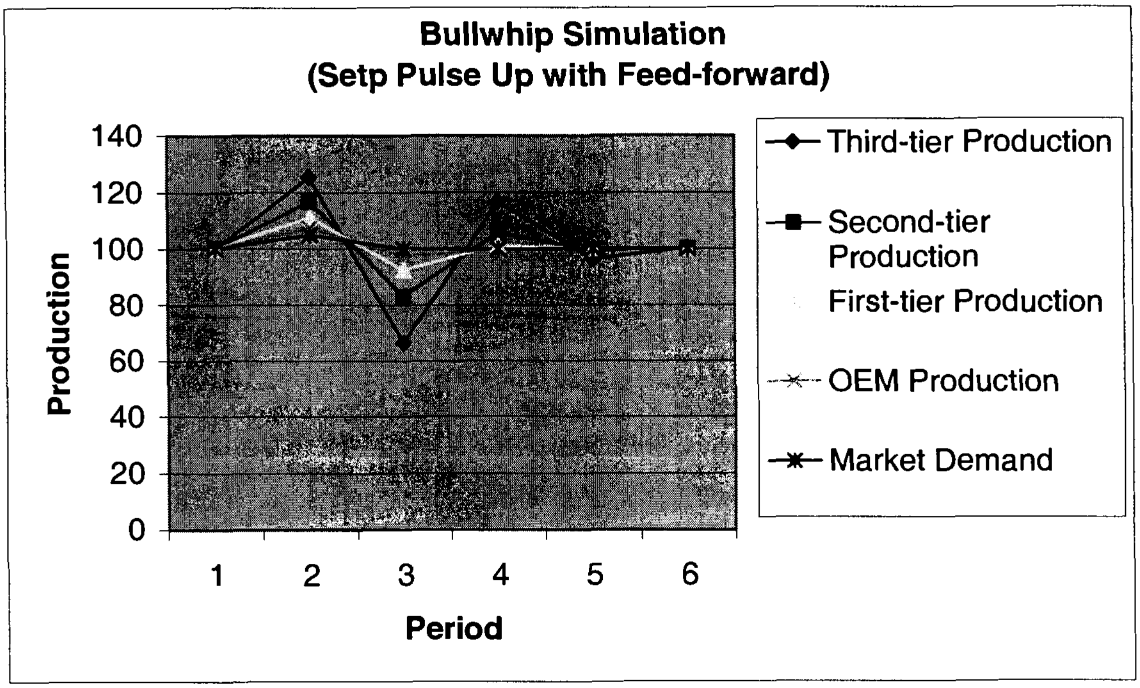


Figure 10 Step pulse up simulation with feed-forward

With feed-forward model, the fluctuation in third-tier supplier production is 59 units compared with the fluctuation of 280 units in section 5.2.3. Besides, with feed-forward model, the supply chain needs 5 periods to regain stability instead 7 periods needed for the simulation without feed-forward.

5.2.5 Step Pulse Down

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[redacted]	OEM			[redacted]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock		Prod-uction	Start Stock	End Stock	
1	100	100	100	100	100	100		100	100	100	
2	20	100	60	60	100	80		90	100	95	
3	260	60	160	160	80	120		105	[illegible]	[illegible]	
4	-20	160	70	70	120	95		100	[illegible]	100	
5	140	70	105	105	95	100		100	[illegible]	[illegible]	
6	95	105	100	100	100	100		100	100	100	
7	100	100	100	100	100	100		100	100	100	
8	100	100	100	100	100	100		100	100	100	

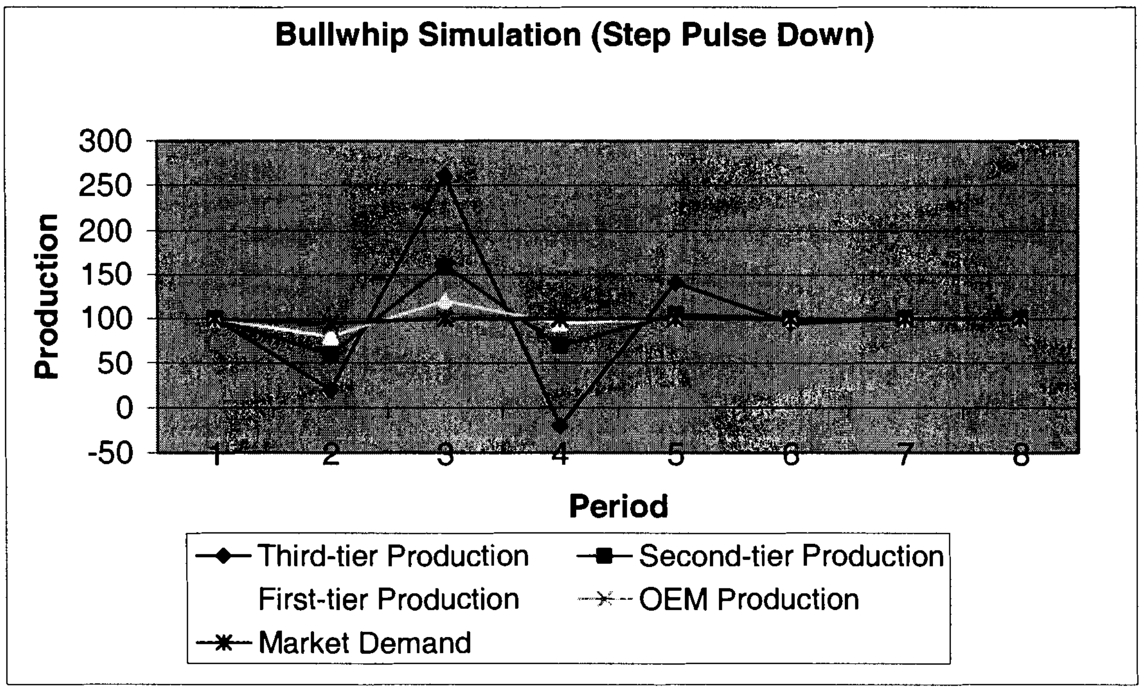


Figure 11 Step pulse down simulation

In this scenario, the market demand decreased by 5 units for one period, then comes back to and stays at the original volume. The causes of the step pulse down include price variation, behavior error, rational game or unfavorable exchange rate in global sourcing.

From the data and chart above, we can see that the fluctuation of 5 units in market demand is amplified to 280 units change in the production of third-tier supplier, and the supply chain takes six periods to regain stability.

