INFORMATION-SHARED POSTPONEMENT STRATEGIES IN SUPPLY CHAIN MANAGEMENT

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SUMMARY

Postponement strategy is one of the effective strategies for improving a supply chain's responsiveness to increasing product variations and shortening product life cycle. Over time, the scope and application of postponement has expanded to various aspects in the supply chain. Recent research shows that information sharing strategy plays an important role on postponement implementation. From a supply chain dynamic model developed in this study, it is also easy to find the significant dynamic interaction between information sharing strategy and postponement strategy in a context of supply chain management. However in research detailed cost-benefit analyses on various forms of postponement strategies and information sharing strategies has not been pursued yet. This gap motivates us to consider further into the characteristics of information sharing and postponement strategies and design comprehensive experiments to analyze them two in a supply chain network. This study also extends the extant of academic literature on both postponement strategies and information sharing strategies.

In this study, we define the situation in which both information sharing and postponement are available as information-shared postponement. The research was carried out via simulation. A simulation system was developed via GPSS to model a three-tier linear supply chain network. Sensitivity analyses of system variables were carried out for in-depth understanding of such information-shared postponement. ANOVA tests were used to examine the significance of results.

This study provided a detailed analysis of the correlations of postponement and information sharing strategies on supply chain performance and illustrated clearly how these two strategies would affect the benefit of inter-organizational collaboration. Results showed that different information sharing strategies do not perform equally well on all performance measures in a supply chain. Managers should choose suitable information sharing strategies according to the characteristic of their postponement types and system environments.

The benefits of information-shared postponement strategies are significantly influenced by the trended demand. In a market with an increasing trend on product demand and such trend is relatively high, shipment information sharing becomes a dominating strategy for manager to consider in all postponement-type supply chain, regardless the centrality of the supply chain itself. When the market demand turns to decrease, demand information sharing is the choice.

However such benefits from information-shared postponement strategies are not equally contributed to all tiers in a supply chain. For example, the front tier does not enjoy significant benefits in most information-shared postponement environments. The information provider cannot improve, sometimes even reduces, its performances by sharing out the shipment information. These “unfair” treat may become a barrier for tiers to share information in a supply chain. In practice, sometimes the organizations in a supply chain may have different incentives to optimize its performances locally and may be wary of the possibility of other partners abusing information to reap more benefit. As a result, it is valuable to find out the beneficial way to share the minimum amount of necessary information with partners during information systems construction or collaboration negotiation. This study can help organizations achieve this goal.

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CHAPTER 1 INTRODUCTION

Supply chain management (SCM) is "a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouse, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right times, in order to minimize system-wide costs while satisfying service level requirement" (Simchi-Levi et al., 2000). Due to increasing global competition, shorter product life cycle, increasing product variety and higher customer expectations, all business enterprises today are required to develop their inter-organizational collaboration network tightly and to create a smooth material, information and financial flow along the supply chain. For example, Compaq estimated a sale loss of 0.5- to 1-billion in 1994 because of stock-outs on its laptop and desktop computers (Martin, 1998) and the Efficient Consumer Response (ECR) report estimated a potential 30-billion opportunity from streamlining the inefficiencies of the grocery supply chain (Lee et al., 1997a).

Supply chain could be a complex network of facilities and organizations with conflicting objectives, to manage it efficiently and economically there are two main concerns in SCM: to facilitate the smooth and efficient flow of products down the value-added chain at the least cost, and to match the supply with the market demand (Bradley and Nolan, 1998).

Expanding product variety, motivated by requirements from producers (Lancaster, 1999) and consumers (Chong et al., 1998; Kahn, 1999), is one major strategy for a supply chain competing in both regional and global markets (Lee and Tang, 1997). However, the proliferation of product variety brings many consequences that challenge the efficiency of material flow in a supply chain. First it increases the number of variable patterns in purchasing, manufacturing, inventory, distribution and marketing management, which consequently increase the forecasting complexity but reduce the forecasting accuracy. To increase the accuracy of the forecast, research shows that moving the forecasting point closer to the differentiation point is one possible solution (Bitran et al., 1986; Fisher and Raman, 1996). Second, the variety of product in a manufacturing process means that more operation stages, at which certain features are added, are needed. As more procedures are required, correlative manufacturing costs increase. Without optimization, costs usually increase at a rate of *25%* to *35%* per unit each time the product variety doubles (Stalk, 1988). One suggested solution is to redesign the product/process to delay the differentiation point, such as using vanilla boxes (Swaminathan and Tayur, 1998, 1999). Thirdly, because the demand of each end product varies over time and the exact required number of products is often unavailable before manufacturing, inventory variability and holding cost increase as the product variety increases. As a result, a later decision point in time, which is usually set at the product differentiation point in time, is seen as one of the effective determinants for solving this problem. In summary, a delayed differentiation point in production is a possible solution to counteract the consequences brought by increasing product variety and how to delay the time point becomes an important consideration to organizations.

Due to intense competition, a high customer service, i.e. an efficient material flow from suppliers to their customers, becomes essential in SCM. However maintaining such a given customer level may be costly. First, there is the tradeoff between economies of scale and mass-customization in production: On one hand, implementing production plans based on economies of scale can optimize manufacturing cost, reduce lead-time but increase inventory cost of overstocking. On the other hand, build-to-demand mass-customization reduces inventory holding cost and risk of overstocking but increases lead-time, manufacturing cost and the danger of stock-outs. Second, conforming to customer requirement both in quantity and quality while maintaining a certain service level affects the efficiency of the whole SCM. If the supply of a certain product exceeds its demand, there are unwanted inventory costs throughout the supply chain; if demand exceeds supply, there are lost sales that possibly lead to the loss of market share. Thus, designing products and processes so that high customer service and supply chain efficiency can be simultaneously met becomes important in SCM. Postponement strategy defined as delaying the product differentiation point to the latest possible time (Lee, 1993) can be an effective way to achieve this goal. For example, this year a joint executive study carried out by CGE&Y (Cap Gemini Ernst & Young U.S.), Oracle and APICS surveyed more than *350* supply chain professionals at both large and mid-sized companies across various industries including Aerospace, Automotive, Education, High-Tech, Healthcare, Retail, Telecommunications etc. and found that the majority of companies that had implemented postponement strategies were realizing significant improvements in customer satisfaction, inventory costs and more accurate demand forecasting.

Matching supply with market demand is the other concern in SCM. In the past decade many models on inventory and production control have been developed and proven to be optimal solutions for single stages given specific assumptions. However, such localized optimizations do not work well, sometimes even become worse, in a supply chain (e.g. Lee et al., 1997a, Baganha and Cohen, 1998, Chen et al., 1998, and Fransoo and Wouters 2000). Researchers explored this operational puzzle and found that one major reason was lack of information or misconceptions of information feedback (e.g. Sterman, 1989 and Lee et al., 1997b). The situation becomes worse when the information distortion at one tier increased as tiers moved upwards in a chain. To manage this challenge, one suggestion is to share timely and useful information in the supply chain so that members can reduce the information distortion and consequently reduce the inventory costs and improve service by utilizing information.

Since the postponement implementation requires product and/or process redesign, the nature of demand after postponement usually changes as well, which in turn would affect the information value in a supply chain. For example, Hewlett-Packard Inc. (HP) used a universal power supply, which could automatically adapt to either *110* or *220* volts (i.e. the different power requirements in different regions over the world), to replace the original separate power suppliers in its LaserJet printers (Feitzinger and Lee, 1997). As a result, the different demand on that product in different countries/regions, due to specific power requirements, need not be treated separately anymore and the plant could therefore determine the total combined amount of that product, rather than the separate amount required from different regions, before manufacturing. At the analytical level, the demand parameters of the product, i.e. the demand variance and correlations in between, from various regions were pooled together for forecasting and decision-making. Therefore it became reasonable to argue that the information value of forecasting demand in each region market is reduced after such postponement while the accurate and timely shipment information from the plant to each market might become more desired and valuable to the company.

As various works on postponement and information sharing strategies have been carried out separately, recent research shows that information sharing strategy plays an important role on postponement implementation. One observation is that the value of postponement is the value of information (Whang and Lee, 1999): as time passes, more information about the customer demand would be acquired. Thus as the forecasting point moved closer to production period, demand forecast quality would improve and the quality of decision would be optimized. Other research, such as Anand and Mendelson, 1998, Gavirneni and Tayer 1998, and Zhang and Tan, 2002, also proved the information sharing strategies could play a paramount effect on implementing an effective postponement. However detailed cost-benefit analysis on various forms of postponement strategies and information sharing strategies has not been pursued yet. This gap motivates us to consider further into the characteristics of information sharing and postponement and to design comprehensive experiments on analyzing them in the context of a supply chain network.

In summary the goal of this thesis is to study the impact of information sharing on supply chains that implement different types of postponements. We compare the performance of such supply chains with different available information to discover how information strategies influence the effectiveness of postponement strategies. In this study, we defined four different types of postponement situations, i.e. form, time, and place, together with a no-postponement case for comparison purpose, after categorizing postponement strategies. Later, three types of information strategies are chosen from perspective of channel focus, they are order information sharing, demand information sharing and shipment information sharing. Altogether six measurements, including service level, fill rate, order leadtime, absolute error of service level, dynamic effect and inventory cost, are applied to under the supply chain performances.

This study was carried out via simulation. A simulation system was developed via GPSS to model a three-tier linear supply chain network consisting of a retailer, a manufacturer and a supplier. This setting represents a typical production-inventory system. The behaviors of the chain members were periodically activated, observed and recorded for statistical analysis of the combined impact of various information-shared postponement strategies in a supply chain network. Sensitivity analyses on four system variables, i.e. demand correlation, demand variance, production leadtime and service level, were carried out for in-depth understanding of the managerial implications of such combined effects. ANOVA tests were used to examine the significance of results.

In this way, this study provided a detailed analysis of the correlations of postponement and information sharing strategies on supply chain performance and clearly illustrated of how these two strategies would affect the benefit of inter-organization collaboration and information system (IS) construction, i.e. given an existing postponement environment, how an organization or a supply chain would choose the information strategy that is most beneficial. In practice, sometimes the organizations in a supply chain may have different incentives to optimize its performances locally and may be wary of the possibility of other partners abusing information to reap more benefit. As a result, it is valuable to find out a beneficial way to share the minimum amount of necessary information with partners during information systems construction or collaboration negotiation. This study can help organizations achieve this goal.

The thesis is organized as follows: Chapter 2 first introduces the concept and problems in supply chain management and then provides the background of postponement strategies and information sharing strategies in a supply chain network, including their concepts, applications, classifications and values in SCM. In Chapter 3, research question about information-shared postponement strategies in this study are raised, followed by a methodology introduction. Chapter 4 describes the experiments design for the information-shared postponement in a supply chain, including the supply chain structures and parameters settings, followed by the simulation model implementation and its validation. Chapter 5 reports the simulation results, describes and explains the combined behavior of strategies in a supply chain. Some possible improvement and future work are discussed in Chapter 6.

CHAPTER 2 LITERATURE REVIEW

To clearly understand the information-shared postponement strategies, in-depth literature review is carried out in this study.

2.1. The Concept Of Supply Chain And Supply Chain Management

A supply chain is a system of business enterprises that links together to satisfy consumer demand (Riddalls et al., 2000), or a network of autonomous or semi-autonomous business entities collectively responsible for the procurement, manufacturing and distribution activities associated with one or more families of related products (Swaminathan et al., 1998). In this study, the common definition that a supply chain is a system of suppliers, manufacturers, retailers, and customers where materials flow downstream from suppliers to customers and information flows in both directions (Ganeshan et al., 1998) is used since it highlights several important elements that this study focuses on, i.e. the material flow and the information flow. The following Figure 2-1 represents a typical supply chain.

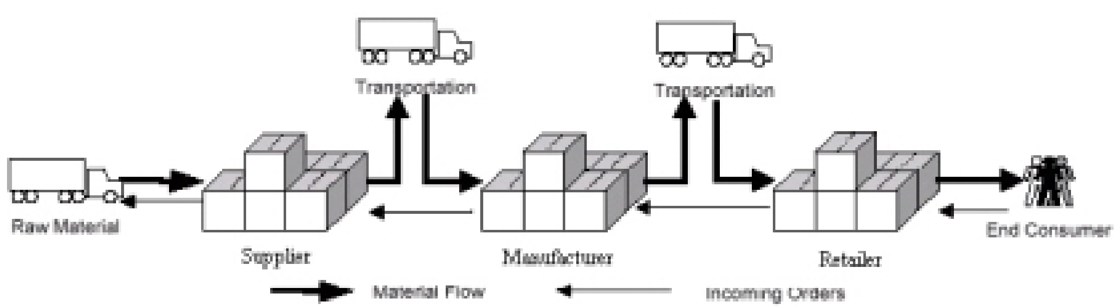

Figure 2-1: A supply chain diagram

The supply chain could be a complex network of facilities and organizations with conflicting objectives. To manage it efficiently and economically a set of approaches is utilized to efficiently integrate suppliers, manufacturers, warehouse, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right times, in order to minimize system-wide costs while satisfying service level requirement (Simchi-Levi et al., 2000). These managerial approaches form supply chain management (SCM) that was first introduced by Houlihan (1985).

Due to increased global competition, shorter product life cycle, increased product variety and higher customer expectations, all business enterprises today are required to develop their inter-organizational collaboration network and to create a smooth material, information and financial flow along the supply chain. Research also proves that inter-organizational collaborations could benefit the supply chain more than local optimization within each organization. For example, Cohen and Lee (1988) presented a comprehensive model framework for linking decisions and performance throughout the production-distribution supply chain. Towill et al. (1992) reviewed dynamic operations of supply chains via a simulation model. Authors found that the improvement made possible by Just-in-Time (JIT) operation of an individual business could be negated by the failure to design and manage the supply chain dynamics as a total system. Henig et al. (1997) showed that the difference in costs could be significant when comparing the costs of suboptimal policies for each tier to those of the optimal inventory policy for a supply chain. Graves et al. (1998) developed a new model for studying requirements planning in a multi-stage production-inventory supply chain to capture some of the key dynamics in the planning process. The results proved the significant value of optimizing the supply chain as a whole rather than sub-optimizing each tier.

2.2. Challenges In SCM And Suggested Solutions

There are two main concerns in SCM: to facilitate the smooth and efficient flow of products down the value-added chain at the least cost and to match supply with market demand (Bradley and Nolan, 1998). For example, Lederer and Li (1997) found that a faster, lower variability and lower cost firm always had a larger market share in the competition between firms that produced goods for customers sensitive to delay time. Robinson and Satterfield (1998) argued that the interactions among a firm's distribution strategy, market share, and distribution costs were an important consideration in the design of supply chain networks.

Expanding product variety, caused by producer-based motivation (Lancaster, 1999) and consumer-based motivation (Chong et al., 1998; Kahn, 1999), brings many consequences to the efficiency of material flow in SCM. First of all, the proliferation of product variety firstly increases the amount of variable patterns in purchasing, manufacturing, inventory, distribution and marketing management, which makes demand forecasting more complex and usually results in larger forecasting error. For example, Srinivasan et al. (1994) found that shipment performance degraded substantially due to increases in part variety and trading partners from diverse industries. Second, the variety of product in a manufacturing process reduces the benefit from economies of scale in production. As more procedures are required, correlative manufacturing costs increase. Without optimization, costs usually increase at a rate of 25% to 35% per unit each time variety doubles (Stalk, 1988). Furthermore, increased production complexity makes the manufacturer's service level more difficult to maintain. Third, product variety increases the complexity of inventory management: to cope with increasing demand complexity and larger forecasting error, tiers usually use the inventory as the buffer between the production line and the demand and naturally build up more the safety stock that results in more holding cost paid for the redundant inventory. However, without a good match of demand and supply, a less efficient inventory management generally reduces tier's service level to satisfy customer's demand. If the loss of customer's willingness to purchase can be quantified into a penalty cost format, such cost is negatively correlated with tier's service level, i.e. the smaller service provided, the more loss of sale occurs which results in more penalty cost. That is also how the total relevant cost at one tier is influenced by these cost factors, including inventory cost, production cost and penalty cost. We can draw the diagram to demonstrate this dynamic impact of product variety on a manufacturer, as shown in Figure 2-2.

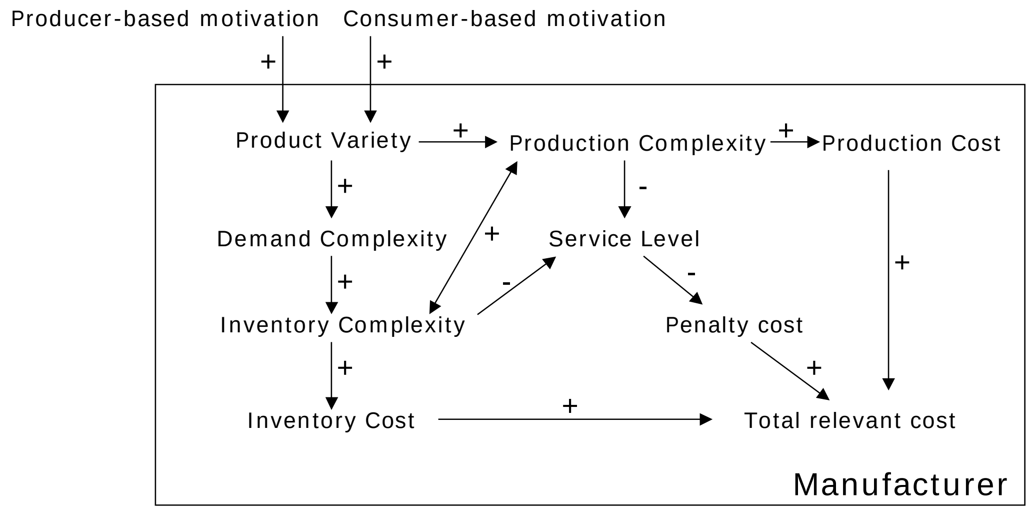

Figure 2-2: The dynamic impact of product variety in a manufacturer. The arrow shows item A has an impact on item B. Plus stands for a positive impact, while subtraction sign means a negative impact.

In SCM, one member's behavior will affect its successive partners in several ways. Firstly, one member's inventory complexity aggravates its order problem that can affect its upper tier's performance since lower tier's order is one important type of upper tier's demand information. Secondly, conforming to customer requirement both in quantity and quality while maintaining a certain service level affects the efficiency of the whole supply chain management. As upper tier's service to its lower tier consumer worsens, the shipment becomes more uncertain, which consequently affects the lower tier's inventory management. Similarly, the lower tier's service level influences its shipment to its customers and consequently the customers' inventory management. The affected inventory management will increase the tier's order distortion on real demand. Finally, this impact returns to the upper tier when it makes decisions based on the lower tier's order.