5.2.6 Step Pulse Down with Feed-forward

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[redacted]	OEM			[redacted]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock		Prod-uction	Start Stock	End Stock	
1	100	100	100	100	100	100		100	100	100	
2	75	100	83	83	100	89		93	100	95	
3	134	83	117	117	89	108		103	95	100	
4	83	117	94	94	108	98.75		100	100	100	
5	104	94	101	101	99	100		100	100	100	
6	100	101	100	100	100	100		100	100	100	

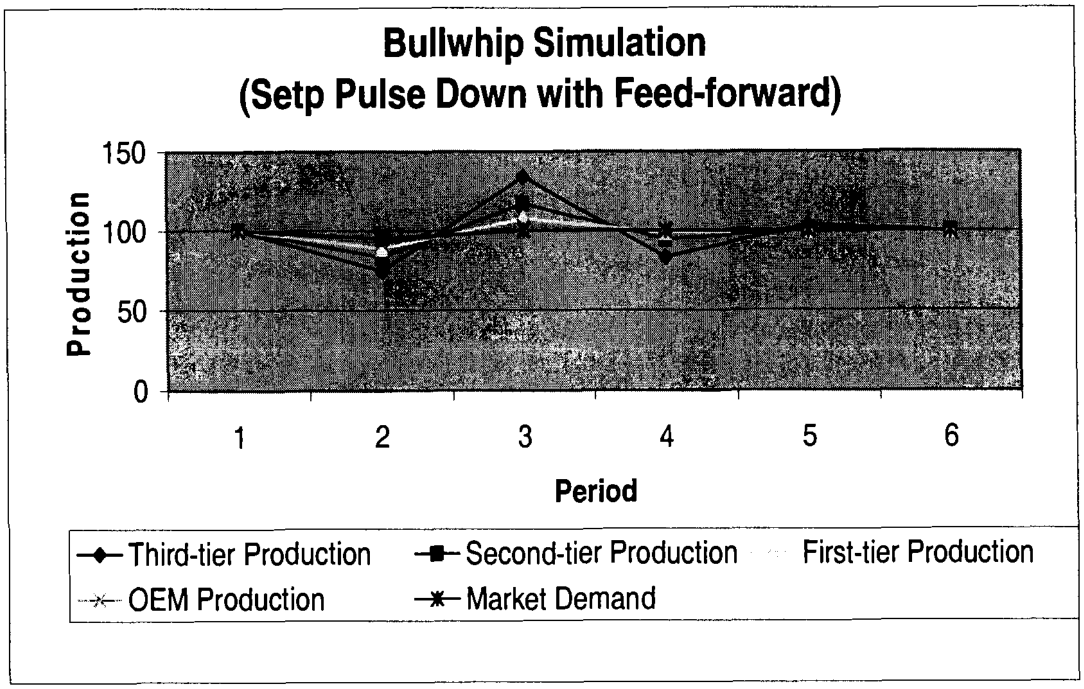


Figure 12 Step pulse down simulation with feed-forward

With feed-forward model, the fluctuation in third-tier supplier production is 59 units compared with the 280 units in section 5.2.5. Besides, with feed-forward model, the supply chain needs 5 periods to regain stability instead 6 periods needed for the simulation without feed-forward.

5.2.7 Ramp Up

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[redacted]	OEM			[redacted]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock		Prod-uction	Start Stock	End Stock	
1	100	100	100	100	100	100		100	100	100	
2	180	100	140	140	100	120		110	100	105	
3	100	140	120	120	120	120		115	105	110	
4	140	120	130	130	120	125		120	110	115	
5	140	130	135	135	125	130		125	115	120	
6	145	135	140	140	130	135		130	120	125	

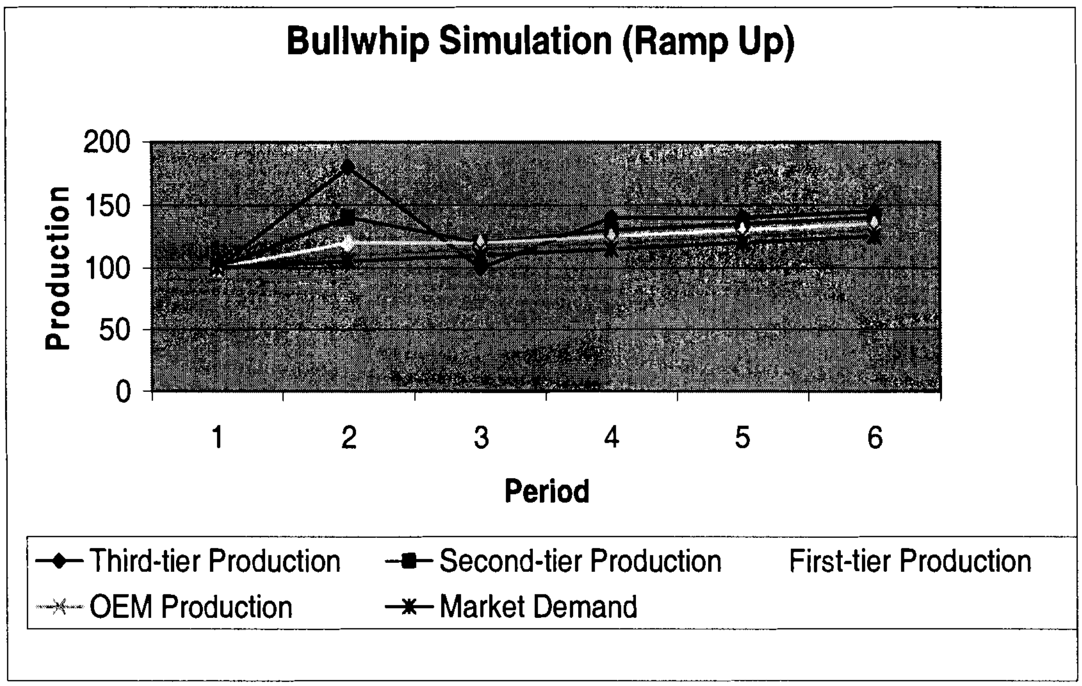


Figure 13 Ramp up simulation

In this scenario, the market demand increases by 5 units each period. Ramp up is the demand trend for a developing market. The primary cause of it is the real demand increase in market.

From the data and chart above, we can see that the 5 units increase between each period in the market demand is amplified up to the fluctuation of 80 units in production of the third-tier supplier before the supply chain regaining relative stability in period 5.

5.2.8 Ramp Up with Feed-forward

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier				OEM			
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	[redacted]	Prod-uction	Start Stock	End Stock	[redacted]
1	100	100	100	100	100	100	[redacted]	100	100	100	[redacted]
2	125	100	117	117	100	111	[redacted]	108	100	105	[redacted]
3	117	117	117	117	111	115	[redacted]	113	105	110	[redacted]
4	125	117	123	123	115	120	[redacted]	118	110	115	[redacted]
5	130	123	128	128	120	125	[redacted]	123	115	120	[redacted]
6	135	128	132.5	133	125	130	[redacted]	128	120	125	[redacted]