In research, several studies have pointed out the dynamic effect of how one tier's ordering, inventory, production, and shipment behaviors would affect other tiers and the whole supply chain. Stenger (1996) stated that the effective planning and control of inventories in multi-echelon operations became difficult in modern manufacturing organizations because the lack of coordination between tiers frequently led to excessive inventories both in the organizations and throughout the supply chain. Authors suggested managers to understand the supply chain dynamic before making inventory decision and the inventory decisions should be made within the context of the efficient functioning of the entire supply chain. Levy (1997) suggested two key elements inside the supply chain dynamic: design for manufacturing and low defect levels stabilized the supply chain. Bhaskaran (1998), via simulation, found that stable production schedules were important when managing supply chains because they helped control inventory fluctuation and inventory accumulation and the failure to control schedule instability resulted in high average inventory levels in the system. In summary, the following Figure 2-3 clearly describes how the dynamic impact of product variety extends from a single tier to a whole supply chain.

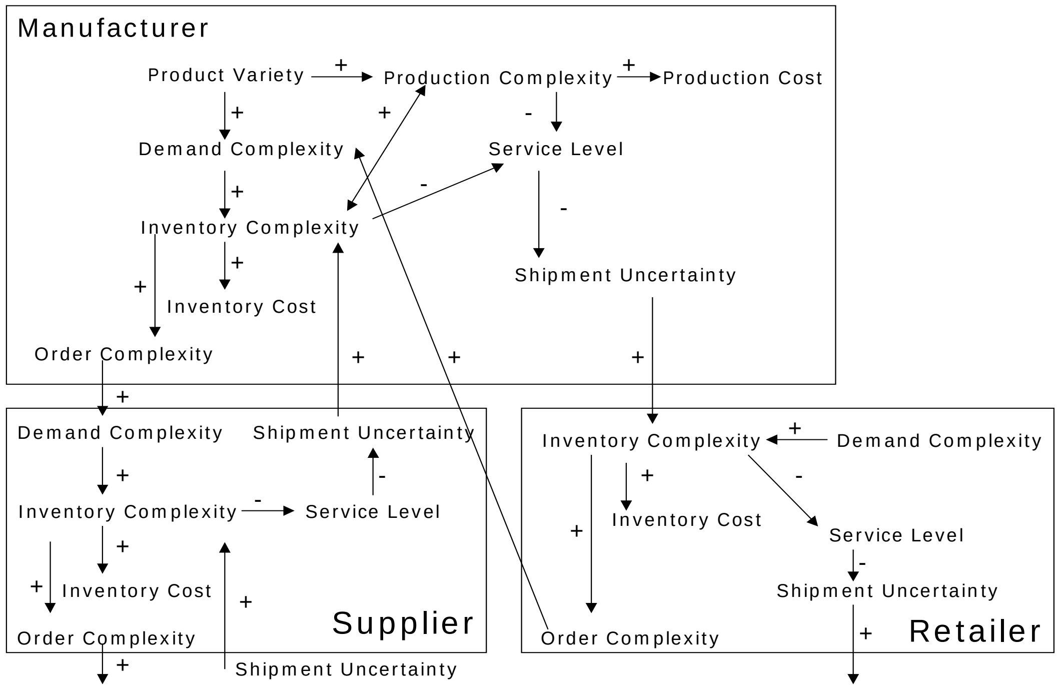

Figure 2-3: The supply chain dynamics. The arrow shows item A has an impact on item B. Plus stands for a positive impact, while subtraction sign means a negative impact.

The problem becomes even worse when there is a material delivery delay or an information transmission delay among transactions, which unfortunately often occurs in practice. For example, Lee and Billington (1992) mentioned several real-world cases in which a manufacturer usually took more than *1* week to inform a customer of a shipment date while another manufacturer shipped more than *30* percent of its orders after the promised date and *40* percent of its actual shipment dates differed from the promised date by more than *10* days. Levy (1997) also stated that the rapid flow of goods and information in production was costly and difficult to achieve.

However, postponement, defined as delaying the point of product differentiation in a production process to the latest possible time, has been proven to be an effective strategy to resolve the problem caused by product variety. For example, Zinn and Bowersox (1988) showed that there was a cost advantage in postponing the distribution of a substantial number of products and authors claimed that the principle of postponement offered an opportunity for management to improve the productivity of physical distribution systems by reducing cost associated with anticipatory distribution. Lee and Tang (1997) evaluated how different types of postponement strategies benefited a supply chain. Many industries also have embarked on reengineering efforts to improve the efficiency of their supply chains. CGE&Y, Oracle and APICS (2003) surveyed more than *350* supply chain professionals at both large and mid-sized companies across various industries and found that the majority of companies that have implemented postponement strategies are realizing significant improvements in customer satisfaction, inventory costs and more accurate demand forecasting.

An important challenge arising from matching supply with demand in SCM is demand distortion, i.e. the demand variability increases when transferring from the downstream organizations to the upstream organizations along a supply chain, which worsens tier's performance (Lee et al., 1997b). As shown in the dynamic effect of supply chain, lower tier's distorted demand will affect upper tier's inventory and production decision. One famous example of its outcome is called Bullwhip Effect, which was first used by the Logistics Executives at Proctor and Gamble (P&G) when they were examining the order of one of their best selling products, Pampers disposable diapers (Lee et al., 1997a, 1997b). After that bullwhip phenomenon has been widely recognized in many diverse markets. A "Beer Game" experiment, a famous example of bullwhip effect and first developed in the 1960s at the Massachusetts Institute of Technology, simulated a simple inventory management task and clearly indicated the whole process of information distortion (Kimbrough et al., 2002).

The demand distortion, or bullwhip effect, becomes an important challenge in SCM for several reasons. First, the increased order variability requires each supply chain member to hold excessively high and variable inventory levels in order to meet a boom-and-bust demand pattern. Second, despite the overall overstocking throughout the supply chain, the lack of synchronization between supply and demand leads to a very high inventory at certain times and complete stock-out at other times. Third, the bullwhip effect increases not only the physical inventories but also the operating costs. Poor demand forecasts based on the distorted orders result in erratic capacity planning and production schedule. Therefore, the bullwhip effect should be minimized.

Because one main cause of bullwhip effect is the unavailability of accurate market information in the upstream tiers of a supply chain, sharing useful and timely information in a supply chain has been proven to be an effective approach to reduce the demand distortion, or bullwhip effect, and improve members' decisions on inventory and production. The goal of information sharing is to better match supply with demand so that the information distortion, and consequently the associated costs, can be reduced. For example, Towill et al. (1992) found that the supply chain integration with exchange of information was as beneficial as leadtime reduction throughout the supply chain via JIT. Srinivasan et al. (1994) found that increasing vertical information integration using EDI could enhance suppliers' shipment performance. O'Brien and Head (1995) proved the benefit of information sharing that linked all participants in JIT production. Fisher and Raman (1996) studied how sharing real customer demand could reduce the cost in upper tiers in a supply chain. Gavirneni et al. (1998) found information was most beneficial at moderate variances at higher capacities in a supply chain. In summary, we can use the following diagram Figure 2-4 to describe the respective impacts of postponement strategy and information sharing strategy on supply chain dynamics.

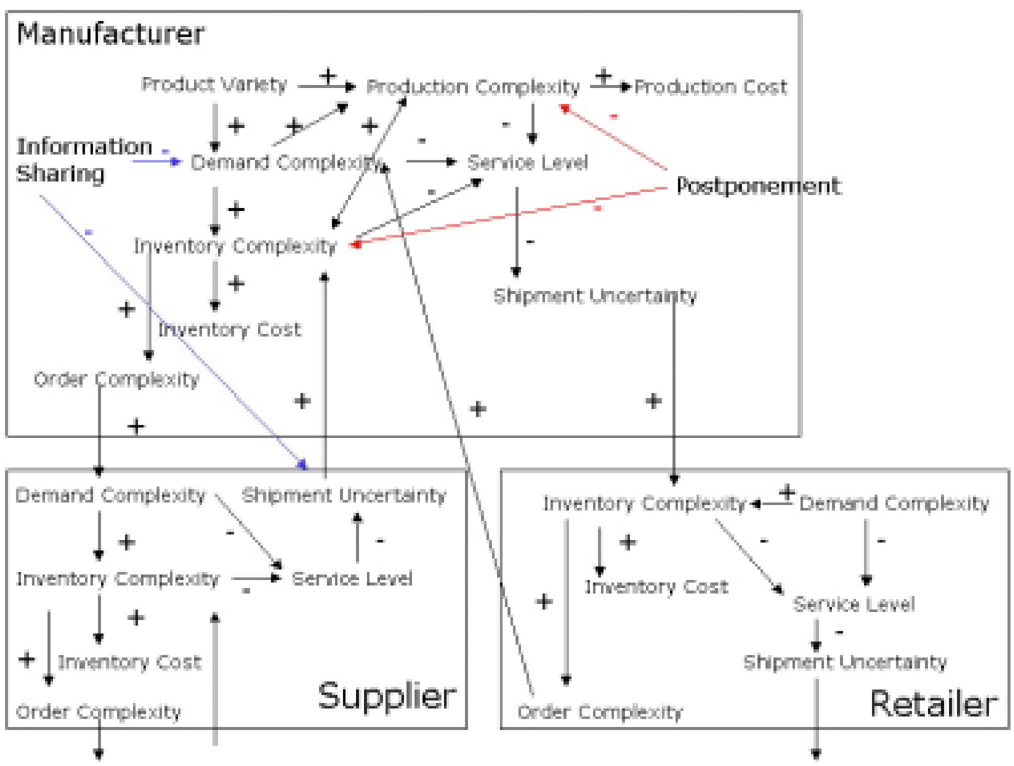

Figure 2-4: The impacts of postponement strategy and information sharing strategy on the supply chain dynamics. The arrow shows item A has an impact on item B. Plus sign stands for a positive impact, while subtraction sign means a negative impact.

Recent research shows that information sharing strategy plays an important role on postponement implementation. One observation is that the value of postponement is the value of information (Whang and Lee, 1999): as time passes, more information about the customer demand would be acquired. Thus as the forecasting point moved closer to production period, the quality of demand forecast and order decision would be improved. Other research, such as Anand and Mendelson (1998), Gavirneni and Tayer (1998), and Zhang and Tan (2002), also proved the information sharing strategies could play a paramount role in implementing an effective postponement. From the dynamic diagram, it is clear how the postponement and information sharing strategies directly or indirectly impact on the production complexity, demand complexity, inventory complexity and consequently the whole supply chain. It is quite obvious that these two strategies dynamically influence, probably may strengthen, neutralize or weaken, each other in a supply chain context. However detailed cost-benefit analysis on various forms of postponement strategies and information sharing strategies has not been pursued yet. This gap motivates us to consider further into the characteristics of information-shared postponement strategy and to design comprehensive experiments on analyzing them in the context of a supply chain network.

2.3. Postponement Strategies

With rising consumer expectation on product variety and customization, companies are struggling to produce and to manage increasing product varieties with shorter lifecycle in a quicker respond time. This challenge makes company easy to lose control of supply chain efficiency and agility to satisfy the market (Lee, 1998). To reduce costs, companies are less willing to hold finished good inventory until customer needs, which may result in an increasing lost of sale if not responding in time. Postponement has been proven to be an efficient solution to boost the "bottom line" of this challenge, i.e. to reduce inventory related costs while maintaining customer service by pushing the point of product differentiation closer to the customer.

Postponement was first defined as a strategy for postponing changes in form and identity to the latest possible point in marketing (Alderson, 1978), and later was applied to manufacturing and distribution sites (Zinn and Bowersox, 1988). The concept was applied to product design and/or manufacturing process so that the decisions on time and quantity of a specific product being produced could be delayed to as late as possible. This idea is also known as *delayed product differentiation* (e.g. Zinn and Bowersox, 1988; Lee, 1993; Lee and Billington, 1994; Lee and Tang, 1997; Aviv and Federgruen, 1998; Whang and Lee, 1999; and van Hoek, 1999). Bowersox and Closs (1996) considered the risk pooling effect in the logistics postponement strategy that stocked differentiated products at the strategically central locations to achieve balance between inventory cost and response time. Other related concepts include the *point of differentiation*, which refers to the tier in a supply chain where the postponement takes place, and the *level of postponement*, which refers to the relative location of the differentiation point. For example, in the HP Deskjet printer case, HP decided to perform local customization in European countries for the printer line by postponing the final assembling procedure, i.e. by storing the semi-finished products in the local warehouse and carrying out the local customization process at the distribution centers in Europe (Lee et al., 1993). This strategy enabled the company to reduce the inventory level while maintaining or even increasing the customer service level. Other examples, such as Benetton Case (Signorelli and Heskett, 1986), IBM Case (Swaminathan and Tayur, 1998), Feitzinger and Lee (1997), van Hoek (1997), Lee (1998), van Hoek et al. (1999), Brown et al. (2000), van Hoek (2001) and CGE&Y, Oracle and APICS' survey in 2003 also showed the great success and the extent of postponement implementation. In the following sub sections, we first give a classification of different ways to implement postponement strategies in a supply chain based on a wide range of literature reviews, followed by a summary of various analytical works and case studies on this topic.

2.3.1. Types of postponement strategies

Different classifications of postponement strategies reflect respective perspectives on understanding the postponement strategy. Zinn and Bowersox (1988) summarized five types of postponement: labeling, packaging, assembly, and manufacturing, which were based on the type of manufacturing operation postponed, and the time postponement which occurred during transportation. Lee and Billington (1993) focused on the view of reducing the variability of production volumes so as to reduce the cost at manufacturing and related stages, and their category comprised form and time postponement. Bowersox and Closs (1996) focused on reducing the risk of anticipatory product/market commitment and defined two types of postponement, manufacturing postponement and logistics postponement. Lee and Tang (1997) considered the variety of design changes in the production and distribution processes, and then developed a category comprising standardization of components, modular design, postponement of operations, and re-sequencing of operations. Lee (1998) revaluated the strategy which delayed the timing of the crucial processes where the end products assumed their specific functionalities, features or "personalities", and described three types of postponement: pull, logistics and form. van Hoek (1999) focused on the interrelation of outsourcing and postponement and he defined time, form and place postponement.

As the possibility of implementing a postponement strategy has been extended to the whole supply chain while the existing categories were somewhat incomplete, we develop a new classification to understand basic essences of postponement strategies based on three characteristics of production/process in the SCN: (a) *product design* — the specific content of delayed operation, (b) *process design* — the delayed time point when the activities takes place in the process, and (c) *place design* — the location where the delaying takes place. As a result, postponement strategies can be classified into three categories: form, time and place (Zhang and Tan, 2001).

Form postponement (Form-PP) This involves the redesign of the function-added process ("function-added process" here refers to the procedures before the products finally come into being) to postpone the point of product differentiation. For example, Hewlett-Packard's LaserJet printers had an internal power supply of either 110 or 220 volts due to different countries/regions requirement and a specific choice had to be made before initiating manufacturing. By switching to a universal power supply, HP was able to reduce the safety stock level in the power supply and successfully decreased the total cost of delivering the final product to the customer by 5% annually (Feitzinger and Lee, 1997).

There are two main methods for implementing this strategy. One is to standardize the upstream product/process so that the point of product differentiation can be delayed to a later stage. Examples include Lee and Billington's (1994) form postponement (to standardize the upstream stages), Bowersox and Closs' (1996) manufacturing postponement (to manufacture the generic product in sufficient quantities while deferring finalization of features), Lee and Tang's (1997) standardization (to standardize the product so that the family products may be replaced by it), and Lee's (1998) form postponement (to standardize the components or process steps to delay the product differentiation). The other is to modularize the components so that the assembly activity can be postponed to a later stage in the process. Lee and Tang's (1997) modularization postponement (to place functionality in modules which can be easily added to a product) and Lee's form postponement fall into this part.

Time postponement (Time-PP): This involves the reconfiguration of the process sequence, which refers to the sequence of procedures in each stage of the whole supply chain, to postpone the product differentiation. In the Benetton case (Signorelli and Heskett, 1986), the factory reversed the manufacturing process, "dyeing" and "knitting", to postpone the dyeing of the garment till after the sweater was completely knitted. This strategy led to a demand variance reduction (Lee and Tang, 1998) and allowed organizations to respond customers' orders quickly and economically.

There are two potential methods for implementing this strategy. One is to redesign the process sequence so that production decision based on forecasting can be delayed. Examples include Lee and Tang's (1997) re-sequencing of operations. The other way is to delay implementation time of activities that determine the form and function of products. Examples are Lee and Billington's (1994) time postponement (to delay the various product differentiation tasks), Lee's (1998) pull postponement (to move the decoupling point earlier in the process so that the differentiation tasks can be delayed to the point when customer needs become clearer), and van Hoek's (1999) form postponement (to delay activities that determine the form and function of products).

Place postponement (Place-PP): the redesign of the implemented location of process which refers to the geographic location where the procedures in a supply chain take place, in order to postpone the product differentiation. In the HP Deskjet printer case (Lee, 1993), HP put off the final assembling activities (the localization procedure), and made the final product at their distribution centers. In this way, HP reduced the response time to customer order and inventory cost since risk pooling took positive effect in this case.

This strategy can be implemented in several different ways. The first focuses on delaying the differentiation tasks to downstream organizations in final processing and manufacturing. Zinn and Bowserox' form (1988) (labeling, packaging, assembly, manufacturing) postponement, Lee and Billington's (1994) time postponement, Lee and Tang's (1997) postponement of operations, Lee's (1998) logistics postponement, and van Hoek's (1999) time postponement all deal with this issue. For example, a European computer manufacturer (van Hoek, 1996) implemented this strategy by completing the final assembly of personal computers at its local distribution centers (DCs) in response to customers' specific orders instead of completing the computers at its factory. The second focus is on delaying downstream movement of goods. Zinn and Bowersox's (1988) time postponement and van Hoek's (1999) place postponement discussed this issue. A special topic in goods movement is Bowersox and Closs' (1996) logistic postponement, which is a delay in the forward deployment of inventory. An example of this approach is Rover (Martin, 1998), a car manufacturer, which centralized the inventory from its dealers so that it could respond to customers' orders quickly.

Table 2-1 summarizes the categories of postponement strategies discussed above, including their definitions, implementing focuses and possible stages in the supply chain where the postponement strategies would take place (Zhang and Tan, 2001).

<table>
<tr><th>Category</th><th>Definition</th><th>Focus</th><th>Scope</th></tr>
<tr><td rowspan="2">Form Postponement</td><td rowspan="2">To redesign the function-added process to postpone the product differentiation</td><td>To standardize the upstream stages (e.g. Lee and Billington's form postponement, Bowersox and Closs' manufacturing postponement, Lee and Tang's standardization postponement, and Lee's form postponement)</td><td>Manufacturing, Integration, Customization, Localization, Packaging</td></tr>
<tr><td>To modularize the functionalities (Lee and Tang's modularization postponement, and Lee's form postponement)</td><td>Manufacturing, Integration</td></tr>
</table>

Category	Definition	Focus	Scope
Time postponement	To reconstruct the process and production time to postpone the product differentiation	To redesign the process (e.g. Lee and Tang's re-sequencing of operations, and parallel processing)	Manufacturing, Integration, Customization, Localization, Packaging
		To delay implementation time of activities that determine the form and function of products (e.g. Lee and Billington's time postponement, Lee's pull postponement, and van Hoek's form postponement)	Primary Production, Final manufacturing
Place postponement	To redesign the implemented location of process to postpone the product differentiation	To delay the differentiation tasks to downstream in final processing and manufacturing (e.g. Zinn and Bowersox's form (labeling, packaging, assembly, manufacturing) postponement, Lee and Billington's time postponement, Lee and Tang's postponement of operations, Lee's logistics postponement, and van Hoek's time postponement)	Final manufacturing, Packaging, Labeling
		To delay downstream movement of goods (e.g. Zinn and Bowersox's time postponement, and van Hoek's place postponement,)	Packaging, Labeling
		To delay the forward deployment of inventory (e.g. Bowersox and Closs' logistics postponement)	Distribution

Table 2-1: Three categories of postponement strategies with different focuses and scopes.

2.3.2. Value of postponement strategies

Another dimension to understand postponement strategy is quantifying their values in SCM. In research, many analytical models have been introduced to study postponement from various perspectives (van Hoek, 2001). These analytical works mostly evaluated systematic cost-benefit tradeoff at operational level (sometimes they transferred the service level into the format of cost of lost sale, i.e. the backlog cost). Given various model assumptions, model structures, analytical focus, and postponement cases in previous works, choosing suitable criteria to summarize them is helpful. Based on our knowledge those works basically tried to analyze either one or two operational benefits that postponement could achieve: one is risk-pooling effect (or more generally: pooling effect) in production and inventory, i.e. making decision based on aggregate demand instead of separate demands to reduce decision error arise from uncertainty of demand variability and demand correlation. Similar terms include Whang and Lee (1999)'s uncertainty resolution and Aviv and Federgruen (1998, 2001a)'s statistical economies of scale and risk pooling effect. The other is forecasting accuracy improvement, i.e. adjusting forecasting by received information as time passes. Similar terms include Whang and Lee (1999)'s forecasting improvement and Aviv and Federgruen (1998, 2001a)'s learning effect. In this section, we will organize literatures based on their contributions to understandings of these two postponement values.

2.3.2.1. Risk pooling effect

Risk pooling effect is achieved when a certain stock of materials, work-in-progress or end products can serve as a common buffer for various production and delivery requirement. By postponing the point of differentiation, materials and unfinished products can be stored in the inventory to meet the demand for family products, instead of specific end product requirement. Figure 2-5 presents a periodic-review order-up-to inventory model of two products. The demands of products are independent and identically distributed. The demand variances are the same. The standard part of product, as a result of *t*-period production on material ($0 \le t \le T$), will be customized into one of two final products after *T-t* periods of production. Given a pre-determined safety factor *z* and the same cost factors of these two products, we can find that the expected average stock of products should equal to the value of expected safety stock, i.e. $SS_1 = z\sigma\sqrt{4(T+1)-2t}$, which decreases as *t* increases. This result shows that as the differentiation point *t* is delayed, the inventory cost is decreasing while the service level keeps unchanged. The reason is that during the production period *t* before reaching the point of product differentiation, a "common buffer" $z\sigma_{12}\sqrt{t}$, instead of two separate $z\sigma\sqrt{t}$, keeps less safety stock given a per-determined service level. Such postponement value can be quantified as $VOP_1 = 1 - \frac{SS_1}{SS_0} = 1 - \sqrt{1 - \frac{t}{2(T+1)}}$. With small modifications, this model is also suitable to describe a MTO (Make-To-Order) inventory system where the inventory is held at the differentiation point. Please refer to Schwarz (1989) and Whang and Lee (1999) for more detailed discussion.

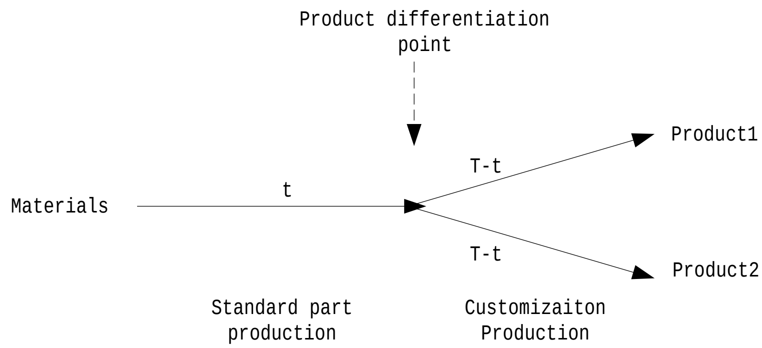

Figure 2-5: A simple production process consists two stages, standard part production and customization production, with a total T-period production time.

On this topic, Zinn and Bowersox (1988) considered five types of delaying time and location of differentiation in the final product processing, i.e. labeling, packaging, assembly, manufacturing and time, and proved the significant cost advantage by postponing via simulation. Lee (1996) studied the basic format of postponement in a make-to-order (MTO) and a make-to-stock (MTS) inventory models using an order-up-to inventory policy. In MTO, the value of postponement came from shortening the leadtime of the intermediate products being produced to the end products format. To do so, more production processes should be carried out on the intermediate product before it was put into work-in-progress (WIP) stock. In MTS the value of postponement came from postponing the allocation decision on customization quantity in the production. The basic idea in these two different models in fact was similar as Schwarz (1989) work that analyzed the impact of leadtime on risk-pooling effect in a one-inventory multi-retailer model. Later Lee and Tang (1997) developed a more complicated model consisting of multiple inventory positions along the production process to analyze three types of postponement strategies: standardization, modular design and process restructuring. In their study, the whole production system was treated as a *N*-single-stage supply chain, each of which carried out one or a few operations and maintained its own stock. Authors also analyzed how different additional costs arise from postponement implementation would affect the risk-pooling benefit from postponement and pointed out that postponement was not always beneficial. Due to the flexibility of this *N*-stage design, this model could be extended to analyze the whole supply chain performance. Also Lee and Tang (1998) studied how the operation reversal in production could help organizations reduce demand variance and hence improve the performance of production decision in a two-stage manufacturing system. By focusing on how the demand variance could be reduced, authors determined several factors which made this postponement strategy valuable: demand variance, demand correlation and leadtime.

Because previous works chose only one differentiation point to study, Garg and Tang (1997) extended the scope to the possibility of two points of postponement in a periodic-review base-stock system. Considering the inventory benefit from different points of postponement, authors found that the demand variability, demand correlation and lead-time in the system played an important role in determining the point to be postponed.

Then researchers evaluated several specific postponement strategies under different system settings. Graman and Magazine (1998) considered a more specific postponement, delayed packaging (i.e. storing products partially without being packaged in stock till customer order comes) and analyzed how it could reduce end product inventory in a single-stage order-up-to-level model. Their numerical result showed that given the assumption that the delayed process time was acceptable to customers, the inventory cost reduced 0% - 6.5% while the service level was maintained. Later Graman and Magazine (2002) considered further about the capacity limit in this postponement strategy and found that only a relatively small amount of production capacity was needed to achieve all benefits from packaging postponement. Similarly focusing on capacity, Gupta and Benjaafar (2001) studied the different performances of MTO, MTS and postponement in a general framework and tried to determine a suitable position to build stock for intermediate products in a system given a capacity limit. In their study, authors found that the pooling effect from postponement could be diminished by tight capacity because of the increasing cost from loss of sale (or order delay). As a result, there was a decreasing desirability of applying postponement and an increasing favor of choosing MTS if the capacity reduced. This finding conflicted with Graman and Magazine (2002), mainly caused by their different assumptions that whether a delayed time was acceptable to customers or not. Swaminathan and Tayur (1998, 1999) considered another specific form postponement, i.e. to modularize and store intermediate products into vanilla boxes, with production capacity restriction in a periodic-review system. Authors compared different performances of using vanilla boxes in a MTS and a MTO environment. Each time when demand was available, products were assembled from vanilla boxes by adding other components. By simulation, authors found that vanilla box reduced both inventory costs in MTS and MTO when the capacity was moderate and such value was significant with high demand variance and negative demand correlation.

Later, the chance of implementing two postponement strategies simultaneously in a supply chain was considered by Ernst and Kamrad (2000). Although authors used the term "modularization" to explain the concept of components combination for final assembly, which was similar as the concept of vanilla box (e.g. Swaminathan and Tayur, 1998, 1999), and the term "postponement" to explain out-bound logistics of distribution, their approach was actually to study the form postponement, place postponement and the combined effect of these two strategies in a three-stage production-distribution system using order-up-to inventory policy. In their study, authors claimed that implementing combined postponement strategies might be better than separate ones.

Factors beyond postponement operations also drew researchers' attention. Gavirneni and Tayer (1998) studied the pooling effect of form postponement under two informative environments: one was that the upper-stage had the information of inventory policy used by the customer and the product demand distribution while the other was that the upper-tier had full information about the customer. By analyzing the upper-stage's inventory cost, that computational work compared the value of information sharing strategies and postponement strategies and studied the combined effect of these two. Authors found that postponement was a dominant strategy under a wide variety of conditions while information sharing strategy was beneficial only under a few conditions such as high holding cost (if the backlog cost kept fixed), high capacity and low demand variance. After studying the combined effect of using two strategies simultaneously, authors concluded that two strategies complemented each other well. However the increased benefit did not show any consistent trends under various conditions that might motivate researchers to analyze good combinations of information sharing and postponement in a supply chain framework.

2.3.2.2. Forecasting accuracy improvement

Forecast accuracy improvement applies in the situation that forecasting error of demand before decision making can be decreased as time passes by. By postponing the differentiation point, production and delivery decisions on specific products can be delayed and more accuracy about demand forecasting can be obtained. As a result, the decision quality is improved and system cost can be reduced. Recall the same simple model we used to discuss about risk pool effect in the previous section. Here we make only one modification: the demand variability can accumulate over time, e.g. in the format of $D(t) = u + \sum_{j=1}^{t} \eta_j$ where $\eta \sim N(a, \sigma^2)$. With this change, when system makes production decision on final product quantity at period *t*, it has to forecast the demand *T-t+1*-period later given the available demand information at that time, i.e. $\tilde{D}(T) \mid D(t) = \left(u + \sum_{j=1}^{t} \eta_j \right) + \sum_{j=t+1}^{T+1} \hat{\eta}_j$. Since $D(t) = \left(u + \sum_{j=1}^{t} \eta_j \right)$ is known at period *t*, the forecasting error will come from the demand of future T-t+1 periods, i.e. $\sum_{j=t+1}^{T+1} \hat{\eta}_j$. Therefore it is obvious that given a larger *t*, i.e. as differentiation point is delayed more, less forecasting error will occur to estimate demand at period-*T*, i.e. when the final products come into being. As a result, system cost, including holding cost for redundant products and backlog cost for lost of sale, can be reduced and service level can be improved. Given a pre-determined safety factor *z*, we can find that the value of postponement is $VOP_2 = 1 - \sqrt{1 - \frac{t}{2(T+1)} - \frac{t(T+1-t)(4T-2t+7)}{2(T+1)(T+2)(2T+3)}}$, which is larger than

VOP_1. The increased value comes from the improvement of forecasting accuracy (Please refer to Whang and Lee (1999) for more detailed discussion).

To analyze this type of benefit, researchers developed various models and the key point inside is to assume the demands are correlated across time. Whang and Lee (1999) developed a periodic-review order-up-to inventory system to deal with two-stage production process. Firstly they analyzed the pooling effect of postponement in the context of IID demand and quantified the postponement value as the reduced safety stock. It was clearly shown that such value was directly associated with the value of demand variability and leadtime. Then authors considered the random walk model in demand forecasting and studied how the system gained benefit from both pooling effect and forecasting improvement enabled by postponement. As postponement delayed the differentiation point, it delayed the production decision on customized products (also called as allocation decision). Therefore, more accuracy on forecasting aggregated demand could be achieved at that later time point and decision quality could be improved in two ways: reducing the error on estimated demand in the future and determining a suitable order-up-to level.

Specially, van Mieghem and Dada (1999) analyzed how to improve forecasting accuracy by postponement in a price and competition model. In various forms of competition models in economics, price and quantity are two important decision factors that affect each other: Given a price (or production quantity) in the competitive market, optimal quantity (or optimal price) is inferable. From this perspective, authors analyzed several possible postponement strategies organizations might use when demand was unknown. In their two-stage game, an organization decided the production quantity (or price) but delayed its price decision (or production decision). Because of the assumptions of rational human and perfect symmetrical information (or partly) in the market, market demand and competitor action would respond to that decision, which could be inferred or known by the organization. Therefore, in the second stage, that organization could make better decision about the price (or production) with reduced demand uncertainty and improved forecasting accuracy. Their model was especially suitable in the situation of introducing new product into the market since at that time demand was extremely uncertain to the company.

Robinson and Elofson (2000, 2001) used simulation to study another way to improve forecasting accuracy during postponement, i.e. changing supply chain structure by adding in a broker tier to deal with customer demand. If so, the demand could be pooled and demand correlation could be reduced (although demand variability might be increased due to broker's own behavior). As a result, the value of postponement, i.e. reduction of inventory cost in this case, was increased.

As previous studies mostly assumed the demand distribution was known, Aviv and Federguen (2001a) went further to study the postponement benefit in cases of unknown demand distribution or demand correlation across time. In their model, the demand distribution parameter was estimated on the basis of observed history demand data and its accuracy could be improved when more information about prior distribution became available in a Bayesian framework. This parameter forecasting in fact was a form of time-correlated demand analysis but author put it into a postponement environment. In their study, authors found different optimal inventory policies under different cost structures for postponement. In another work, Avivi and Federguen (2001b) considered two more factors in an inventory system to implement postponement: inventory capacity and the demand with seasonal pattern.

The information sharing factors that could affect the forecasting accuracy also drew researchers' attention. Anand and Mendelson (1998) modeled a two-stage periodic-review order-up-to production-inventory system to study the value of postponement and considered how demand variability, demand correlation and information precision (similar as the term forecasting accuracy) would affect such value. By analyzing the information role in postponement, authors claimed that informational considerations had a paramount effect on the effectiveness of postponement strategies. For example, if better information precision could not be achieved at the delayed point, postponement could not give organizations the benefit of forecasting improvement but increase costs. Also, if information sharing strategy already promised a good aggregate forecast, the differentiation point would not change organizations' operation performance much. At that time, useful information about specific product demand was more valuable to postponement implementation. These findings motivate researchers to perform cost-benefit analysis and quantify the anticipated effect of implementing postponement strategies under different informative environments. Zhang and Tan (2002) also studied the combined impact of place postponement and various information sharing strategies, including order information sharing, partial information sharing and demand information sharing, on reducing information distortion and provides an illustration of how these two strategies affect the demand parameters simultaneously. The result showed that place postponement, combined with demand information sharing strategy, performed better on reducing information distortion than that of place postponement alone, whether it was better than information-sharing alone conditionally depended on lead-times before/after postponing among the participants in the chain.

In summary, as various works on postponement have been carried out, the two essential values of postponement: risk pooling effect and forecasting accuracy improvement, are becoming clear to researchers. Therefore the research focus turns to analyze how other SCM approaches could influence postponement values. Recent research shows that information sharing strategy plays an important role on postponement implementation. One observation is that the value of postponement is the value of information (Whang and Lee, 1999): as time passes, more information about the customer demand would be acquired. Thus as the forecasting point moved closer to production period, demand forecast quality would improve and the quality of decision would be optimized. Other research, such as Anand and Mendelson, 1998, Gavirneni and Tayer 1998, and Zhang and Tan, 2002, also proved the information sharing strategies could play a paramount effect on implementing an effective postponement. However detailed cost-benefit analyses on various forms of postponement strategies and information sharing strategies have not been pursued yet. This gap motivates us to consider further into the characteristics of information-shared postponement strategies and design comprehensive experiments to analyze it in a supply chain. In this way, this work extends the extant of academic literature on postponement strategies.

2.4. Information Sharing Strategies

There are two main flows shuttling along the supply chain: the material flow and the information flow, which draw researchers' much attention. Understanding the value of information flow between member organizations of a supply chain, such as POS (point-of-sales) data from retailers and advanced shipping notice (ASN), is one of the main tasks in SCM. With more available information, tiers along the supply chain would improve their decision quality.

Researches have been carried out to study the influence of information flow in a supply chain from various perspectives (Swaminathan and Tayur, 2003). From the view of inventory management, Chen (1998) showed that information sharing reduced inventory system costs by up to 9%. Chen and Zheng (1997) and Cachon and Fisher (2000) argued that an inventory policy that considered shared information was close to optimal. However research also showed that the information sharing might not benefit all supply chain members. For example, Bourland et al. (1996) found that information sharing reduced inventories of upstream supply chain members by up to 62% but increased downstream members' inventories by 4% in their study. From the view of demand management, Lee et al. (1997b) found that information sharing reduced the supplier's demand variance while Chen et al. (2000) studied how centralized demand information sharing could reduce the bullwhip effect in supply chains. Lee et al. (2000) analyzed benefits of sharing demand information and identified some of the drivers behind using a two-level supply chain model. Li et al. (2000) quantified the benefit of demand and inventory information sharing on reducing demand uncertainty. From the view of collaboration, Subramani (2004) studied how suppliers would benefit from information sharing while many other studies focused on the benefits to dowmstream members in supply chains. These results motivate organizations and researchers to consider the implementation of information sharing strategies among members in a supply chain. Here we define Information sharing strategy (ISS) as a type of inter-organizational coordination in which the participants share useful information among to improve the chain-wide performance.

The important elements inside the information flow, which are essential to the tight coordination along the chain, are the demand information for product from downstream organizations to upstream organizations and supply information from upstream to downstream. While previous studies mostly focus on analyzing demand information sharing, i.e. the backward information from members' market they are facing to, recently there are a few studies extending the perspective to another kind of ISS that shares the forward information from members' supply source in a supply chain. For example, Lee and Whang (2000) mentioned that a supplier could use its supplier's delivery schedule to improve its own production schedule; Lim (2001) analyzed how members in a two-tier supply chain would react to different available information on the shipment uncertainty due to various product qualities provided by the producer; and Fu and Piplani (2004) studied the benefit for a supplier to share its inventory policy and planned service level in a two-tier supply chain. Based on the direction of information flow to be utilized in inter-organization collaboration, ISS can be mainly classified into two categories: backward information sharing and forward information sharing. A similar term is “channel focus”, meaning the scope of the integration effort including either upstream organizations or downstream organizations, or both (Sahin and Robinson, 2002).

From this view, we name the downstream-to-upstream information flow as *backward* information sharing that provides information about demand availability, while the upstream-to-downstream information flow as *forward* information sharing that provides information about supply availability. The following figure briefly demonstrates these two different types of information flow.