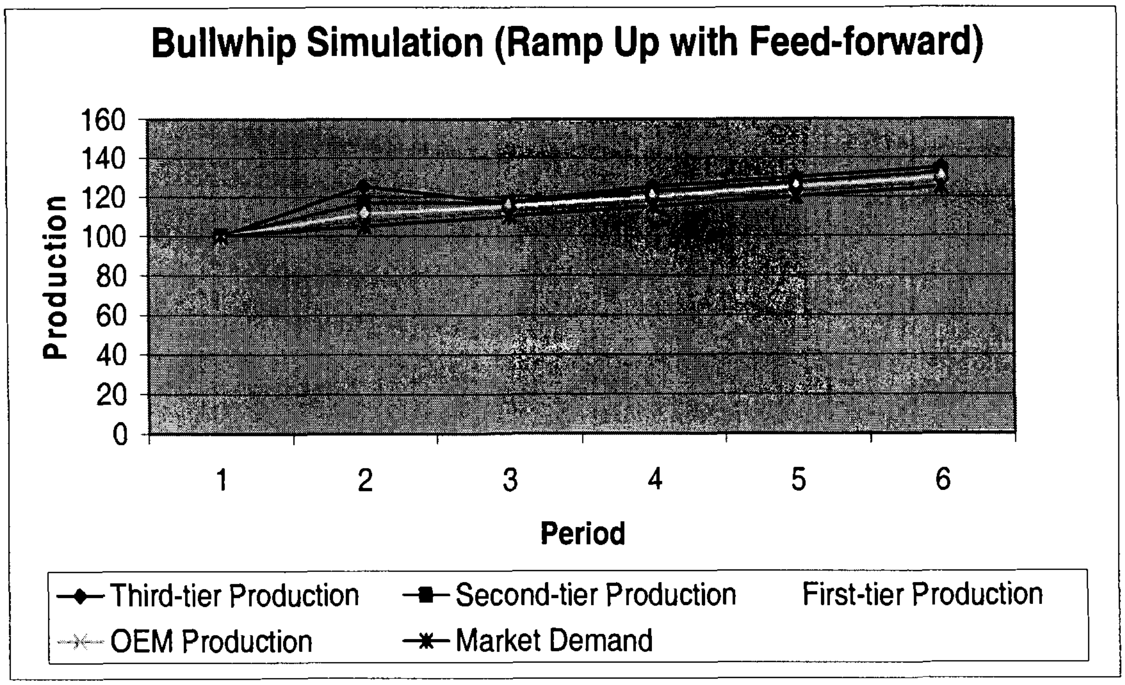


Figure 14 Ramp up simulation with feed-forward

With feed-forward model, the maximum fluctuation in third-tier supplier production corresponding to the 5 units increase in market is only 25 units and regains the same increasing rate as the market demand at the beginning of period 4.

5.2.9 Ramp Down

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[illegible]	OEM			[illegible]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	[illegible]	Prod-uction	Start Stock	End Stock	[illegible]
1	100	100	100	100	100	100	[illegible]	100	100	100	[illegible]
2	20	100	60	60	100	80	[illegible]	90	100	95	[illegible]
3	100	60	80	80	80	80	[illegible]	85	95	90	[illegible]
4	60	80	70	70	80	75	[illegible]	80	[illegible]	85	[illegible]
5	60	70	65	65	75	70	[illegible]	75	85	80	[illegible]
6	55	65	60	60	70	65	[illegible]	70	80	75	[illegible]

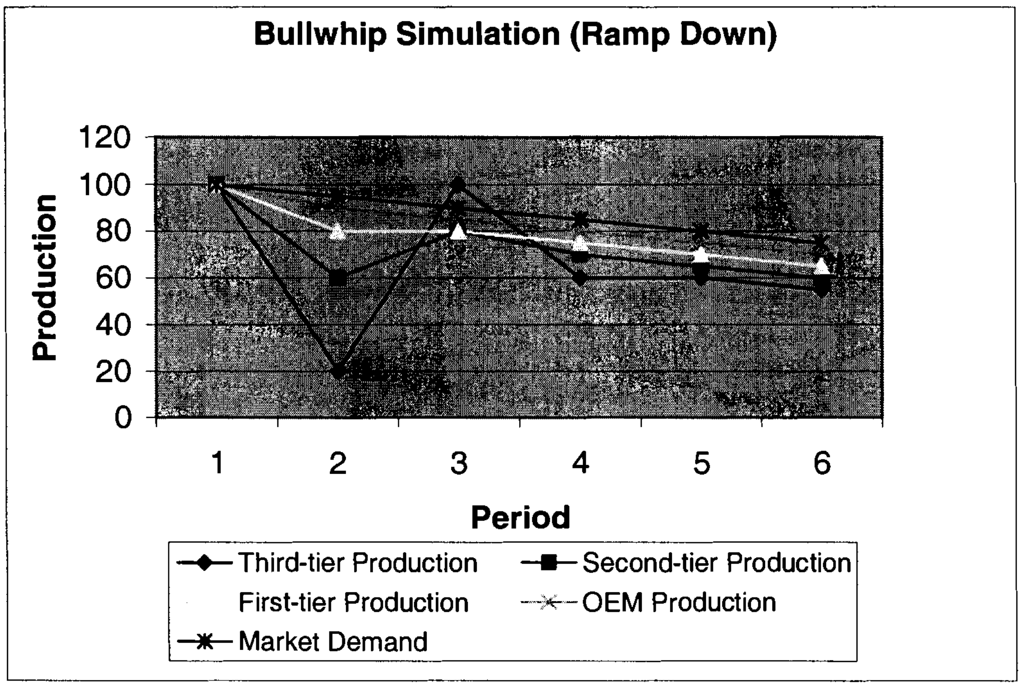


Figure 15 Ramp down simulation

In this scenario, the market demand decreases by 5 units each period. The ramp down scenario represents the typical market trend for a falling market. From the data and chart above, we can see that the 5 units decrease between each period is amplified up to an 80 units change in the third-tier supplier's production. The supply chain takes 4 periods to regain relative stability.

5.2.10 Ramp Down with Feed-forward

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier				OEM			
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	[redacted]	Prod-uction	Start Stock	End Stock	[redacted]
1	100	100	100	100	100	100		100	100	100	
2	75	100	83	83	100	89		93	100	95	
3	83	83	83	83	89	85		88	95	90	
4	75	83	78	78	85	80		83	90	85	
5	70	78	73	73	80	75		78	85	80	
6	65	73	68	68	75	70		73	80	75	