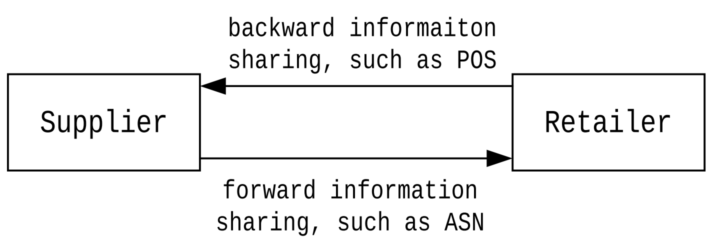

Figure 2-6: Backward and forward information flow in a supply chain.

Another important essence when we analyze ISS is the purposes of shared information along supply chains, i.e. which decision in SCM they can help to make, and literatures show that there are various ways to use in information sharing in SCM. In this study, firstly we introduce how the supply chain performs in benchmark situation (we name it as order information sharing when referring it in the rest of this paper). Then we review different types of ISS and categorize them based on the purpose of information sharing, including improving inventory decision, improving production decision and improving strategic decision. As the focus of this research is at the operational level of the information value on a production-inventory system, we limit our discussion mainly within the scope of operational information sharing versus order information sharing and analyze how ISS can improve the decision quality on inventory decision and production decision in a supply chain.

2.4.1. Order information sharing

Order information sharing (OIS) is the situation in which only orders from one tier in a supply chain are sent to its immediate upstream suppliers. This order information is the basic form of information flow to link members in supply chains. In this form, each tier in a supply chain makes decisions independently and can be viewed as isolated islands linked only by order message. The main task for each tier is to optimize its production and inventory decision locally by balancing among order cost, production cost, inventory cost and service level. Various concepts, models, technologies on inventory and production control have been developed from this point, including EOQ (economic order quantity), EOI (economic order interval), four basic types of inventory systems: (s, Q) (order-point, order-quantity), (s, S) (order-point, order-up-to-level), (r, S) (periodic-review, order-up-to-level) and (R, s, S) (periodic-review of order-point, order-up-to-level), EPQ (economic production quantity), and MRP (material requirement planning), which have become the foundation of production / inventory management in operations research, e.g. Silver and Peterson (1985) and Tersine (1994). Although in general these methods have their own advantages and disadvantages, they all have been proven to be optimal solutions on cost and service for a single stage given specific environments.

However, evidences show that these localized optimizations do not work well in multi-stage systems, and sometimes even make performance worse (e.g. Lee et al., 1997a, Baganha and Cohen, 1998, Chen et al., 1998, and Fransoo and Wouters 2000). For example, forecasting demand only based on the order from its immediate downstream tier will amplify demand variability from downstream organizations to upstream organizations in a supply chain. The degree of such information distortion increases as tiers moves upwards in a chain that results in higher inventory cost and worse customer service level. This phenomenon is called bullwhip effect (Lee et al. 1997a, 1997b). A famous example of bullwhip effect is Beer Game (Senge, 1990), which is repeated later by simulation in various forms, such as MIT Beer Game (Simchi-Levi et al. 2000) and Columbia Beer Game (Kimbrough et al. 2002).

Sterman (1989) and Diehl and Sterman (1995) explored this operational puzzle from the perspective of decision dynamics. Their studies showed that tiers irrational behaviors were mainly caused by lack of information and misconceptions of information feedback. Although decision rules, e.g. the inventory policy, were locally optimized beforehand, they could not perform well, or even became worse, if the input information was distorted. They suggested that direct feedback, without any inferring work on the part of receivers, and faster feedback, with shortened delay time, would reduce the dynamic complexity of decision-making and improve decision quality.

Lee et al. (1997b) developed a multi-stage model to analyze four sources of bullwhip effect summarized in Lee et al. (1997a). Authors considered four cases in their study: when demand followed auto-correlated AR(1) process in a two-stage order-up-to system, when shortage occurred at upstream organization in a one-period three-stage system, when customers' order dates were collided in the same period in a two-stage periodic order-up-to system and when retailers determined different inventory policies in responding to suppliers' price variation. Based on these quantified result, authors discussed several countermeasures to reduce bullwhip effect, in which information sharing strategies appeared repeatedly. Later, Chen et al. (1998, 2000) analyzed the effect of forecasting and leadtime on the bullwhip effect when demand was correlated across time in an AR(1) process. The system they constructed was a multi-stage periodic-review order-up-to inventory system, using a simple moving average forecast method to estimate future demand. This time, authors clearly quantified how order amplification moved up along each tier in a supply chain and how such variability decreased as the moving window size in forecast increased and the lead-time between tiers decreased.

Motivated by observation of increasing production and sales variability as one moved up along the supply chain in economic reports, Baganha and Cohen (1998) developed a multi-stage periodic-review inventory model facing with IID demand from many retailers. By comparing the order variance at different stage in the chain, authors found the bullwhip effect and proved that single-stage inventory policy had such a destabilizing effect to increase the volatility of demand as it passed up through the chain. However authors also discovered that under certain conditions such demand amplification could be decreased, e.g. adding a distribution center between the manufacturer and multi-retailers. This finding was similar to what Robinson and Elofson (2000, 2001) found, i.e. distribution center stabilized the order variance from retailer to the manufacturer by neutralizing different order patterns into one and such stability were highly dependent on leadtime factor.

Because of the bullwhip effect, optimized inventory / production models cannot perform well in the context of a whole supply chain. One intuitive solution is to reduce such information distortion directly so that the bullwhip effect can be largely avoided. Therefore, researchers begin to study various ways that can share suitable demand/supply information in a supply chain to improve the effectiveness of decision models.

2.4.2. Types of information sharing strategies

Since organizations have found that local optimization cannot promise a satisfactory performance, they turn to construct closer collaboration relationship with partners in a chain to make profit together. With the development of information technology, such as EDI (electronic data interchange), information at operational level can be transferred fast between organizations with less delay. As a result, members anticipate downstream needs and supply capacity more accurately and consequently adapt its inventory / production plan to reduce cost and maintain service quality in daily operations. In short, organizations become clearer about what customers really want and what suppliers are capable to provide in an information-rich environment.

The situation that the market information is centralized and available to whole supply chain is a type of information collaboration. However such centralized control might not be feasible or desirable (Lee and Billington, 1993) due to organizational barriers and restricted information flows. Therefore it might be more common that one tier only shares demand information with its close partners. Also, organizations can share out their operation information, such as inventory policies, inventory level and master production schedule, to synchronizes production and delivery schedule with partners to improve service level and reduce cost. Forecasting information sharing is another type of strategy that can help upstream organizations estimate future demand more accurately.

In the following, we will describe various types of information sharing strategies based on their purposes and channel focus, including demand information sharing, inventory information sharing, forecasting information sharing, production information sharing, shipment information sharing and strategic information sharing.

2.4.2.1. Demand information sharing

In this situation, the market information is available to the whole supply chain. To implement it, the font tier closest to the market agrees to share out its sell-through data to all members in the chain, even to those not directly linked to its business. In research, demand information sharing (DIS) has been a frequent suggestion for reducing bullwhip effect. Chen (1998) constructed a linear multi-stage inventory model, using order-point order-quantity inventory policy, to study the information value of market demand on inventory cost reduction. With demand information available, each tier determined its order point based on downstream order point and market demand given a fixed order quantity. Without such information, each tier would decide its order point locally, i.e. each tier is unaware of downstream order point and determines its order point only based on order from its immediate customer. Computational results showed that this information sharing strategy could reduce total inventory cost by 1.75% in average and 9% at most. Authors also found that such value tended to positively associate to the number of tier, the leadtime, the batch size and the target service level, but negatively relate to demand variance.

Lee et al. (2000) analyzed the value of demand information sharing by putting it into a two-stage supply chain with AR(1) demand over time. This inventory system consisted of one supplier and one retailer using periodic-review order-up-to inventory policy. In their setting, the retailer might share the market information to its supplier or only send orders. By comparing the difference of average inventory cost between these two different informative environments, authors found that the supplier reduced its inventory and total cost greatly enabled by information sharing, although retailer benefited little. Such value increased when demand was highly correlated over time with higher variance and longer leadtime. Then Chen et al. (2000) quantified the bullwhip effect and examined the value of demand information sharing. Results showed that even by sharing end market demand to each tier in a supply chain, the bullwhip effect could not be completely eliminated: the increasing information distortion at each tier with information sharing became an additive function of the leadtime divided by forecasting periods.

There is another form of demand information sharing, i.e. downstream shares its future demand with its supplier and orders in advance. In this way, the supplier obtains enough time to respond to demand. Hariharan and Zipkin (1995) studied the timing factor of such information sharing in a single-stage inventory model, which was extended to a multi-stage case later. In this case, customers provided advance warning of their demands to the retailer instead of ordering unannounced (Authors used the term demand leadtime, starting from a customer's order till the due to date, to measure such advanced warning). Therefore the retailer had more time to prepare for order fulfillment. Of course if the demand leadtime was equal or larger than the supply leadtime, i.e. the time required to replenish retailer's orders from its supplier, and if the shipment uncertainty at upper tier was not considered here, retailers could always promise a perfect service to its customer without any safety stock. Even if the demand leadtime was less than the supply leadtime, authors showed that organizations could perform effectively, and even optimally in some cases, when followed either a periodic-review order-up-to inventory policy or an order-point order-up-to one. By subtly converting this inventory model with both demand leadtime and supply leadtime into a conventional system with supply leadtime only, authors successfully proved that such advanced information sharing improved system performance in precisely the same way as a reduction in supply leadtime. Later, Chen (1999) developed the similar idea in a multi-stage decentralized supply chain and Chen (2001) considered the price discount for such advance information sharing.

Demand information sharing also helps upstream organizations to determine an optimal allocation policy. Ernst and Kamrad (1997) studied how to use demand information in allocation policies for order fulfillment in a two-stage periodic-review inventory model, which consisted of one distribution center and two retailers with IID demand. In this model, retailer's service level was chosen as the performance measure for allocation rules. Authors discussed three allocations policies at the distribution center: static (preferentially satisfying one retailer), myopic (partially utilizing demand information from the retail to determine the proportion of allocation) and dynamic (fully utilizing demand information to dynamically adjudged proportions between two retailers). Results showed that the dynamic policy performed better than the myopic in most cases. However one interesting finding was that dynamic policy did worse than the myopic when first retailer's demand variance was larger than the second one. This finding motivated us to consider the difference between using more information and well utilizing information. A related work was done by Mitra and Chatterjee (2004) who studied the total inventory cost, including inventory holding and backlog cost, in a two-stage periodic-review order-up-to inventory model consisting of one distribution center and two retailers with IID demand. Authors examined three cases when the distribution center could not completely fulfill demands from retailers: one was to send out emergency shipment (maybe directly from upstream factory) with additional costs; one was to allocate to retailers leading to equal stock-out probabilities; the other was to allocate to retailers by the proportion of order quantities. Retailers could share their future demand (i.e. the demand during the period between distribution center's replenishment interval and the leadtime) with their suppliers to help them update order-up-to level and order quantity. Results showed that for each case the total cost with such demand information sharing was always lower than that without information sharing.

2.4.2.2. Inventory information sharing and VMI

Besides demand information, other types of information at downstream organizations, such as its inventory policy, day-to-day inventory status, capacity etc, are also valuable to upstream organizations and the whole supply chain, which is named as inventory information sharing (IIS) in this study. For example, Lee et al. (2000) stated that in the industry some retailers were pushing for their suppliers to participate in vendor-managed-inventory (VMI) and suggested comparing demand information sharing with VMI in which retailer's inventory status was shared with its supplier. On this topic, Gavirneni et al. (1999) considered three different information sharing cases in a two-stage inventory model consisting of one supplier and one retailer: in the first case there was no information sharing between two stages except orders; in the second case, retailer shared out patterns of its order-point order-up-to inventory policy and the demand distribution; in the last case, retailer shared out its inventory position besides other information available in case*2*. Authors also considered the capacity limit at supplier's site, which was expressed by the modified order-up-to level in the model, and various demand distributions, including uniform, normal, exponential etc. Computational results showed that total cost at supplier site in case*2*, including inventory holding cost and backlog cost, was reduced *10%* to *90%* with an average around *50%* and such reduction was positively related to higher capacity and higher holding cost rate. However authors found the extra benefit from case*2* to case*3* was significant only when capacity was high enough or the ratio of backlog to holding cost was moderate or the demand variance was moderate. Overall, authors concluded that information was always beneficial.

Cachon and Fisher (2000) developed a two-stage inventory model that consisted of one supplier and multiple identical retailers with stationary random demand. Measured by inventory cost, including holding and backlog cost, authors compared supply chain costs between the situation of no shared information and that of sharing inventory position from retailers to the supplier. This inventory information was utilized in two ways in their study: one was to help supplier infer the supply chain's total inventory and consequently improve its order quantity, the other was to help supplier allocate shipment based on inventory position, instead of order quantity. Based on their simulation results, authors found that with such information sharing, supply chain cost was averagely *2%* lower than that without information and such reduction could reach *12%* at most. Later authors studied how sensitive such value was to the changes of two conditions in the system: shorten leadtime and smaller batch sizes, enabled by information technology. The result showed that average cost reduction by shortening half leadtime and reducing half batch size were *21%* and *22%* respectively. Therefore authors concluded that although shared inventory information reduced cost, implementing information technology to smooth the physical flow of goods through a supply chain was significantly more valuable. This conclusion was quite similar as Silver (1992)'s discussion about "changing the given", i.e. changing one given condition without further optimization in a system often could largely improve performance, sometimes even much greater than the optimized result given the original condition.

VMI is a system coordination enabled by inventory information sharing. It is a strategy that the supplier is authorized to manage inventories at retail locations that has been successfully applied in many companies, like Wal-Mart (Cetinkaya and Lee, 2000). On this topic, Aviv (2002) developed a two-stage inventory model consisting of a retailer and a supplier with an AR(1) demand. Three different information sharing cases were studied: one was that only order information was shared; one was that the supplier took the full responsibility of managing the retailer's inventory but did not use retailer's forecasting information about the market; the third case was that the inventory was managed centrally by the supplier with all demand-related information-shared. Authors studied these three settings to provide managerial insights into the value of information sharing, VMI, and collaborative forecasting. Through numerical examples, authors showed the significant value of sharing forecasting information when the demand process was more correlated across time in a VMI environment because this early-estimated demand information enabled organizations to reduce the demand uncertainty largely. Cetinkaya and Lee (2000) and Axsäter (2001) also discussed about how VMI with known demand information and downstream inventory information performed in a supply chain. However their focus was on the optimization of inventory and delivery decision.

There are some other works studying the information value in VMI. Fry et al. (2001) constructed a two-stage supply chain, which consisted of one supplier and one retailer, to study the information value in a particular VMI: supplier managed retailer's inventory and made delivery decision based on the pre-promised inventory level at which it should help the retailer to maintain. In their paper, authors used the term (z, Z) to describe such rule, where z was the minimum required inventory level while Z was the maximum one. Supplier could access retailer's inventory level and end market demand in both VMI and RMI (retailer-managed inventory) situation and would pay penalty cost when retailer's inventory level was out of that scope in VMI. Numerical analysis was conducted to compare the performance of a supply chain under these two different environments. Results showed that the (z, Z) type of VMI performed significantly better than RMI in many settings, but would perform worse in others when choosing unsuitable penalty cost and inventory level range.

Cheung and Lee (2002) evaluated the value of information sharing in VMI from two perspectives in a two-stage model which consisted of one supplier and multiple retailers: One was the value of utilizing retailers' inventory positions to coordinate shipments from the supplier to enjoy economies of scale in shipments, such as full truckloads. Because of another assumption that retailers were located in a close proximity in the study, the information obtained a new value, i.e. to eventually unload of the shipments to the retailers to rebalance their stocking positions. In fact, the information value in this paper could be viewed as a form of risk pooling effect. By evaluating retailers' total cost, computational results showed that total cost with shipment coordination became lower and stock rebalancing provided additional cost reduction. Both information values increased as the number of retailers increased. Furthermore, the value of stock rebalancing increased as leadtime increased. These results were quite intuitive if we treat the value as a risk pooling effect.

Besides downstream organizations shares its inventory information with its supplier, it is also beneficial for the upstream organizations to share its inventory information with the customers. For example, Fu and Piplani (2004) studied the case when a supplier shared its inventory policy parameters with its customer in a two-stage inventory system. In that paper, downstream organization estimated supplier's replenishment leadtime from these shared-out patterns to adjust its safety stock level, i.e. the order point, in an order-point, order-quantity inventory system. Authors found this information from supply side helped downstream organizations got better stabilizing effect and service level.

2.4.2.3. Forecasting information sharing

The efficiency of forecasting method in information sharing (FIS) also draws researchers' attention. For example, Raghunathan (2001) analyzed the forecasting efficiency in Lee et al. (2000)'s model. In their study, all setting followed Lee et al. (2000) except changing the forecasting model at the supplier site so that more history data of previous orders from the retailer were used to forecast future demand. As a result of forecasting improvement, value of information sharing was reduced. This result motivated researchers to consider the efficiency of chosen forecasting model in the information sharing.

Later, Zhao et al. (2002) studied the impact of forecasting model selection on the value of information sharing in a supply chain in a two-stage production-inventory model that consisted of one capacity-limited supplier and multiple retailers. In their model, the demand contained either seasonality or trends, or both. Retailers had five choices on forecasting methods, including naive method, moving average, exponential smoothing and Winters' method. Then three information sharing cases were studied: one was only current order was shared between the supplier and the retailer, one included current order and forecasted future demand and the third one included current orders and forecasted future orders. Through simulation, results showed that information sharing could significantly reduce supply chain total cost, i.e. the sum of inventory holding cost, backlog cost, order cost and setup cost and such value from information sharing was significantly influenced by demand patterns, the forecasting model and capacity tightness at the supplier. There were other two interesting findings in their study: First authors found that sharing forecast order information with the supplier was more beneficial than sharing future demand. Although it seemed to conflict with ideas of reducing information distortion, we think this conclusion was reasonable in a decentralized system in which the supplier still would pay backlog cost for unfulfilled order from its downstream partners while in a centralized supply chain the backlog cost was only for unfulfilled market demand at the front tier. Therefore a closer estimation of lower tiers' order might help upper tiers better than that of end market demand. The other finding was that although such information sharing was always beneficial to the supplier, retailers' performance sometimes might even worsen. This result might be caused by the local optimized production plan and reduced inventory at the supplier side. Because pervious research commonly focused on one-tier or total supply chain cost but did not compared the changes of each tier, this interesting finding from Zhao et al. (2002), and similar findings from Krajewski and Wei (2001), Mishra et al. (2001), Zhang et al. (2002b), and Zhang

(2003), is a motivation for researchers to consider whether information is always beneficial to both the information sender and receiver members in a supply chain.

2.4.2.4. Production information sharing

With production information sharing (PIS), supplier could adjust its delivery schedule based on downstream production update and could forecast customer's future requirement. Krajewski and Wei (2001) studied the value of sharing production schedule and forecasted future demand from downstream to upstream in a two-stage supply chain. By measuring the total supply chain cost, including setup cost, inventory holding cost, and schedule changing cost, authors found that the cost reduction had a positive relationship with forecast effectiveness but a negative relationship with inventory holding cost and leadtime. However such information was not always beneficial: firstly sometimes the information provider, i.e. the downstream organizations in this case, faced an increased cost after information sharing; Secondly, the whole supply chain cost even increased in a chain with high holding cost and long leadtime. In another word, in such informative environment, the cost reduction at the beneficiary could not absorb the increased cost at others in a chain.

2.4.2.5. Shipment information sharing

Lee and Whang (2000) mentioned that a supplier could use its supplier's delivery schedule to improve its own production schedule. However, as the producer sometimes seeks to avoid the risk of revealing its production capability to its competitors, it may be unwilling to share its production information (such as when a particular order is scheduled or when the production is carried out) with its customers. On the customers' side, they usually do not care when the products are produced but when and how much the goods will appear "on their doorstep". For them, accuracy and quality on arrival shipping quantity is most valuable in making better inventory and production decisions. In other word, the information for the upstream members to safely share and the useful information for the downstream members to receive is the information of the product availability. For example, a large computer scanner producer in Asia plans to share its shipment information with its wholesalers and local sales agents via the Internet. Therefore its wholesalers can access the producer's web-based information system to check the exact shipment dates and available quantities of each order when the goods are ready for shipping out. Other examples include UPS' package tracking service.

One motivation to share supply information is that orders could not always be satisfied on time with perfect product quality due to the suppliers' imperfect service on transportation and production. For example, Lee and Billington (1992) reported that a manufacturer shipped more than 30 percents of its orders after the promised data and 40 percents of its actual shipment dates differ from the promised date by more than 10 days. If supplier timely shares the information about the shipping quantity and/or the sampling result of product quality, the customer might resolve this uncertainty in time by adjusting its future order decisions, which is one countermeasure against bullwhip effect suggested by Lee et al. (1997b).

There are several types of supply uncertainties that cause this information valuable. One is lead-time variability in the delivery due to uncertain transportation, administrative processing and/or production times (such as Silver and Peterson (1985) and Tersine (1994)). The other arises from quantity variability, i.e., shipments quantities arriving at the customer, after a given lead-time, may be less (or possibly more) than the customer expects. Due to limited resources (finance, materials, capacity, etc.), it is usually uneconomical or impossible for supply-chain members to promise a perfect (100% fill-rate) delivery service. Furthermore the imperfect quality of the products, i.e. defective products from the supplier, also causes the uncertainty of available shipping quantity to the customers. The higher the product quality provided by the supplier is, the greater percentage of usable products is in each shipment. Bowersox and Closs (1996) used a similar term the consistency of transportation, referring to variations in time required to perform a specific movement over a number of shipments, for this issue. If transportation lacks consistency, inventory safety stocks will be required to protect against unpredictable service breakdowns.

While lead-time variability has drawn much attention (and organizations responding by offering lead-time guarantees), such as Song (1994), Song et al. (2000), and many others, there are few studies being carried out on quantity variability. Lim (2001) analyzed how members in a two-tier supply chain would react to different available information on the shipment uncertainty due to various product qualities provided by the producer, focusing on the quality control strategy with informational asymmetry. It analyzed the direct cost on quality but ignored how such uncertainty would affect tier's inventory control and consequently the whole supply chain. In fact, the study on lead-time variability may be more suitable for the case when the order, which cannot be fulfilled in time, will be delayed for a certain period until it can be completely fulfilled, while the study on quantity variability considers the case where the order can be split and partly fulfilled in several times.

On the topic of shipping quantity uncertainty, Zhang et al. (2002a, b) evaluated the benefit of a supplier sharing its available shipping quantity with its immediate downstream customer via analytical model and simulation respectively. Results indicated that in a linear supply chain network, this strategy benefited customers (the information receivers), but not always benefit the supplier (the information sender). This unequal impact may cause implementation barriers. Later, Zhang (2003) went further on analyzing the benefit of sharing the information of product availability in a dual-supplier network, in which the downstream organizations had multiple suppliers so that the supply uncertainty could be shared. In their study, authors also analyzed the issue of information competition, i.e. what was the result if only one supplier shared the information or all suppliers did so, and provided several comprehensive insights into information sharing management in a supply chain. By developing equilibrium of supply chain performances in various informative environments, authors evaluated possible countermeasures the supply chain members might use from a game-theory perspective. One interesting finding was that although the receiver benefits from the information of product availability from its supplier, it was not required to pay for this: By developing a good multi-source supply system with appropriate order proportion to each supplier, suppliers should be self-motivated to provide such information, as a result of market competition.

2.4.2.6. Strategic information sharing

Previous strategies discussed about the information in organizational daily transaction. Here the strategic refers to long-term and high-level collaborations among organizations via informative communication, such as sharing local culture and end customers' preferences, product design plan, specific knowledge and experience on forecast, production and market etc. These information helps members better understand its product, market and learn more about how to collaborate more efficiently with partners (Angeles and Nath, 2003). For example, during new products development, Pfizer (Pharmaceutical) utilized information of consumer's preference and feedback from Wal-Mart who had the best knowledge of local consumer preference through their interactions with customers. Wal-Mart could also get benefit from Pfizer's specific knowledge about the product property to improve its demand forecasting and replenishment planning (Bradley and Foley, 1996). Furthermore, to collaborate effectively, "speaking the same language" is necessary, i.e. supply chain members should share information and knowledge with partners in a way that they can understand each other. Otherwise, collaborative activities will be seriously hindered (Kumar and Zhao, 2002). Unlike the previous operational level, this knowledge-related strategic information policies requires more qualitative factors to be verified and specified, such as cultural factors and consumer preferences, which are far beyond the scope of the simulation and will not be further studied in this study.

In summary, we have analyzed various types of information sharing strategies. Based on channel focus, they can be mainly classified into two categories: backward information sharing and forward information sharing. From the purpose of the information, we can further categorize them based on the decisions they can place value on, including inventory decision, production decision and strategic decision. The following Table 2-2 summarizes these different forms of ISS with example set of related researches.

Information Direction	**Types of Decision**	**Type of shared information**	**Benefits**
Backward (downstream to upstream)	Inventory Decision	Order information (e.g. Sterman, 1989; Lee et al. 1997a, b; Baganha and Cohen, 1998; Chen et al., 2000)	Demand signaling, one cause of bullwhip effect
		Demand information (e.g. Hariharan and Zipkin, 1995; Ernst and Kamrad, 1997; Chen, 1998; Gavirneni et al., 1999; Chen et al., 2000; Lee et al., 2000; Mitra and Chatterjee, 2004)	Help upstream organizations accurately forecast future customer needs to make better inventory decision (purchase storage)
		Inventory information (e.g. Gavirneni et al., 1999; Cachon and Fisher, 2000; Fry et al., 2001; Aviv, 2002; Cheung and Lee, 2002)	Help upstream organizations synchronize its inventory plan (purchase, storage) with downstream organizations
	Production Decision	Demand information (e.g. Anand and Mendelson, 1998)	Help upstream organizations make better production decision

Information Direction	Types of Decision	Type of shared information	Benefits
Backward (downstream to upstream)	Production Decision	Production information (e.g. Krajewski and Wei, 2001)	Help upstream organizations synchronize production plan with downstream
		Forecasted information (e.g. Zhao et al., 2002)	Help upstream organizations estimate future market demand to make production schedule
	Strategic Decision	Strategic information (e.g. Bradley and Foley, 1996, Kumar and Zhao, 2002, Angeles and Nath, 2003)	Help upstream organizations understand product life cycle, product R&D, market preferences in long-term
Forward (upstream to downstream)	Inventory Decision	Shipment information (e.g. Zhang et al., 2002a, b, 2003)	Help downstream organizations partially eliminates shortage gaming, and understand supply schedule and capacity
		Inventory information (e.g. Fu and Piplani, 2004)	Help downstream organizations estimate shipment uncertainty
	Strategic Decision	Strategic information (e.g. Bradley and Foley, 1996, Kumar and Zhao, 2002, Angeles and Nath, 2003)	Help downstream organizations understand the supply in long term and devise product promotion and other marketing strategies

Table 2-2: The categories of ISS from two dimensions: the channel focus and the type of decision, with its own benefit and sample literatures follow.

Based on this classification, we will choose one typical information strategy at operational level from different channel focuses and use no-information-sharing case as the benchmark. Therefore altogether there are three different informative environments will be evaluated in this study. They are *order information sharing (OIS)*, i.e. only orders from immediate downstream organizations are received by the supplier; *Demand information sharing (DIS)*, i.e. the exact sales of end consumers become available to every tier in a SCN; and *Shipment information sharing (SIS)*, i.e. one tier in a supply chain shares its information of product availability with its immediate downstream partners. Those information strategies are quite representative because they directly provide organizations with the information about how much demand customers may require and how much supply suppliers can provide in the future periods, while other types of information are used to infer these demand availability and supply availability from some other ways.

In this chapter, the supply chain concept and dynamics have been presented, followed by the introduction to SCM challenge and two suggested solutions: postponement strategy and information sharing strategies. In addition, the details of these two strategies, including their concepts, applications, values and classifications in SCM were reviewed. Based on above knowledge, the research question and details of experiment design will be presented in the next section.

CHAPTER 3 RESEARCH QUESTIONS AND METHODOLOGY

In this chapter we will raise research questions based on the understanding of the strategic nature of postponement and information sharing in a supply chain, followed by an introduction of the main methodology, i.e. simulation, that we use in this study.

3.1. Supply Chain Model

The system mechanism of order fulfillment process in a three-tier supply chain can be described as follows: Customers come to retailer and make their purchases. Retailer sells end product to its customer and places new order with its manufacturer based on its inventory management policy and forecast on future demand to ensure continuous selling. The manufacturer ships its end product from stock to the retailer after receiving retailer's order, makes production decision based on its own inventory policy and forecasts on retailer's future demand to ensure a continuous fulfillment to retailer. Then it produces end products by assembling components in stock and places order on components to its upstream supplier. After receiving the manufacturer's order, the supplier will ship out components to the manufacturer and place order to its supplier. At the end of each cycle, every tier summaries its cost and service performances and updates information about demand and shipment for future usage. The following notation for each tier will be used in this work.

S_{it}: order-up-to inventory level of tier i in period t

L_i: supply leadtime of tier *i*

Q_{it}: order quantity from tier *i* in period *t*

o_{tt}: order quantity to tier *i* in period *t*

$\hat{d}_{it}$: forecast demand of tier *i* in period *t*

$\hat{\sigma}_{it}$: forecast demand standard deviation of tier *i* in period *t*

d_t: real consumer demand in period *t*

r_{it}: net inventory, as on-hand inventory minus backorders, of tier *i* in period *t*

y_{it}: shipment arriving at tier *i* in period *t*

α_i: target service level of tier *i*

β_{it}: actual fill rate of tier *i* in period *t*

z_i: the safety stock factor of tier *i*

The supply chain adopts a periodic-review order-up-to inventory system in which the inventory level is reviewed every period, if the current inventory is less than the order-up-to level, i.e. S level, the entity will place order with upper tier. We use retailer to demonstrate the periodic order process occurring in a supply chain: at the beginning of period *t*, the retailer receives the shipments y_t from its supplier and the demand d_t from the market (subscript *t* denotes the variable in period *t*). The market demand process follows a general AR(1) process without seasonality, i.e. $d_t = u + \rho d_{t-1} + \varepsilon_t$, where $u > 0$, $|\rho| < 1$ and ε_t is normally-distributed $(0, \sigma^2)$. Then the retailer checks its inventory level r_{it}, fulfills the market demand d_t, and places the order Q_{it} to the upper tier based on its inventory policy and forecast on future demand. The order-up-to S_{it} level is set as the estimated mean of leadtime demand $\hat{d}_{it} \cdot L_i$, plus a safety stock which is the product of safety factor z_i, determined by the target service level that follows the equation $z_i = 0.5^{\sqrt{2/\pi}} \ln\left(\frac{\alpha_i}{1-\alpha_i}\right)$, and the estimated standard deviation of leadtime demand $\hat{\sigma}_{it} \cdot \sqrt{L_i}$. The shipment starting at period t from retailer's supplier reaches the retailer at the beginning of period $t + L_i$ in a one-off, not continuous, manner and there is no delay in pushing them into inventory. When the supplier cannot fulfill the order in time due to the limited capacity on production/inventory, it will backlog the order with priority of being replenished at next period. Figure 3-1 shows a three-tier supply chain and decision process at retailer.

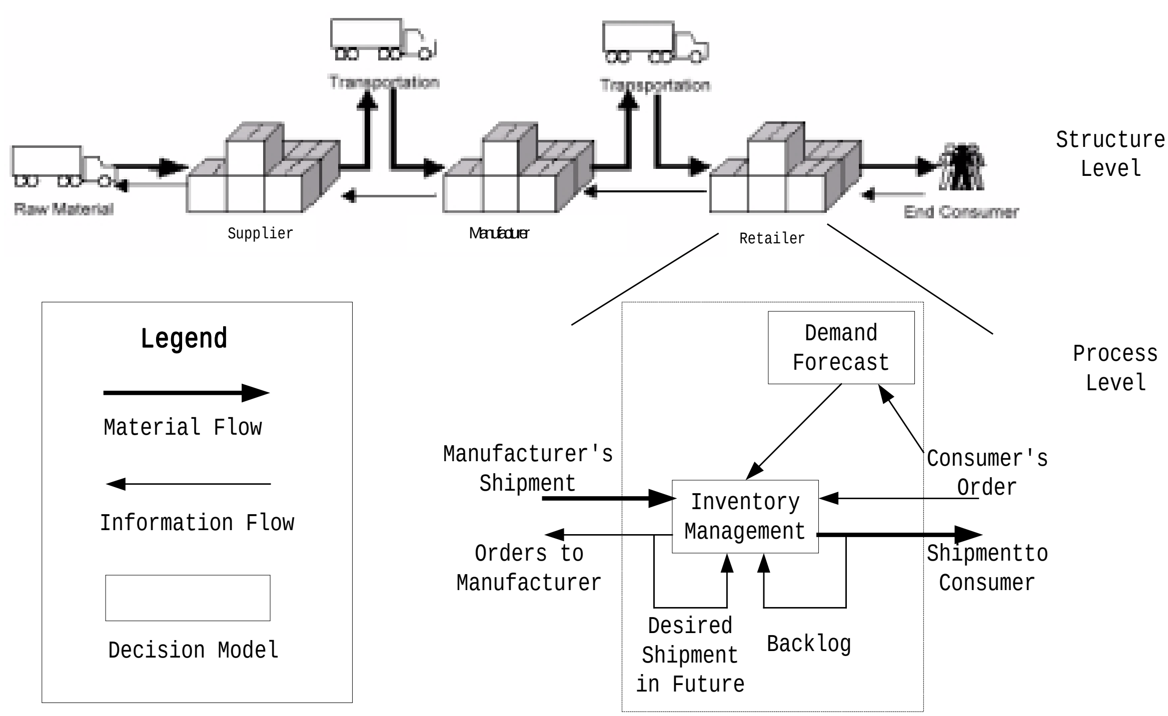

Figure 3-1: A basic framework of supply chain and decision processes in each tier.

The other upper tiers' behaviors in a supply chain follow almost exactly the previous description. The only difference is that they receive the order instead of the market demand from its customer. If we treat the end market as the customer, or downstream, of the retailer, all tiers' behaviors in the chain are exactly the same as what describe above.

By summarizing tier's inventory decision dynamic in a supply chain, Figure 3-2 concisely describes a detailed investigation of the inventory decision process at one tier in the context of supply chain dynamic and how various information sharing strategies we have reviewed in the previous section place its role in such a decision process. It is clear that a tier's inventory (production) decision is based on five factors: customer's order, accumulative backlog (inferring from shipments to customer and orders from customer), demand forecasting (which depends on customer's order), arrived shipment from supplier, desired shipment in the future (inferring from orders to the supplier) and inventory policy. As orders from downstream are received, the upper tier will use this information for demand forecast and order decision. However if downstream organization shares its demand information and/or forecasting information, upper tier can use the available information to improve the forecast accuracy on market demand. In order information sharing situation, the tier assumes that the coming shipment should equal to the amount it ordered and uses order quantity it places with its supplier to forecast the future shipment from its upper tier. With shipment information available, the tier can calculate exactly the coming quantity of products in future periods and uses this information to improve its order decision and inventory management. Furthermore, if downstream and upstream organizations could provide it with their inventory/production status, the tier could estimate the future demand/supply availability more accurately to improve its decision quality of inventory management. Note that the production decision can be easily extended in it if necessary and the only difference is that the orders come from tier's inventory but not directly from tier's customers.

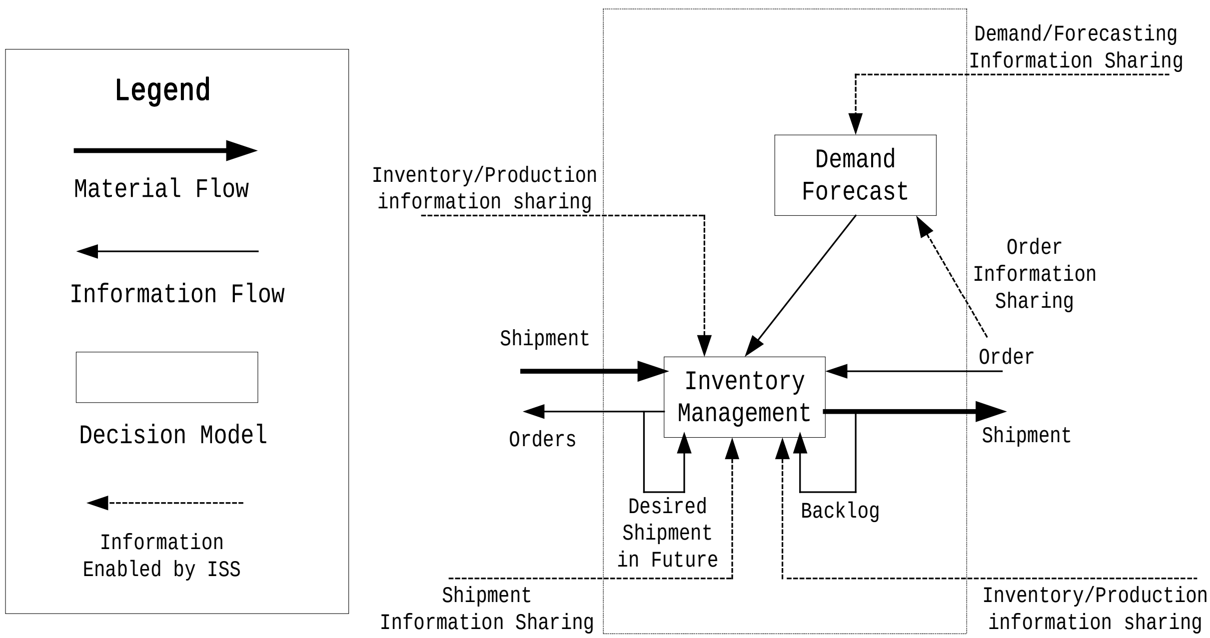

Figure 3-2: The decision framework of one tier in a supply chain at the process level. Solid line: information / material flow available to the tier. Dot line: available information enabled by specific ISS that can join in the decision. Rectangle: tier's decision model. Rectangle with dot line: decision process within one tier. Arrow: the information / material flow with the arrow points to the target.