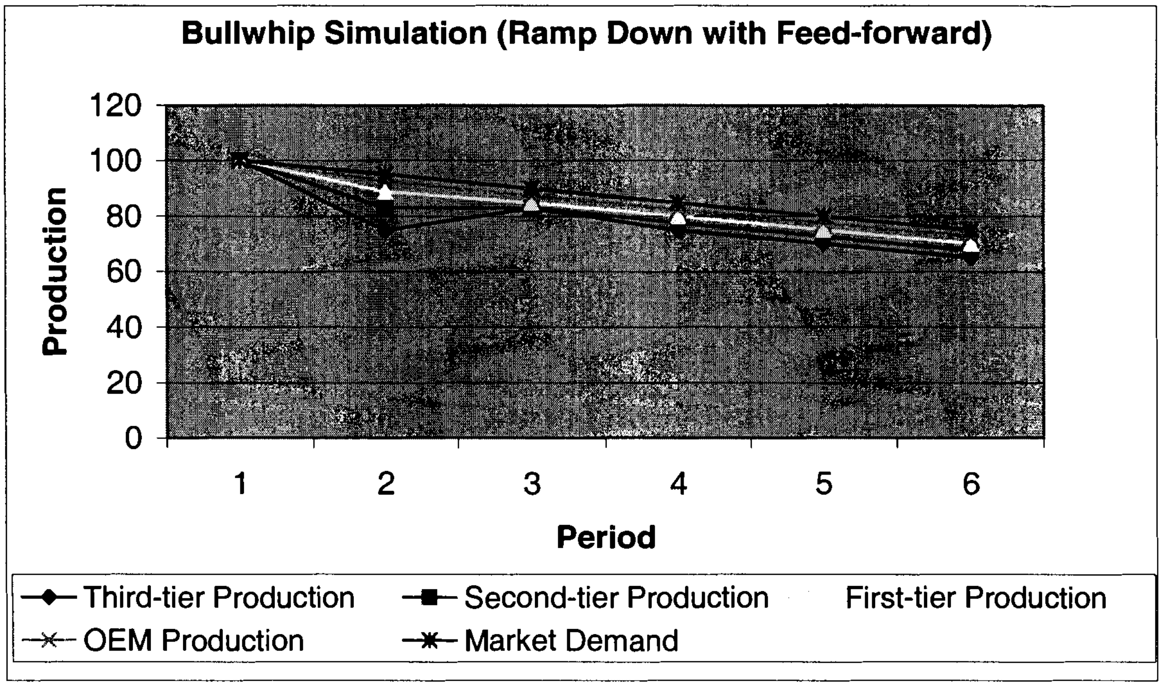


Figure 16 Ramp down simulation with feed-forward

With feed-forward model, the maximum fluctuation in third-tier supplier production corresponding to the 5 units increase in market is only 25 units and regains the same increasing rate as the market demand at the beginning of period 4.

5.2.11 One-period Order Lead Time

The previous examples do not include any time lag between a demand occurring in one part of the supply chain and it being transmitted to its supplier. In practice, there will be such a lag, and this will make the fluctuations even more marked.

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[illegible]			OEM			[illegible]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	[illegible]	[illegible]	[illegible]	Prod-uction	Start Stock	End Stock	[illegible]
1	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	100	100	100	[illegible]
2	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	100	100	100	[illegible]
3	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	100	100	100	[illegible]
4	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	90	100	95	[illegible]
5	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
6	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
7	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
8	100	100	100	60	100	80	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
9	100	100	100	120	80	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
10	20	100	60	90	100	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
11	180	60	120	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
12	60	120	90	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
13	100	90	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
14	95	95	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
15	95	95	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]

Notes:

1. End stock of period n = demand of period n-2 (one-period order lead time)

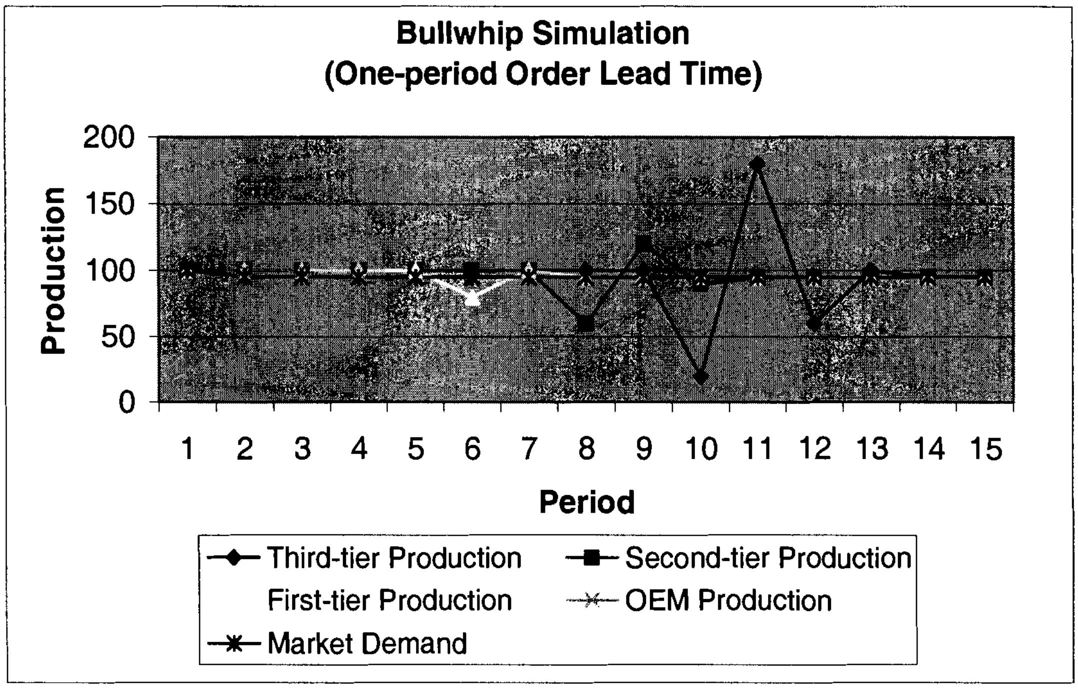


Figure 17 One-period order lead time simulation

In this scenario, the demand decreases by 5 units in one period and stays at this volume. Besides, there will be one period of order lead time. That is, demand placed in period 1 is supposed to be satisfied in period 3.

In the real business situation, the lead time can strengthen the bullwhip effect. In this example, we assume that any order placed in period n will be fulfilled in period n+2.We can see greater fluctuation with lead time than zero lead time. Besides, the 5 units fluctuation in market demand causes 160 units change in the production of third-tier supplier and costs the supply chain 13 periods to regain stability.

5.2.12 One-period Order Lead Time with Feed-forward

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[redacted]	OEM			[redacted]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock		Prod-uction	Start Stock	End Stock	
1	100	100	100	100	100	100		100	100	100	
2	100	100	100	100	100	100		100	100	100	
3	100	100	100	100	100	100		100	100	100	
4	100	100	100	100	100	100		95	100	95	
5	100	100	100	100	100	100		95	95	95	
6	100	100	100	100	100	100		95	95	95	
7	100	100	100	100	100	100		95	95	95	
8	100	100	100	83	100	89		95	95	95	
9	100	100	100	100	89	96		95	95	95	
10	75	100	83	94	96	95		95	95	95	
11	108	83	100	95	95	95		95	95	95	
12	92	100	94	95	95	95		95	95	95	
13	95	94	95	95	95	95		95	95	95	
14	95	95	95	95	95	95		95	95	95	
15	95	95	95	95	95	95		95	95	95	

Notes:

1. End stock of period n = demand of period n-2 (one-period order lead time)

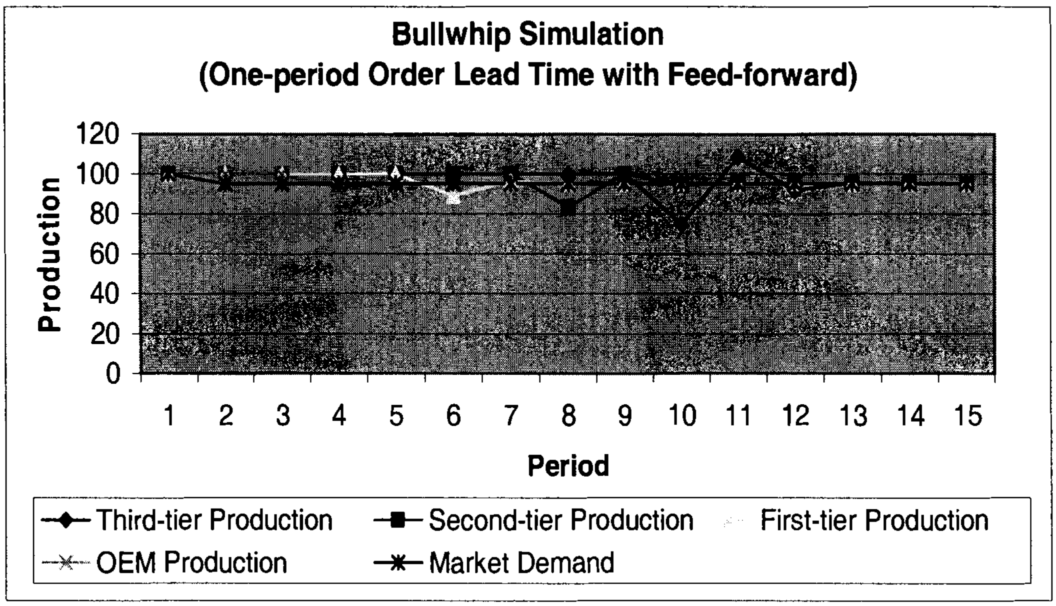


Figure 18 One-period order lead time simulation with feed-forward

With the feed-forward model, the fluctuation of 5 units in the market demand caused the maximum change of 33 units and it takes the supply chain 12 periods to regain stability.

5.2.13 Two-period Order Lead Time

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[illegible]			OEM			[illegible]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock	[illegible]	[illegible]	[illegible]	Prod-uction	Start Stock	End Stock	[illegible]
1	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	100	100	100	[illegible]
2	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	100	100	100	[illegible]
3	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	100	100	100	[illegible]
4	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	100	100	100	[illegible]
5	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	90	100	95	[illegible]
6	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
7	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
8	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
9	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
10	100	100	100	100	100	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
11	100	100	100	60	100	80	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
12	100	100	100	120	80	100	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
13	100	100	100	90	100	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
14	20	100	60	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
15	180	60	120	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
16	60	120	90	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
17	100	90	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
18	95	95	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]
19	95	95	95	95	95	95	[illegible]	[illegible]	[illegible]	95	95	95	[illegible]

Notes:

1. End stock of period n = demand of period n-3 (two-period order lead time)

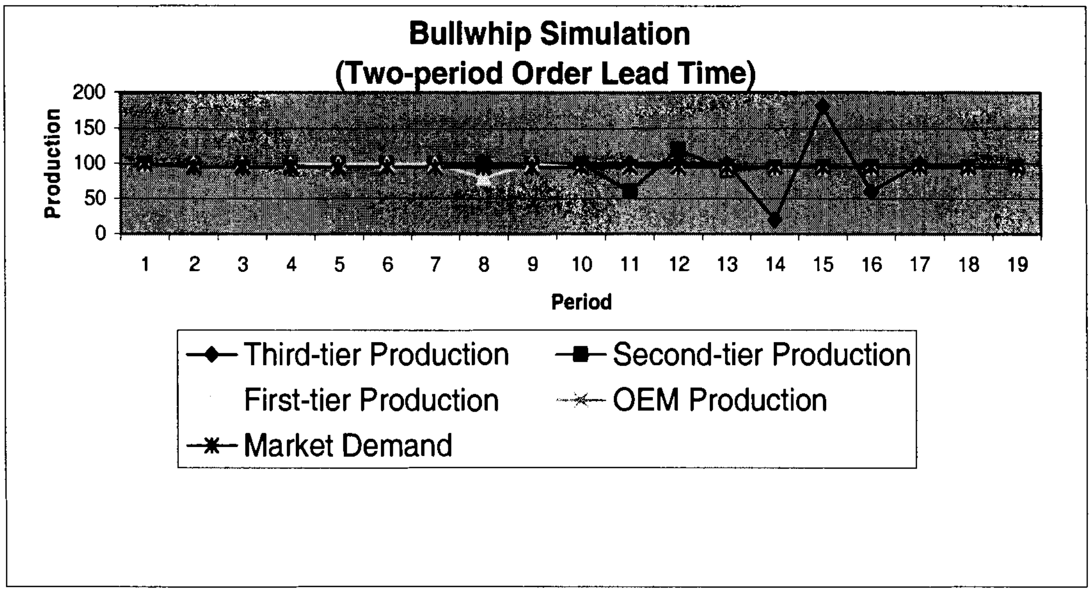


Figure 19 Two-period order lead time simulation

In this scenario, the market demand decreases by 5 units and remains there. Besides, the order lead time is two periods, that is, the demand in period 1 is supposed to be satisfied in period 4.

When the lead time is two periods, the bullwhip effect is greater than that with one period lead time. As it is shown in the table and chart above, we could see that the 5 units fluctuation in market demand will cause 160 units change for the third-tier supplier and cost the supply chain 17 periods to regain stability.

5.2.14 Two-period Order Lead Time with Feed-forward

Bullwhip Simulation

Period	Third-tier supplier			Second-tier supplier			[redacted]	OEM			[redacted]
	Prod-uction	Start Stock	End Stock	Prod-uction	Start Stock	End Stock		Prod-uction	Start Stock	End Stock	
1	100	100	100	100	100	100	[redacted]	100	100	100	[redacted]
2	100	100	100	100	100	100	[redacted]	100	100	100	[redacted]
3	100	100	100	100	100	100	[redacted]	100	100	100	[redacted]
4	100	100	100	100	100	100	[redacted]	100	100	100	[redacted]
5	100	100	100	100	100	100	[redacted]	93	100	95	[redacted]
6	100	100	100	100	100	100	[redacted]	95	95	95	[redacted]
7	100	100	100	100	100	100	[redacted]	95	95	95	[redacted]
8	100	100	100	100	100	100	[redacted]	95	95	95	[redacted]
9	100	100	100	100	100	100	[redacted]	95	95	95	[redacted]
10	100	100	100	100	100	100	[redacted]	95	95	95	[redacted]
11	100	100	100	83	100	89	[redacted]	95	95	95	[redacted]
12	100	100	100	100	89	96	[redacted]	95	95	95	[redacted]
13	100	100	100	94	96	95	[redacted]	95	95	95	[redacted]
14	75	100	83	95	95	95	[redacted]	95	95	95	[redacted]
15	108	83	100	95	95	95	[redacted]	95	95	95	[redacted]
16	92	100	94	95	95	95	[redacted]	95	95	95	[redacted]
17	95	94	95	95	95	95	[redacted]	95	95	95	[redacted]
18	95	95	95	95	95	95	[redacted]	95	95	95	[redacted]
19	95	95	95	95	95	95	[redacted]	95	95	95	[redacted]

Notes:

1. End stock of period n = demand of period n-3 (two-period order lead time)

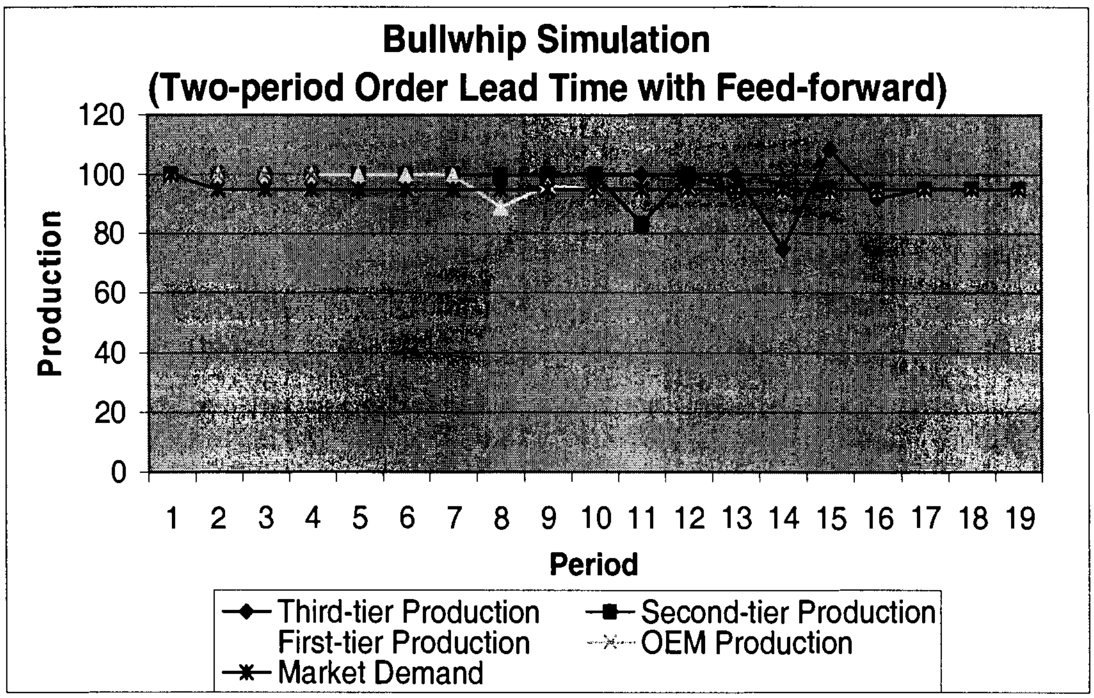


Figure 20 Two-period order lead time simulation with feed-forward

With feed-forward model, the fluctuation in third-tier supplier is 33 units and the time for the supply chain to regain stability is reduced to 16 periods.

5.2.15 Order Batching

Bullwhip Simulation

Period	Manufacturer	Area Distributor	Local Distributor	End User
1	100	50	10	5
2	0	0	0	5
3	0	0	10	5
4	0	0	0	5
5	0	0	10	5
6	0	0	0	5
7	0	0	10	5
8	0	0	0	5
9	0	50	10	5

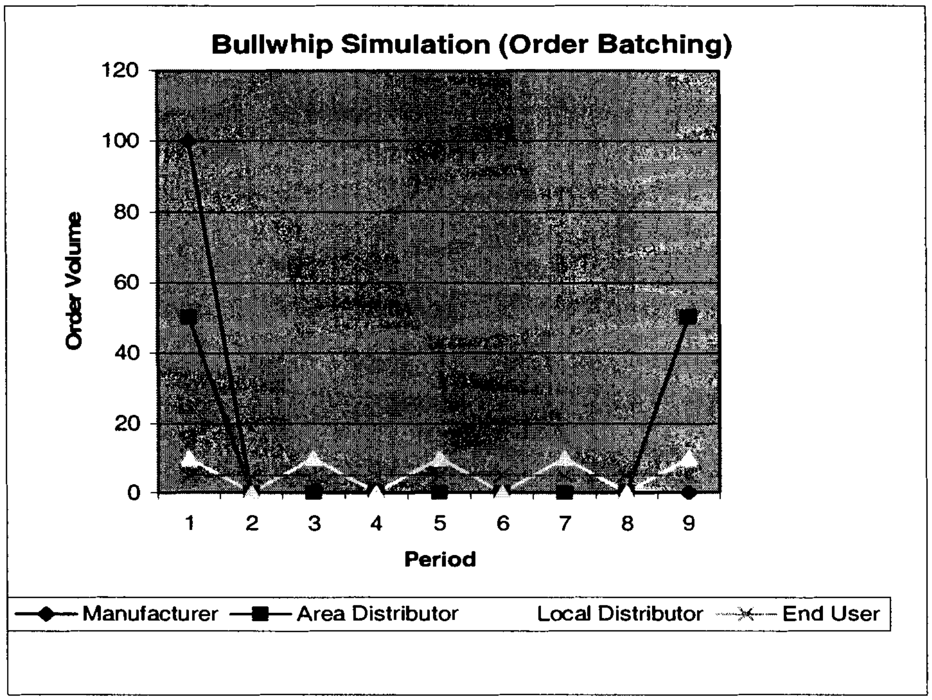


Figure 21 Order batching simulation

The way different parts of the supply chain batch their manufacturing quantities can cause distortions which make production volumes fluctuate in upstream suppliers. Figure 21 shows a simple example to illustrate the effect of order batching.

In Figure 21, there is reasonable steady end-customer demand of 5 units per period. The end customer orders from a local distributor at this rate. However, this local distributor, perhaps because of custom and practice, places bi-period orders with the area distributor- for this part, this is at a rate of 10 units every two periods. The area distributor delivers at this bi-period rate but, to replenish its stock, places orders every 8 periods back to the manufacturer. In Table 2, this involves ordering 50 units in the first period, none in the second to the eighth period and 50 units in the ninth period. (The manufacturer actually makes them in economic batches of 100 units, and so therefore makes them only occasionally).

Order batching is common in supply chain due to high ordering cost and quantity discounts. So the constant market demand still gives rise to the fluctuation of 100 units in the manufacturer's production rate.