Note that the supply chain we designed in this study was a decentralized one. In concept there are two different types of supply chain: centralized and decentralized. In a centralized supply chain, a central planner (which can be one tier in a chain or a thirdparty member) has access to the status of the inventories at all tiers and makes all stocking decisions for the entire chain, which has been proven by research to be an efficient way to manage a supply chain. However in practice this completely centralized control of the material flow in a supply chain is rarely feasible or desirable due to the organization barriers and information restriction among members (Lee and Billington, 1993). Therefore in practice, supply chains with multiple tiers often operates in a decentralized model, i.e. each tier manages its own inventory and makes decisions to satisfy its own performance measurements.

3.2. Supply Chain Performance Measurements

Cost-benefit tradeoffs always exist when implementing a certain information sharing or postponement strategy in a supply chain (e.g. Lin and Shaw, 1999; and Tan, 1999), i.e. some performances of the tier and the chain may be improved while the others may become worse. Therefore this study observes the impact of combined strategies on these measurements and help organizations to find out suitable information-shared postponement to meet its strategic purpose. Lee and Whang (1999) argued that alternative performance measurement scheme in decentralized chain was often used to align the incentives of different tiers in a supply chain. However, since this study is to understand the impact of various information and postponement strategies on supply chain performances, we will avoid discussing which performance is better or more suitable in this supply chain but concentrate on how performances are influenced by those strategies.

Based on in-depth literature reviews in SCM, the chosen performance measurements can be divided into two main sections: service measurements and cost measurements. Service measurements include the tiers' service level, fill rate, order leadtime in response to customers' orders, absolute percent error of service level and dynamic effect, while cost measurements include the tiers' inventory cost.

3.2.1. Service measurements

Service indexes should measure supply chain members' service capabilities, including service availability, service performance and service reliability, to satisfy its customers (Bowersox and Closs, 1996). From these perspectives, we choose service level, fill rate, order leadtime to measure service availability and performance, and use absolute percent error of service level and dynamics effect to measure its reliability.

Service Level (SL)

Service level refers to the probability of not running short of stock during order cycles (e.g. Silver and Peterson, 1985 and Tersine, 1993), which has been widely used as the main measurement in research. In each period of our simulation experiment, it is calculated as:

Service level = {0, 1} (0: not completely fulfilled; 1: else), and

$$\text{Average Service Level} = \frac{\text{sum of periods that fulfill orders completely}}{\text{total periods}}$$

In brief, the service level should be a function of the trade-off between holding cost and shortage cost, the two major costs affected by the safety stock, as well as the frequency at which the tier is exposed to the possibility of running out of stock (Tersine, 1993). Given a fixed inventory level, a higher service level means satisfying its customers better. Noting that in data analysis and discussion part, the indexes we are referring to are their average values over the total running periods.

Fill Rate (FR)

Fill rate refers to the percentage of units demanded that will be in stock when needed, which is a bottom-line measure of service in practice rather than previous index "service level" (Coleman, 2000). Previous backlogs are prioritized for fulfillment at the beginning of each period. Its calculation formula in each period of the simulation is:

$\text{Fill Rate} = \dfrac{\text{units of product being fulfilled}}{\text{units of product in demand}}$, and its overall average value is

$$\text{Average Fill Rate} = \frac{\text{sum of fill rate in periods}}{\text{total periods}}$$

Similarly as service level, a higher fill rate stands for better satisfaction from its customers given a fixed inventory level. Most of time the fill rate is higher than the service level. For example, in a year a firm completely fulfills customer orders for eight times but only satisfies 90% quantity of the order in the ninth and tenth time, each time the order is of the same quantity. By calculation it shows that the firm's service level is 80% but the fill rate is 98%.

Service level and fill rate are two important service measurements. Organizations usually use either one, or both, of them in practice depending on customer requirement and cost calculation factors. In our study, we will use both of them.

Order Leadtime (OLT)

Order leadtime in response to customers' orders is calculated as the total time used to complete the fulfillment to customers' orders. Since backlog always exists under imperfect service level, the actual response time to fulfill customers' orders often fluctuates. Therefore the smaller the order leadtime, the more satisfaction the tier may obtain from its customers.

$$\text{Average Order lead time} = \frac{\text{sum of order lead time in periods}}{\text{total periods}}$$

Absolute percent error of service level (APESL)

Absolute percent error of service level is used to compare the accuracy of the decision-making and to measure the control ability of organizational performance. Given a target service level it is calculated as

$$\text{APESL} = \frac{|\text{ actual service level - target service level }|}{\text{target service level}}$$

Due to the changing environment, such as fluctuating demand, unstable supply and so on, members' target service is usually different to keep unchanged. The smaller the percent change of service level, the better control it is on the service performance.

Dynamics effect (DE)

Dynamics effect (Fu and Piplani, 2004) is the ratio of order variation generated by a member to the demand variation received by the member and can be expressed as:

$$\text{Dynamics Effect} = \frac{\text{variance of tier's order to its supplier}}{\text{variance of tier's demand from its customer}}$$

When *DE* >1, it is known as bullwhip effect, i.e. the variance of order is larger than that of sales and such distortion tends to increase as one moves upstream (Lee et al. 1997b). Else when *DE* ≤1, it is the stabilizing effect that the demand volatility decreases as it passes up through the supply chain (Baganha and Cohen, 1998). In this study, we measure the bullwhip effect and stabilizing effect by *DE*. The smaller *DE*, the better supply chain performance is to reduce bullwhip effect.

3.2.2. Cost measurements

Cost indexes, including material cost, inventory cost, production cost and transportation cost, measure supply chain members' cost incurred to satisfy its customers' requirements. These costs can be summed up together within a tier or be summed up by tiers along the supply chain to show the impact of a particular strategy on a tier or the whole supply chain performance. Other indirect overhead and transportation cost are excluded here since they are not related with the key points of product/process redesign and information strategies and we assume their changes can be ignored in this study.

Traditionally, manufacturing costs fell under three headings: material cost, labor cost and overhead (Browne et al., 1996, Ullman 1997), but it is often very difficult to estimate these costs accurately. Furthermore there was an argument in the recent years that traditional cost accounting system may distort manufacturing cost performance and may distract the management (e.g. Goldratt, 1983 and Kaplan, 1984). Based on literatures, a typical manufacturer usually spends about *60%* of its total sales, or *50%-70%* of the costs of manufactured goods (Harmon and Peterson, 1992, Ullman, 1997), on purchased items, such as raw materials, parts, subassemblies and components, and service (Krajewski and Ritzman, 1996). As a result, material cost usually holds the main portion of the total relevant cost in an organization in a supply chain. Labor cost usually covers about *5%-15%* of total manufacturing cost (Gould, 1985, Browne et al., 1996, Ullman, 1997) although in the past it used to account for almost half of production costs in the companies.

Total logistics cost, which mainly includes the delivery cost and the inventory cost, typically ranges from *5%* to *35%* of total sales for individual firms, depending on the type of business (Bowersox and Closs, 1996). For example, Ganeshan et al. (1998) estimated it as 30%. Based on 13th annual "State of Logistics Report" (Delaney, 2002), the average transportation cost is about *60%* of the total logistics cost for the manufacturing enterprises in the last *10* years while the inventory related cost accounts for approximately *37%* of it (Note that since inventory may be a larger percentage of assets for wholesalers, distributors, and retailers, the percentage of inventory cost for them may be consequently higher than that for the manufacturer). Furthermore, studies in operations management point out that a typical annual inventory carrying cost varies within a large range, i.e. from *9%* to *50%*, depending on enterprise policies (Bowersox and Closs, 1996). For example, the annual cost of carrying a unit of inventory was *15%* of the unit value for a make-to-stock manufacturer in Blackburn (2001)'s study while Chase (1998) estimated it between *25%* and *35%*.

Given so great variability on cost factors in a supply chain, it is difficult, or arbitrary, for us to set particular values for them unless assigning a specific industrial background. Furthermore, for simulation experiments, the results are usually very sensitive to cost values setting. Therefore, we are required to design cost factors carefully without disturbing the focus of observing general performances of information-shared postponement in a supply chain context. To simplify our analysis, we retreat the whole system from another perspective: Considering a certain postponement case with different information sharing approaches, it is clear that the total demand and average unit material cost always keep the same (the demand is determined as a system parameter across all information strategies while the unit material cost cannot be affected by information approaches). Consequently, the average values of material cost, production cost and delivery costs in the experiment keep the same as well when analyzing them in the same postponement context. As a result, decisions under various informative environments would only affect the inventory cost. In this way, we can concentrate on the changes of inventory cost when evaluating supply chain performance of a postponement under various informative environments.

In real world, inventory cost usually consists of a fixed part and a variable part. The fixed part is a constant investment, occurring periodically to keep the inventory and production tasks going, such as investment on equipment, administration and setup cost. The variable part usually linearly, or non-linearly (e.g. in the case of running out of capacity), associates with unit product being produced or being stored. In this study, we focus on the unit changes of related cost without capacity limitation and assign it as *1* standard unit cost of product value.

Inventory cost (IC)

Inventory cost is the measurement representing the tiers' cost of storing the on-hand stock in every period after fulfillment. Its value every period in this experiment is

$$\text{Inventory Cost} = \text{Quantity of product/component in inventory} * \text{unit holding cost}$$, and

$$\text{Average Inventory Cost} = \frac{\text{sum of inventory cost in periods}}{\text{total periods}}$$

On-hand stock is mainly used as a safety stock to maintain a certain service level against demand fluctuation. However if ignoring the risk of stock-out and its related payoff, inventory cost is a type of redundant investment in finance that occupies the tiers' capital but cannot contribute to its revenue. Due to existing demand forecast error, there is an excessive part of on-hand stock that is unnecessary for helping organizations respond to demand fluctuation. Therefore, given a promised service level, a lower inventory cost stands for a better efficiency to manage inventory.

Backlog cost, or penalty cost, is another cost factor widely used in calculating inventory cost. It is a compensatory cost for not fulfilling customer's order in time. In other word, it is a cost format of service level and fill rate, particularly useful in analyzing systems in a cost-only style. However in practice such a penalty cost is very difficult to be accurately estimated (Coleman, 2000) and the management in the organization is usually uncomfortable with setting such a value (Blackburn, 2001). The more practical way for organizations to balance their inventory management is to set a satisfied service level as a pre-requisite (Bowersox and Closs 1996). Consequently the focus of inventory management turns to reducing the related holding cost while maintaining the target service level. Therefore the backlog cost is either zero if they can meet customers' service requirement or very huge if they lose the customer. Since we have developed various service measurements and will focus on the tradeoff between service and inventory cost, we will not repeatedly analyze the backlog cost.

3.3. Research Questions

In this section, we will go to the details of how variables change with different ISS and then consider how these impacts will affect the performances of various postponement strategies.

3.3.1. The impact of information on postponement strategies

Figure 3-3 here concisely describes a detailed investigation of the inventory decision process in the context of supply chain dynamics with OIS, DIS and SIS available. In the OIS environment, an organization will make inventory decision based on customer's order, accumulative backlog (inferring from shipments to customer and orders from customer), demand forecasting (which depends on customer's order), arrived shipment from supplier, desired shipment in the future (inferring from orders to the supplier) and inventory policy. In the DIS environment, end market demand becomes available for the tier to make better demand forecasting and consequently affects its inventory management performance. In the SIS environment, information about exact future shipment, instead of desired shipment, contributes to the final inventory decision.

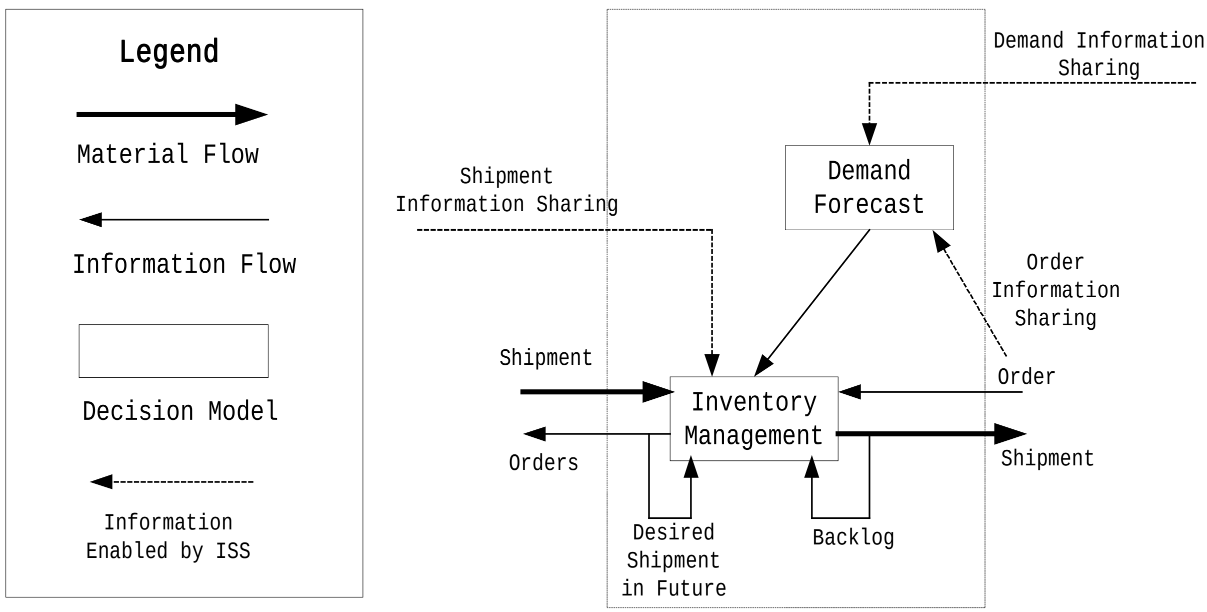

Figure 3-3: The information used in this study for supply chain decision process. Solid line: information / material flow available to the tier. Dot line: available information enabled by specific ISS that can join in the decision. Rectangle: tier's decision model. Rectangle with dot line: decision process within one tier. Arrow: the information / material flow with the arrow points to the target.

Above diagram provides us a clear understanding of tier's decision dynamic at a high level with OIS, DIS and SIS available in a supply chain. Then we analyze detailed variable relationships in decision process.

In the OIS environment, each tier in the chain uses the history of customer's order quantity as the demand information to estimate the future mean demand and demand variance, i.e. $\hat{d}_{i,t} = \sum_{j=1}^{n} o_{i,t-j} / n$ and $\hat{\sigma}_{i,t}^{2} = \sum_{j=1}^{n} \left(\hat{d}_{i,t} - o_{i,t-j} \right)^2 \Big/ (n-1)$ respectively where $\hat{\sigma}_{i,t}^{2}$ is tier i's estimated demand variance, n is the forecasting window size, and $o_{i,t}$ is the order quantity placed by its customer in period t. Therefore the tier's S level is $S_{i,t} = L_i \cdot \sum_{j=1}^{n} o_{i,t-j} / n + z_i \sqrt{\sum_{j=1}^{n} \left(\sum_{j=1}^{n} o_{i,t-j} \Big/ n - o_{i,t-j} \right)^2 \cdot L_i \Big/ (n-1)}$. Net inventory r can be negative in the case of a backlog and its value in period t and is denoted as $r_{i,t} = r_{i,t-1} + y_{i,t} - o_{i,t}$ where $y_{i,t}$ is the shipment it receives from its upper tier in period t. As a result, tier' order decision in period t is $Q_{i,t} \mid r_{i,t} = \left[0, S_{i,t} - \sum_{1}^{L_i - 1} Q_{i,t-i} - r_{i,t} \right]^{+}$, the greater number between *0* and the order quantity, to avoid negative quantities.

When sharing demand information in a supply chain, each tier is aware of end market demand for the products and uses such information to determine its optimal S every period. In this situation, the estimated error of demand at each tier is reduced to the most. Therefore, the future demand and its variance at each tier can be estimated as $\hat{d}_{t} = \sum_{j=1}^{n} d_{t-j} / n$ and $\hat{\sigma}_{t}^{2} = \sum_{j=1}^{n} \left(\hat{d}_{t} - d_{t-j} \right)^2 \Big/ (n-1)$ respectively, where d_t is the real market demand shared by the front tier in a supply chain, i.e. the retailer in this study. In this case tier's order-up-to level can be denoted as

$S_{i,t} = L_i \cdot \sum_{j=1}^{n} d_{t-j} / n + z_i \sqrt{\sum_{j=1}^{n}\left(\sum_{j=1}^{n} d_{t-j} \middle/ n - d_{t-j}\right)^2 \cdot L_i \middle/ (n-1)}$ while its order decision is $Q_{i,t} \mid r_{i,t} = \left[0, S_{i,t} - \sum_{1}^{L_i-1} Q_{i,t-i} - r_{i,t}\right]^+$.

When the supplier shares its shipment information with the manufacturer, the manufacturer is aware of its coming shipment. Hence it can easily infer the proportion of demand filled within next L_i days and uses the real coming shipment quantity instead of its unfulfilled order quantity having placed to the supplier to determine its order decision as $Q_{i,t} \mid r_{i,t} = \left[0, S_{i,t} - \sum_{1}^{L_i-1} y_{i,t+i} - r_{i,t}\right]^+$. However this information cannot improve its estimation quality on future demand from the lower tier because it still use downstream order and formula $\hat{d}_{i,t} = \sum_{j=1}^{n} o_{i,t-j} / n$ to forecast customer future demand, so the estimated value of its $S_{i,t}$ level is the same as *OIS*, i.e. $S_{i,t} = L_i \cdot \sum_{j=1}^{n} o_{i,t-j} / n + z_i \sqrt{\sum_{j=1}^{n}\left(\sum_{j=1}^{n} o_{i,t-j} \middle/ n - o_{i,t-j}\right)^2 \cdot L_i \middle/ (n-1)}$.

Table 3-1 summarizes different information used to estimate future demand, to determine the order-up-to level and to determine the order decision in a supply chain under various informative environments, shown as follows.

ISS \ Used Information	To estimate demand	To determine S-level	To determine order
Order IS	o_i : Customer's order	o_i : Customer's order	Q_i : Previous order o_i : Customer order
Demand IS	d : Market demand	d : Market demand	Q_i : Previous order d : Market demand
Shipment IS	o_i : Customer's order	o_i : Customer's order	y_i : Coming shipment o_i : Customer order

Table 3-1: Different information used in a supply chain under various informative environments

We can understand the supply chain tier's variable relationships in Figure 3-4. It is clear that the order-up-to inventory levels in upstream, i.e. the manufacturer and the supplier, are largely reduced if they use the real market demand by DIS, instead of immediate customer's order, to forecast the demand variance: By avoiding the bullwhip effect, the forecasted variance $\hat{\sigma}$ decreases, and consequently the *S* level reduces. As a result, the related inventory cost in a supply chain can be reduced.

With available information about future shipment enabled by SIS, it is obvious that the tier can adopt its future order to meet the gap between the desired shipment quantity and actual shipment quantity. Therefore tier's service level to its customer can be increased, which is proportional to the increase of safety factor *z*. Because the order leadtime directly associates with service level, a lower order leadtime is expected with the increase of service level. However, Zhang, et al. (2002b) found that SIS would not improve, sometimes even worsen, the information sender's performance because of the misunderstanding of the feedback on the shared information.

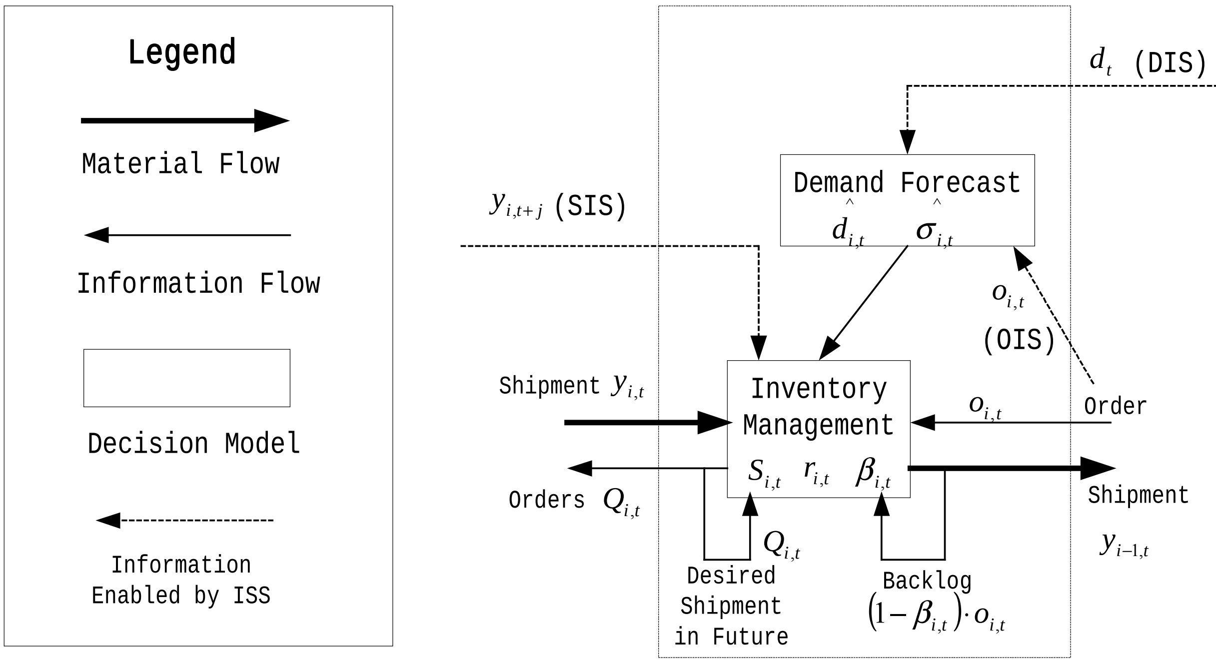

Figure 3-4: The variable relationships in the decision process of one tier in a supply chain. Solid line: information / material flow available to the tier. Dot line: available information enabled by specific ISS that can join in the decision. Rectangle: tier's decision model. Rectangle with dot line: decision process within one tier. Arrow: the information / material flow with the arrow points to the target.

In summary, by improving demand forecast accuracy in a supply chain, DIS can significantly reduce supply chain cost. By helping supply chain reduce the shipment estimate error, SIS can significantly improve supply chain service level. However, whether DIS improves supply chain's service level or SIS reduces inventory cost cannot be clearly deduced from the systematic analysis of supply chain's dynamic decision process. Therefore, in Table 3-2 that summarizes the significant influence by information strategy, we use asterisk to denote the deduced impact on cost reduction by DIS and service improvement by SIS, but use question mark to denote an unclear impact on cost reduction by SIS and an unclear impact on service improvement by DIS.

Recall that basic rule of risk pooling effect (Chapter 2.3.2.1 and Figure 2-5) in postponement is to use a "common buffer" $z\hat{\sigma}_{12}\sqrt{t}$ ($0 \le t \le T$), instead of the sum of $z\hat{\sigma}_1\sqrt{t}$ and $z\hat{\sigma}_2\sqrt{t}$, as the safety stock given a per-determined service level. Therefore it is obvious that postponement strategies can reduce the inventory cost in a supply chain given the same service level. However, given a specific information environment and pre-determined service level, postponement does not show a clear impact on service improvement.

As form postponement combines $\hat{\sigma}_1$ and $\hat{\sigma}_2$ into $\hat{\sigma}_{12}$, the demand variance throughout the supply chain will be more reduced than the other postponement strategies no matter what information sharing strategies are used. Therefore the forecasting error will decrease and inventory cost can be greatly reduced. Furthermore, the place postponement will increase the inventory cost at the retailer but decrease the manufacturer's inventory cost since part of the production is moved to the retailer, although the total cost in the chain is reduced by place postponement. Because time postponement delays the differentiation point inside the manufacturer, supply chain's inventory cost can be reduced. As the differentiation point is moved closer to the market (and the retailer), the leadtime between the supplier and the manufacturer actually increases given a fix total leadtime in a supply chain. Therefore more safety stock should be set up at the supplier's tier to resist the demand uncertainty in the leadtime while the safety stock at the manufacturer is reduced due to its shorter leadtime between the differentiation points to the retailer. As a result, the inventory cost at the supplier site is expected to increase while such cost at the manufacturer site should decrease.

It is clear that the safety factor *z*, the estimated demand variance, $\hat{\sigma}$, and the time before differentiation point, *t*, play important role to determine the final performance of postponement strategy. Recall Figure 2-4 that shows the impacts of postponement strategies and information sharing strategies on the supply chain dynamics.

When implementing form postponement, different products become partly common. Together with it, the benefit of DIS increases while SIS' impact on service level is not affected, which means DIS is expected to help form postponement reduce cost significantly but SIS cannot help its service.

When implementing time postponement, the differentiation point is postponed and consequently the error reduction on $\hat{\sigma}$ is partly achieved by postponement as well. Therefore the time postponement is expected to help DIS improve the supply chain's performance, but not as significantly as form postponement does. When implementing place postponement, the time factor *t* and error reduction of $\hat{\sigma}$ are not significantly affected since the differentiation point in the production process keeps the same.

However as moving inventory from the manufacturer to the retailer, redundant inventory at the manufacturer can be partly avoided and the differentiation point is delayed to the retailer. As a result, the marginal benefit of SIS on supply chain performances improvement is expected to be larger.

From above analysis, it is clear that DIS may work well in the supply chain that implements form postponement. Such significant influence may be reduced in time postponement and place postponement. On the other hand, SIS is expected to work particularly well with place postponement on service improvement. Because of these specific impacts of postponement strategy on system parameters, different combinations of information sharing strategies and postponement strategies influence the supply chain differently. Table 3-2 summarizes the significant impacts of information sharing strategies on postponement that have been deduced from previous systematic analysis on supply chain parameters and its decision process.

Information Value / Postponement	DIS	SIS
Form	Cost: ***** (most)	Cost: **?**
	Service: **?**	Service: *****
Time	Cost: *****	Cost: **?**
	Service: **?**	Service: *****
Place	Cost: *****	Cost: **?**
	Service: **?**	Service: ***** (most)

Table 3-2: The summary of deducible information value on postponement in a supply chain based on the systematic analysis of supply chain framework and its decision process. Cost: the cost performance in a supply chain; Service: the service

*performance in a supply chain; *: deducible significant influence by information; (most): deducible significant influence by information which is the largest compared with other environments; ?: unknown/unclear influence by information.*

3.3.2. Sensitivity analysis

Recall the supply chain model in this study. It is clear that there are two sets of system parameters that determine the supply chain behaviors: first set is the independent parameters of the market demand $d_t = u + \rho d_{t-1} + \varepsilon_t$, where ε_t follows normal-distributed $\left(0, \sigma^2\right)$and u is a constant, which determines the input characteristics of the supply chain model. It is obvious that there are two parameters influencing the demand process over time: the demand correlation ρ and the demand variance σ. The other set is the parameters of inventory decision model that determine the quantities of order, inventory, production and shipment at every tier and link tiers into a supply chain: $S_t = \hat{d}_t L + z\hat{\sigma}\sqrt{L}$, where $z = 0.5^{\sqrt{2/\pi}} \ln\left(\frac{\alpha}{1-\alpha}\right)$. Assume that the forecasting method is fixed and kept the same throughout the chain. Therefore the parameters $\left(\hat{d}, \hat{\sigma}\right)$ is sensitive to the market demand (d, σ), and/or the order o from downstream tier which is determined, again, by the downstream S. It is clear that the rest independent parameters are leadtime L and target service level α that influence the inventory decision model. Therefore altogether, four system parameters, including demand correlation, demand variance, production leadtime, and tier's target service level, play an important role in determining the supply chain performance with information-shared postponement, so we fully cover them in the sensitivity analysis.

Demand Correlation Over Time

Demand process may correlate with time, in the form of either trend or seasonality or both. Same as many other supply chain research do, such as Lee et al. (2000) and Chen et al. (2000), we will focus on the trend impact but ignore seasonality factor in this study. As a result, the demand process can be described in a simple, but without losing generalization, AR(1) model, i.e. $D_t = u + \rho D_{t-1} + \varepsilon_t$ where $u > 0$, $|\rho| < 1$ and ε_t is normally-distributed $(0, \sigma^2)$. When $\rho = 0$, such model restores to a basic random process with mean u and variance σ^2. In this study we assume that the retailer is unaware of the demand model and its patterns, but has to forecast. Recall Figure 3-4. It is easy to find that such trend information about the demand will be distorted through the forecasting model and *S*-level calculation, and consequently the demand distorted result will pass to the supplier in a form of "order". The greater value of ρ is, the larger distortion will be. Because demand correlation directly influences the forecasting efficiency regardless any characteristics of postponed supply chain and information can help organizations resolve the demand distortion, the information strategy will benefit a supply chain more with an increasing demand correlation coefficient.

Note that for comparison purpose, in this study we define the information value as the performance ratio of one ISS to the benchmark information strategy, i.e. OIS, given the same system parameters. Therefore to compare whether the value of a particular information sharing strategy increases with the changes of one system variable, we actually compare ratios of its performance to the benchmark OIS, not their absolute changes in performances. In another word, we are more concerned about the percentage changes of information's marginal value compared with the benchmark, but not the absolute value changes.

With DIS, the upstream organizations can use the real market demand, instead of the order, to forecast the future demand with less error. Therefore the value of demand information is expected to be greater with higher correlation coefficient. There is another way to reduce demand distortion if SIS is available: When the accumulated distortion damages the supplier's performance and if such situation can be quickly fed back to its customer, the downstream organization can timely adjust its order decision in return. Therefore the supply chain may also benefit from the SIS.

In summary, with higher demand correlation, supply chain cost reduction by DIS is expected to increase, while the service improvement by SIS also increases. However, whether DIS will influence supply chain's service level and whether such influence is significantly related to demand correlation is unclear from the deduction. Similarly, the relationship between cost reduction and demand correlation in SIS is not deducible from analyzing supply chain's dynamic decision process. Therefore, in Table 3-3 that summarizes the sensitivity of demand correlation, we use plus sign to denote its positive relationship with cost reduction in DIS and service improvement in SIS, but use question mark to denote its unclear relationship with service improvement in DIS and cost reduction in SIS.

Demand Variance

Another demand parameter that will affect the supply chain performance is the market demand fluctuating, i.e. ε_t in the demand model. Given a simple moving average forecasting model and the no-trend normalized demand process, the forecast accuracy will not be influenced much with demand variances. However as demand variance increases, more safety stock is built up at supply chain members and the marginal redundant inventory reduces. Therefore the DIS is expected to contribute less on inventory cost reduction as the demand variance increases. It does not mean the inventory cost reduction, enabled by DIS, becomes insignificant or lower. In fact the absolute inventory cost reduction should increase as demand variance increases. However the ratio of such reduction to the OIS will decrease. However such variance will not affect the value of SIS because it is not a direct or important factor to influence the shipment uncertainty. Considering the high target service level, i.e. *95%*, in the experiment. The impact of demand variance on SIS behavior would be insignificant. Therefore the demand information sharing strategy will benefit postponed supply chains less with the increasing demand variance.

In summary, with higher demand variance, only the supply chain cost reduction by DIS is expected to decrease. All the other influence, including the cost reduction and the service improvement by SIS, and the service improvement by DIS, cannot be clearly deduced from analyzing the dynamic decision process. Therefore, in Table 3-3 that summarizes the sensitivity of demand variance, we use subtraction sign to denote its negative relationship with cost reduction in DIS, but use question mark to denote other unclear relationship with DIS and SIS.

Production Leadtime

When analyzing postponement, we are interested in the impact of production leadtime on the supply chain performance. Production leadtime is one proportion of the total leadtime which from the time the raw material is available to the time the finished product is delivered to the end customer throughout a supply chain. In practice, manufacturing-oriented industries, in which manufacturing activities take much of the total lead-time, and logistic-oriented industries, in which delivering activities take much of the total lead-time, are two typical types of industry. With production leadtime changes, the impact of postponement strategy to the whole supply chain may also changes (Note that we can change the leadtime between any two tiers to achieve the same purpose but is less efficient than only changing the production leadtime). As we know, the value of SIS largely arises from the faster feedback between two tiers. Therefore a larger leadtime between two tiers, the greater value of shipment information may become realized. However since no-postponement and form-postponement does not change the leadtime between two tiers, SIS is not expected to perform better in these two situations. Because changing production leadtime does not directly affect the reduction of demand distortion, DIS is not expected to significantly influence the supply chain performance with the changes of leadtime. Therefore the shipment information sharing strategy will benefit several postponement supply chains more when the production leadtime increases.

In summary, with larger production leadtime, we cannot deduce its significant influence on supply chain cost reduction and service improvement in DIS. However its influence on service improvement in time postponement and place postponement is expected to increase. Therefore, in Table 3-3 that summarizes the sensitivity of leadtime, we use plus sign to denote its positive relationship with service improvement in SIS, but use question mark to denote its unclear relationship with cost reduction and service improvement in DIS, and cost reduction in SIS.

Service Level

As lower service level directly links to higher shipment uncertainty, a high-service provider can promise a stable shipment and consequently counteracts the value of shipment information. Furthermore, a tier's higher target service level may decrease the marginal value of DIS: As the target service level increases, more safety inventory is set up which counteracts part influence from demand fluctuating. However since the front tier's service level should not directly affect upstream performances except by the order decision, the retailer's target service level will not affect the information value. Therefore the target service level at the upstream organizations, except the front tier, in a supply chain will influence the information value.

In summary, with higher target service level, supply chain cost reduction by DIS is expected to decrease, while the service improvement by SIS also decreases. However, whether DIS will influence supply chain's service level and whether such influence is significantly related to target service level is unclear from the deduction. Similarly, the relationship between cost reduction and target service level in SIS is not clear. Therefore, in Table 3-3 that summarizes the sensitivity of target service level, we use subtraction sign to denote its negative relationship with cost reduction in DIS and service improvement in SIS, but use question mark to denote its unclear relationship with service improvement in DIS and cost reduction in SIS.

Therefore, the deducible significant impacts of four system parameters, including demand correlation, demand variance, production leadtime, and tier's target service level, on supply chain performances can be summarized in Table 3-3.

System factors / Postpone	Demand Correlation (ρ)		Demand Variance (σ)		Production Leadtime (L)		Target Service Level (α)	
	DIS	SIS	DIS	SIS	DIS	SIS	DIS	SIS
Form	Cost +	Cost **?**	Cost **-**	Cost **?**	Cost **?**	Cost **?**	Cost **-**	Cost **?**
	Service **?**	Service +	Service **?**	Service **?**	Service **?**	Service **?**	Service **?**	Service **-**
Time	Cost +	Cost **?**	Cost **-**	Cost **?**	Cost **?**	Cost **?**	Cost **-**	Cost **?**
	Service **?**	Service +	Service **?**	Service **?**	Service **?**	Service +	Service **?**	Service **-**
Place	Cost +	Cost **?**	Cost **-**	Cost **?**	Cost **?**	Cost **?**	Cost **-**	Cost **?**
	Service **?**	Service +	Service **?**	Service **?**	Service **?**	Service +	Service **?**	Service **-**

Table 3-3: The summary of deducible significant impacts of system parameters on the supply chain performance. Cost: the cost reduction ratio in a supply chain; Service: the service improvement ratio in a supply chain; +: deducible positive influence; -: deducible positive influence; ?: unclear / insignificant influence by information.

3.4. The Methodology

Researchers in information systems use various techniques to model, analyze, and solve complex decision problems. Simulation is one of the popular techniques among them. It allows the researcher to capture and experiment with the rules in real or proposed systems. There are some situations in which a problem cannot meet the assumptions set by analytical modeling methods. At this time, especially when a problem exhibit significant uncertainty and is quite difficult to deal with analytically (Evans and Olson, 1998), simulation can be a valuable approach to solve the problem.

3.4.1. The concept of simulation

What is simulation? It is a simple question with no unique answer. Various researchers contribute to the definition of the simulation in its development, which represents different perspectives on this technique. Early definitions, like Naylor et al. (1966), defined simulation as a numerical technique for conducting experiments on a digital computer, which involved certain types of mathematical and logical models that describe the behavior of business or economic system over extended period of real time. More specifically, Shannon (1975) defined simulation as the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system. Law and Kelton (1991) defined simulation as a technique using computers to imitate, or simulate, the operations of various kinds of real-word facilities or processes. Evans and Olson (1998) defined simulation as the process of building a mathematical or logical model of a system or a decision problem, and experimenting with model to obtain insight into the system's behavior or to assist in solving the decision problem. Thompson (1999) defined simulation as the generation of pseudo-data on the basis of a model, a database, or the use of a model in the light of a database.

Although above definitions cannot be form as one, there are several key words: model, experiment and process, inside these definitions that may help us to understand the essence of simulation.

Model: a principal advantage of simulation lies in its ability to model any appropriate assumptions about a problem or system, making it the most flexible management science tool available (Evans and Olson, 1998). Pure mathematical model sometimes is a toy answer to toy problem (Kosko, 1993) and cannot fit the reality of the nature after setting too many assumptions. With the help of simulation, more assumptions can be clearly quantified and become available in the model.