5.2.16 Order Batching with Feed-forward

Bullwhip Simulation

Period	Manufacturer			[redacted]	Local Distributor			[redacted]
	Prod-uction	Start Stock	End Stock		Prod-uction	Start Stock	End Stock	
1	100	100	50		10	5	5	
2	-21	50	3		5	5	5	
3	6	3	5		5	5	5	
4	5	5	5		5	5	5	
5	5	5	5		5	5	5	
6	5	5	5		5	5	5	

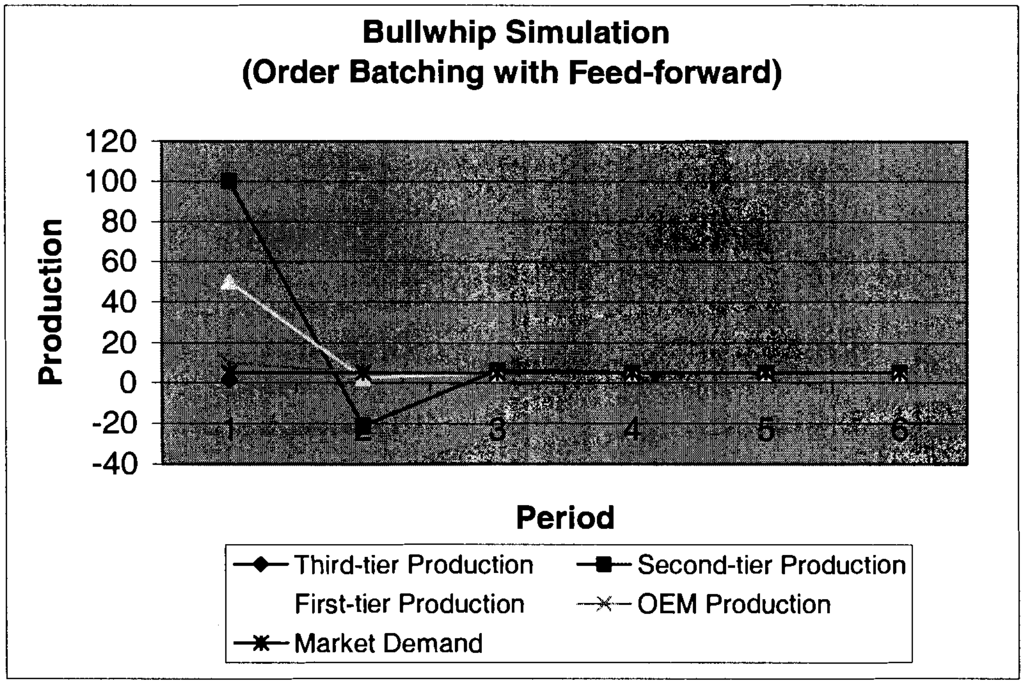


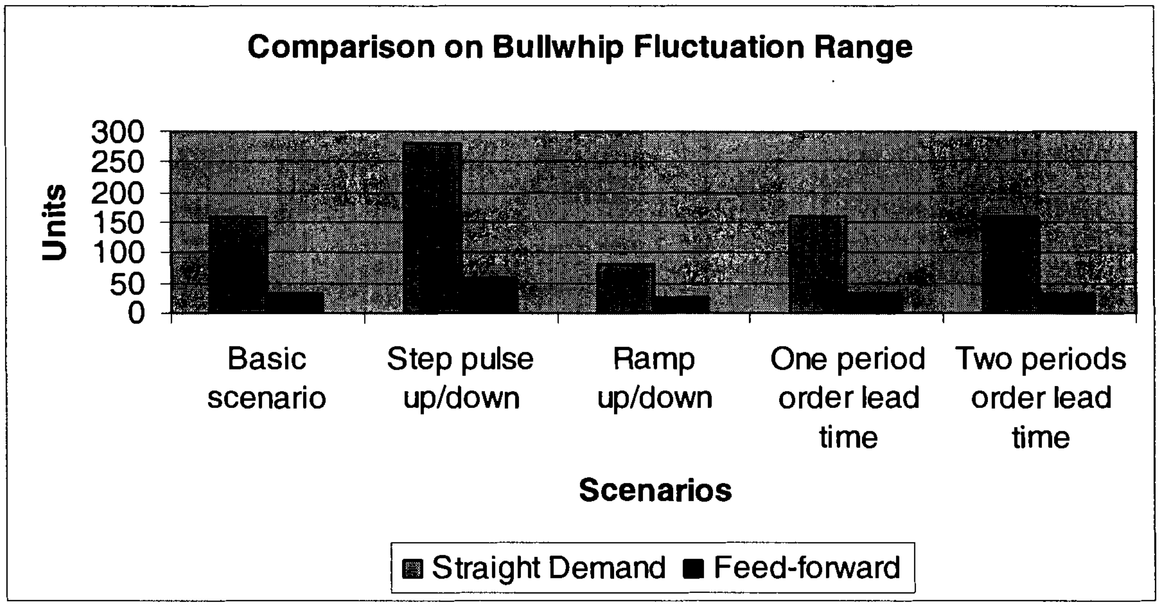
Figure 22 Order batching simulation with feed-forward

In theory, if the manufacturer, area distributor and local distributor pay attention to the market demand from end user, with feed-forward model, they can easily get to 5 units production steadily in period 4. However, the simulation has its limitations. It can not count order cost or shipping cost. Therefore, due to the costs that could not be demonstrated in the simulation, order batching is still common in supply chain.

5.3 Summary

From the simulations and analysis in section 5.2, it does appear that the feed-forward model could reduce the bullwhip effect. Figure 23 illustrates the comparison of the different scenarios.

Scenarios	**Fluctuation Range (unit)**		**Fluctuation Time (period)**	
	Straight Demand	Feed-forward	Straight Demand	Feed-forward
Basic scenario	160	33	5	4
Step pulse up/down	280	59	6	5
Ramp up/down	80	25	5	3
One period order lead time	160	33	13	12
Two periods order lead time	160	33	17	16



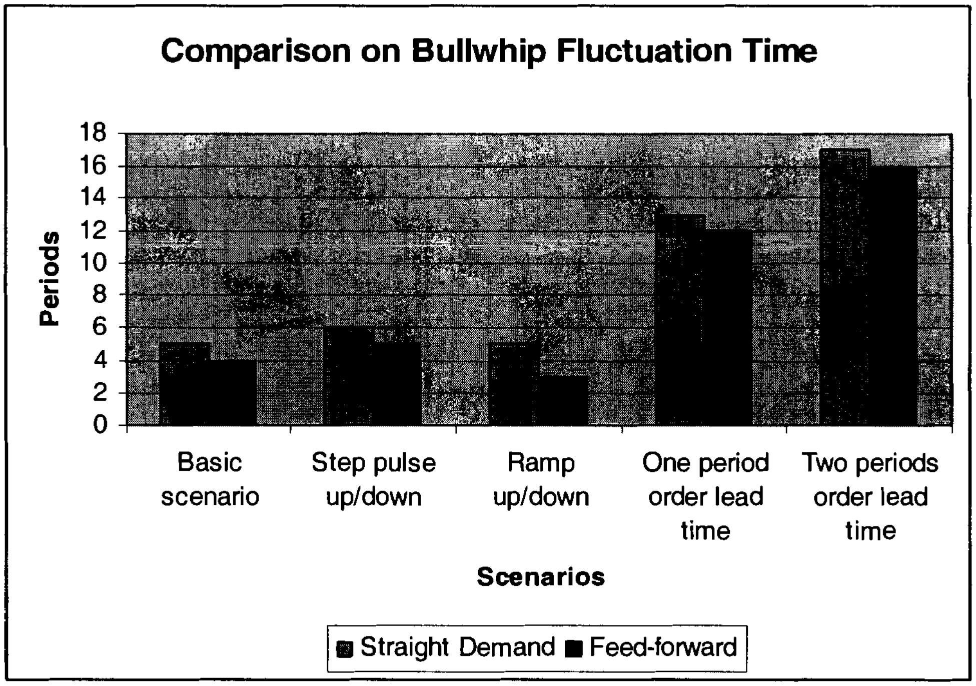


Figure 23 Comparison of straight demand and feed-forward in different scenarios

The feed-forward model is an information sharing model to counter the bullwhip effect. It detects the demand fluctuation in the higher level of supply chain. It then uses calculation weighting scheme to reduce the amplification of the original fluctuation to strengthen the stability of the supply chain.

Feed-forward model has the following advantages:

1. Improve the agility of the supply chain

   Based on the information from simulations, feed-forward model can reduce bullwhip fluctuation time by one period compared with the straight demand model. In the real business world, shortened fluctuation time means more agility in the supply chain. The company can adapt to market demand change more quickly.

2. Reduce inventory cost and human resource cost

   From the data we obtained from the simulations, feed-forward model can dramatically reduce the fluctuation caused by bullwhip effect. In this way, the inventory and production rate are relatively stable. Stable inventory and production rate mean stable inventory cost and human resource cost. The company is less likely to expand inventory, or waste warehouse space, or hire lots of temporary labors during peak periods, or lay off lots of staff when business is low.

Overall, the feed-forward model appears to be a practical model that could aid in countering bullwhip effects and build a more robust supply chain consistent with market dynamics.

6 Conclusion and Recommendations

This thesis addresses the bullwhip effect in supply chain and its causes. We have proposed a feed-forward approach to mitigating bullwhip effects. The 16 simulations developed are categorized in Table 3 below according to the bullwhip phenomenon they are intended to address.

No.	Simulation	Causes
1-2	Basic Bullwhip Effect Simulation	Demand signal processing
3-6	Step Pulse Up/Down	Demand signal processing Price variations Rationing game(limited) Behavioral issues(limited)
7-10	Ramp Up/Down	Demand signal processing
11-14	Lead Time	Demand signal processing
15-16	Order Batching	Order batching(limited)

Table 3 Bullwhip simulations and causes

With the information gained from the simulations, we find that the feed-forward model shows promise in countering the bullwhip effect. Feed-forward appears particularly useful when system wide information sharing is possible. If this can be achieved then it appears that better channel alignment and greater operational efficiencies can be achieved.

6.1 Information-sharing

One of the reasons for the fluctuations described in the simulations earlier was that each operation in the chain reacted to the orders placed by its immediate customer. None of the operations had an overview of what was happening throughout the chain. If information had been available and shared throughout the chain, it is unlikely that such wild fluctuations would have occurred. It is sensible therefore to try to transmit information throughout the chain so that all the operations can monitor true demand, free of these distortions. So, for example, information about market demand, shipping problems, shortages and so on, can be transmitted down the chain so that downstream customers can modify their schedules and sales plans accordingly and upstream suppliers can arrange their inventory.

One obvious improvement would be to make information on market demand available to each level of supply chain. The feed-forward model introduced in this thesis attempts to do this. Demand data from downstream customers are transmitted to the OEM, supplier, manufacturing operations that form its supply chain.

6.2 Channel Alignment

Channel alignment means the adjustment of scheduling, material movements, stock levels, pricing and other sales strategies so as to bring all the operations in the chain into line with each other. This goes beyond the provision of information. It means that the systems and methods of planning and control decision making are harmonized through the chain. With the feed-forward model, upstream suppliers can get market information early, and adjust production, stock levels and orders with an overview of the entire supply chain.

6.3 Operational Efficiency

Operational efficiency means the efforts that each operation in the chain can make to reduce its own complexity, to reduce the cost of doing business with other operations in the chain and decrease throughput time. The cumulative effect of these individual activities is to simplify throughput in the whole chain.

One of the most important approaches to improving the operational efficiency of supply chains is to speed up the flow of materials down the chain and the flow of information back up the chain. With the help of feed-forward model, the information can travel fast to the upstream up the chain. On the other hand, the quick information flow will contributes to more efficient material flow.

Overall, it appears that such a feed-forward model can be a framework that would be useful to counter some causes of the bullwhip effect and limit their impact.

Based on the information we obtained from the simulations, we provide the following initial recommendations:

1. Enhance information sharing among different levels in supply chain with feed-forward model: Feed-forward model can detect the demand fluctuation and detriment it to prevent the fluctuation from totally entering the supply chain. Based on the data in the simulations, we find that the feed-forward model can greatly reduce the bullwhip effect in both the fluctuation volume and fluctuation time when countering the impact of demand signal processing, price variations, rationing game, and behavioral issues.
2. Make efficient and agile supply chain with feed-forward model: The ordering lead time and lead time variability are the main factors for supply chain efficiency and

agility. Feed-forward model can reduce the fluctuation volume and fluctuation time caused by lead time.

3. Find appropriate weights in real situations: To simplify our simulation, we arbitrarily set simple values to the parameters in feed-forward model. However, in reality it is typical to select weights by having an objective function minimized by searching over a range of weights for the system. It is easy to imagine improved parameters being identified by utilizing techniques such as nonlinear optimization methods, quadratic programming, goal programming or multivariable searching, depending on the particular supply chain network under study.

Appendices

Appendix 1: "The Firm" Business Game/Simulation

A 1.1 Introduction

"The Firm"[14] business game is a generic simulation framework for decision making (over the Internet) in supply chains. The system is primarily based on parts-implosion industries, in which business processes use different types of raw materials as inputs, and assembly them into one final product, such as manufacturing processes. This is a common structure seen in the automotive as well as in many other industrial scenarios.

A1.2 Functions

"The Firm" system is a very comprehensive system that is designed to emulate most of the business decision-making processes in any such business environment having extensive, global supply chain requirements. These include asset acquiring/management, inventory management, sales management, ordering management, invoice management, logistics, cash flow, equity and debt financing accounting management and so on.

Appendix 2: Just In Time and Kanban

Just In Time (JIT)[15] is an inventory strategy implemented to build a "pull" model supply chain, in which the consumer requests the product and "pulls" it through the delivery channel. Therefore, JIT can improve the return on investment of a business by reducing in-process inventory and its associated costs. The process is driven by a series of signals, called "kanban"[16], which tell production processes when to make the next part. When implemented correctly, JIT can lead to dramatic improvements in a manufacturing organization's return on investment, quality, and efficiency.

Kanban is the signaling system through which JIT is achieved. The purpose of kanban is to trigger the movement, production, or supply of a unit in a factory. Kanban became an effective tool to support the running of the production system as a whole. In addition, it proved to be an excellent way for promoting improvements because restricting the number of kanban in circulation highlighted problem areas.

Kanban, as a method of implementing JIT has proven to be very valuable in preventing large buildups of inventory since only what is needed is produced (by pulling) rather than permitting upstream production units "push" more inventory downstream than what is immediately needed. Its effectiveness has been demonstrated in environments where production units are closely linked, usually in the same plant, so that a "Kanban pull" system can be coordinated. Its effectiveness in globally dispersed environments is more uncertain. While it remains a topic of further research, it is likely that utilizing a feed-forward information system as described in this paper, in conjunction with a "pull" flow system would result in a system more closely akin to just-in-time.

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