Experiment: a model is worthless unless it provides some insight to the users. Thus, a major focus of simulation is conducting experiments with the model and analyzing the results. Based on computer techniques, large numbers of repetitive computations on variables changing could readily be performed, thus researchers may get and evaluate several possible solutions to the problem.

Process: simulation is a complicated analytical process on problem solving, which includes model validation, input probability distributions selection, output data analyzing, variance reduction and so on. In fact, the process is generally not a sequential process and the researchers may go back to any previous stages at any time during the process for revising. Therefore the word “cycle” is more suitable to indicate the activities taking in the simulation study. Shannon (1975) believed modeling process should be a learning process for both the modeler and the user. Based on the view that a simulation was used to investigate the properties of a real system, Shannon summarized eleven stages in the problem-solving process with simulation: system definition, model formulation, data preparation, model translation, validation, strategic planning, tactical planning, experimentation, interpretation, implementation, and documentation.

Based on the simulation process described by Shannon (1975), Law and Kelton (1991) re-defined the whole process in ten procedures that were more suitable to indicate the steps in the simulation study, as shown in the Figure 3-5. They also pointed out there were several things to pay attention to in the process of simulation research: first, it was not a must for all the simulation research contains all the ten stages. For example, sometimes making pilot runs might be ignored if the analyzer did very well in verifying the program. Secondly, the simulation study was not a sequential process and the research might go back to any previous stages at any time during the process if he had enough reasons to believe the system or some components in the system should be redefined, such as in the situation that some new coming information deepened the researcher’s understanding of the problem. Thirdly, the stages might not be taken in the stated order. For example, the experiment designing might be put forwards before constructing the simulation program. Similarly Evans and Olson (1998) summarized five essential stages in the simulation process.

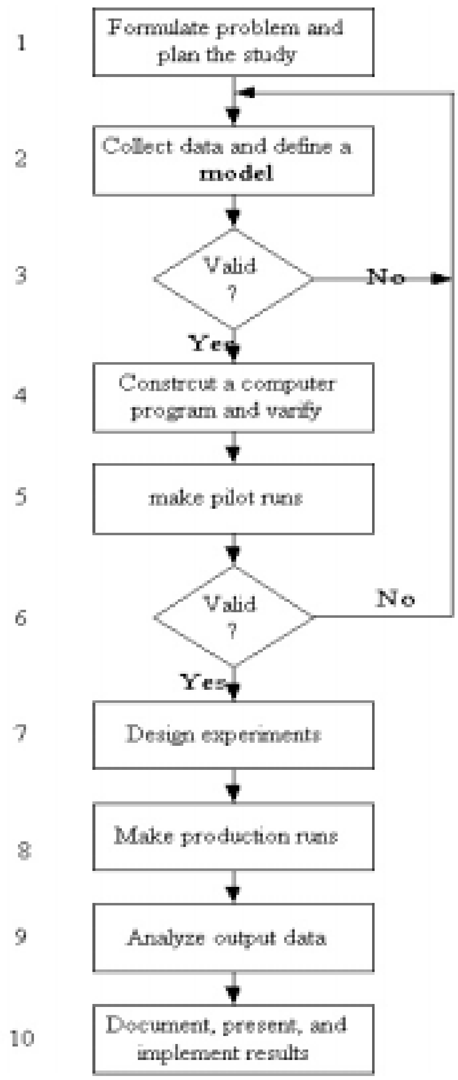

Figure 3-5. Steps of simulation study in Law and Kelton (1991)

Generally speaking, there are two main types of simulation system: discrete and continuous systems. A discrete system is one for which the state variables change instantaneously at separated points in times, while a continuous system is one for which the state variables change continuously with respect to time (Law and Kelton, 1991). The casher's desk can be regarded as a discrete system since the status of variables here, i.e. the coming customers paying for their purchasing, changes only when the customer arrives, or when he finishes paying and leaves. On the other hand, the human metabolic system is a continuous system as it keeps working with respect to time. Although few cases in the real world are solely discrete or continuous system and sometimes the system classification largely depends on analyzer's particular perspective, it is possible for analyzers to classify either the discrete or continuous system if one type of variables changing can be reasonable regarded as the notable factor. Our system in this study is a discrete one.

3.4.2. The value of simulation in supply chain study

Law and Kelton (1991) believed that simulation had become one of the most widely used in operation research and management science, proven by several survey results in their book. After comparing the growth of the simulation with other new technologies of the last twenty or thirty years and surveying a number of major companies, Profozich (1997) drew the conclusion that the simulation had become a mainstream technology on decision-making. A survey held by IIE Solutions in May 1998 showed almost half of the forty-one responded companies used simulation and another twenty percent had plans to use it in the future. Based on this survey result, Garnett (1999) concluded that although the simulation could not yet be considered as a mainstream technology, the steady growth of simulation in recent years seemed destined to continue.

There is such a view which regarding simulation as a last-accepted, or doubtful, method since the simulation results sometimes can not be proven scientifically enough and not accepted by some researchers. However, recent advances in simulation methodologies, software availability, sensitivity analysis, and stochastic optimization have combined to make simulation one of the most widely accepted and practiced tools in system analysis and operation research (Rubinstein et al. 1998). Furthermore, simulation can solve complicated real-world problem with wide scope and scalability (Law and Kelton, 1991) and is an effective way to improve modeling (Galliers and Land, 1987). Since simulation is built on mathematical or logical model, there are few barriers between simulation implementation and models. By simulation, computers are used to evaluate a model numerically, and data are gathered in order to estimate the desired true characteristics of the model and to find out how accurate the logic / analytical model fits the real situation.

Simulation system is a powerful tool to study the dynamic supply chain network since it enables a detailed review of the inner-workings in real time that is not seen in the high level analytical models (Shannon et al. 1980). Mathematical and analytical approaches usually study only specific aspects of the supply chain network in isolation, e.g. only the performances about one tier in a supply chain is analyzed, or only one or two performances is measured in a chain. As we discussed in the previous sections, research showed that the locally optimized performances in one stage did not promise an improvement in the whole supply chain, sometimes even caused the supply chain performance worse. Therefore analyzing few performances at a single stage cannot provide a full and correct picture of the whole chain changes. For example, Dong and Lee (2002) argued that the inventory removed at a certain place in a supply chain might be transferred to another place in the chain when changing the channel structure, which meant other members' cost and service were influenced as well. In this case, analyzing one or two member's performances in a chain was definitely not enough. Simulations, on the other hand, can simulate the actual behaviors of the real world enterprises thoroughly crossing the whole chain.

In summary, simulation is one of the methodologies widely recognized in information system research, particularly used in the situations in which the analytical models with various assumptions cannot represent the problem thoroughly or clearly. This methodology is founded with the appearance of modern computer. Till now, it has become a mature methodology in social science and operation research and covers various fields, including geology, mathematics, government policy-making, army, manufacturing, demography and so on. However, in some research fields it is regarded as unscientific, or not scientific enough, mainly because the process of translating the mathematic/logic model into computer program cannot be clearly indicated by the analyzer, neither does the simulation modeling itself. Lack of the scientific validation to the modeling and the process of simulation, it is hard to persuade readers, sometimes even the analyzer himself, to accept the result. Thus, to do a successful research by using simulation, researchers must use simulation methodology fully and thoroughly along the whole research process.

CHAPTER 4 EXPERIMENT DESIGN AND MODEL VALIDATION

In order to model the information-shared postponement in a supply chain network, we need to define a set of parameters in the simulation model, including the network structure of a supply chain, the product structure, the demand pattern, the inventory / production / transportation process, information sharing policies and the postponement redesign approaches. To understand the behaviors and simplify the model, we define the supply chain network as a linear three-tier supply chain, only one entity in each tier, i.e. a retailer, a manufacturer and a supplier. To simulate postponement implementation, we set two end products, each of which contains both common components and differentiation component. At the beginning of each period, end customer demand quantity is generated according to the demand pattern and sent to the retailer. Upon receiving the order from its customer, each tier makes the order decision on required products and/or components and places relative orders with its upstream supplier. This execution goes from downstream to the upstream, which triggers material flow in the opposite direction, and ends when the end customer receives the shipment. In addition, the manufacturer will produce end products to satisfy customer order. The period is then repeated.

4.1. General Settings And Assumptions For The Experiments

The experiments were divided into two parts: a basic experiment for a given initial environment and a sensitivity experiment for sensitivity analysis. In the first part, the simulation was run with a set of system parameters at their initial values. In the second part, system parameters, including demand variance, demand correlation, production leadtime, and tier's target service level, were independently varied from a lower value to a higher value respectively to perform sensitivity analysis.

In any models of real systems, there is uncertainty associated with parameters value. If the changes in a parameter value results in the numerical changes of other variables, this model is numerically sensitive. In fact, all quantitative models exhibit numerical sensitivities (Richardson and Pugh, 1981). Numerical sensitivity analysis indicates that which parameters must be estimated with great care or may be a point of high leverage in real system. Furthermore, comparing the result of sensitivity analysis with the basic case, the behavioral sensitivities of supply chain performances become clear. This in-depth study provides a comprehensive understanding of the supply chain dynamics in various environments.

Other general assumptions in this study are summarized below:

- We assume a three-tier linear supply chain structure, with one member per tier, consisting of one retailer, one manufacturer and one supplier, to represent a typical production-inventory system.
- Each tier can handle multiple products and components with no limit on its inventory and production capacity.
- There is not significant cost occurring in information communication, e.g. ordering cost. With information technologies, such as EDI and Internet,

information and communication can be shared between each other without significant cost.

- Setup time and setup cost in the production is not considered since we assume a continuous production process.
- One-time investment to implement information-shared postponement strategies is not considered since such cost usually become small enough after sharing to large volume of products and can be reasonable ignored.
- Unfulfilled order is backlogged with priority to be replenished next period.
- Inventory can be monitored continuously and an order is placed periodically when the inventory position falls below the stock level.
- The supplier of the most upstream member, i.e. the supplier's supplier, has unlimited supplying ability to always satisfy its customer's order perfectly in time.

In the following sections, we will introduce basic experiment designs for the supply chain network, for the postponement strategies, for the information sharing strategies and for the performance measurements respectively.

4.2. Experiment Design For A Supply Chain Network

In our example, the supply chain manages two different end products, P1 and P2. The demand processes for them follow a AR(1) process without seasonality. In the basic experiment, we set demand parameters of two products are the same and $u = 100$, $\sigma = 30$ and $\rho = 0$. As a result, two demand processes reduce to being simple normally distributed. Later we will study the demand correlation using sensitivity analysis. These demands could represent a collection of demands aggregated from numerous individual consumers or from a group of industrial customers. Each product contains three components. The original production processes of these two products are the same. In our setting, the main difference of product1 and product2 comes from the different component at the second production stage, i.e. component B1 and B2 respectively. The bill of material (BOM) and the production process for end products are as follows:

Product	Component
P1	
	A(1)
	B1(1)
	C(1)
P2	
	A(1)
	B2(1)
	C(1)

Figure 4-1: BOM of two end products.

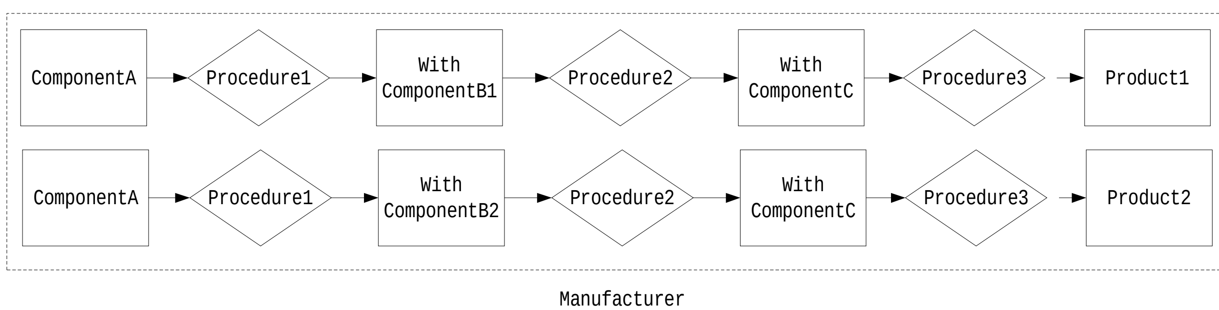

Figure 4-2: The initial production process for product 1 and 2 in the plant.

All the four components have the same material cost c and the same processing time t. The unit production cost, p, and the unit inventory cost, h, period is the linear function of product's value. The cost of semi-finished product at different production stages can also easily be inferred from this relation. In the basic experiment, the inventory holding cost per component is set as *1* unit cost and the total production leadtime is *6*, so $t=2$.

The supply chain contains three tiers: the retailer (tier 1, which could also be a distribution center or a regional wholesaler that stores and distribute products), the manufacturer (tier2, a producer which produces the two functional products) and the supplier (tier3, which provides components or raw materials to the plant), as shown in Figure 3-1. Initially, the products are only produced at the manufacturer side, while the supplier provides necessary materials, i.e. A, B1, B2 and C, to the manufacturer, and the retailer orders the final products, i.e. P1 and P2, from the manufacturer, stores and sells them to the end market. Each tier in a supply chain sets a same service level at *s*. Previous backlogs are prioritized for fulfillment in the future. The initial leadtime between each tier is the same in this study.

The ultimate supplier, i.e. the supplier's supplier, has an infinite capacity to supply whatever its customer orders. Eppen and Scharage (1981) showed that when using linear inventory holding and backlog costs and under fairly moderate assumptions, the optimal inventory policy was to operate each end-product stock as an order-up-to system. Therefore in this study we assume all chain members use order-up-to periodic-review inventory policy. The order-up-to level, S, is denoted as $S_t = L\hat{d}_t + z\hat{\sigma}_t\sqrt{L}$, where z=$\Phi^{-1}[b/(b+h)]$ ($\Phi(\cdot)$ is the standardized normal cumulative distribution, b is the unit backorder cost per period and h is the unit inventory holding cost per period. In this study, $z=1.65$, so the stock out rate is about *5%* consequently), L is the lead-time between the tier and its supplier and is set at *6* in the basic experiment, $\hat{d}_t$ and $\hat{\sigma}_t$ is the estimated mean demand and estimated demand standard deviation respectively in period *t* (subscript *t* denotes the variable in period *t*). Note that under different information circumstances, the optimal inventory policy may not be the same. However to facilitate comparison and to focus on the impact of "changing a given" (Silver, 1992) rather than on optimizing inventory policy, we fixed the base inventory policy to be the same in all cases of this study.

Each tier in the supply chain uses a simple moving average method to forecast the future demand which can effectively eliminate random error in it (Chase et al., 1998). The formula can be expressed as $\hat{d}_t = \sum_{j=1}^{n} d_{t-j} / n$, where $\hat{d}_t$ is the forecast value of the next period-t, $d_{t-1} \ldots d_{t-n}$ is the actual demand in the last *n* periods and *n* is the number of demand observations in the simple moving average forecast. Chen et al. (2000) argued that the variance of the orders, placed by the downstream to its supplier, satisfies a lower bound as $1 + \left(\frac{2L}{n} + \frac{2L^2}{n^2} \right)(1 - \rho^n)$ where *L* is the leadtime between two successive tiers in a supply chain and ρ is the correlation parameter of the demand process. Because ρ in the basic experiment is zero but is changed in sensitivity analysis, we assume that each tier sets forecasting window size as *10* times greater than the leadtime between customers and itself ($n/L = 10$) as a balance between the experiment and its sensitivity analysis.

Each tier in a chain holds its own inventory of products it serves. At manufacturer site materials are held in its own inventory while retailer builds stock on end products. However, depending on its own production / inventory decision, manufacturer has various choices to build up work-in-process stock in production process, besides material stock and end product stock. One simple and reasonable way to consider inventory positions at the manufacturer site is to decompose the whole production process into two different basic channel structures: MTS and MTO (e.g. Lee, 1996; Gupta and Benjaafar, 2001 and Robinson and Elofson, 2000, 2001), as shown in Figure 2-5. The edge of these two channels is the point of production differentiation and is also the place to build stock for intermediate common product, which means at this point products are of no difference. After this point, these products will be assembled to different end products due to customer demand. Production using different postponement strategies will choose different point to set up its stock for intermediate products, we will discuss it in details when designing experiment for postponement.

4.2.1. Algorithm logics in simulation program

This subsection lists the algorithm describing supply chain activities in the simulation. At conceptual level, an experiment is composed of testing for 12 information-shared postponement cases, i.e. the combination of four different postponement environments (one was no-postponement case) with three different informative environments, in a supply chain. At the simulation program level, each test of the information-shared postponement case is a complete experiment. The complete simulation experiment consisted of two processes: the initial stage and the periodic running process. The initial stage was carried out only once, to set system parameters in experiment, initialize randomness, and warm up the system. The periodic running process contained all the activities in a supply chain, including demand forecasting, product ordering, storing and shipping, and collecting performance statistics. This process ran for *2000* computer-simulated periods to simulate daily (or hourly or weekly) operations of each tier in a supply chain after each experiment started. The following summarizes the tasks performed at the initial stage and periodic running process respectively.

**Initial stage*

- Importing configuration file of experiment settings

- Setting system variables with proper values in the experiment

- Initialing random number generators

- Warming up the system to store enough historic data for demand forecasting and order-up-to level calculation

** Periodic activities in a supply chain.*

<u>At Retailer Tier</u>

- Receiving market demand on products

- Receiving shipment from the manufacturer

- Fulfilling demand and any accumulative backlog

- Forecasting future demand and its variance of products

- Calculating order-up-to level

- Determining the order quantity and placing the order with the manufacturer

- Summarizing its service and cost performances at this period

At Manufacturer Tier

- Receiving retailer's order on products
- Receiving component shipment from the supplier
- Receiving finished product from the production line
- Fulfilling the retailer's order and any accumulative backlog
- Forecasting future demand and its variance of products
- Calculating order-up-to level for products
- Determining production quantity and scheduling production
- Forecasting future demand and its variance of components
- Calculating order-up-to level for components
- Determining the components ordering quantity and placing the order with the supplier
- Summarizing its service and cost performances at this period

At Supplier Tier

- Receiving manufacturer's order on components
- Receiving shipment from its supplier
- Fulfilling manufacturer's order and any accumulative backlog
- Forecasting future demand and its variance of components
- Calculating order-up-to level for components
- Determining the order quantity and placing the order with its supplier
- Summarizing its service and cost performances at this period

The in-transit shipment and production quantities are stored in a special data structure to connect the material flow between tiers in a chain. Also note that the activity sequences at each tier may not strictly follow the order described here but does not affect the essence of supply chain activities.

4.3. Experiment Design For Postponement Strategies

Three postponement strategies are implemented into the supply chain. To implement *form postponement*, we consider using a universal component B, which have both functions of B1 and B2, to replace component B1 and B2 in the production stage in the plant. As a result, the differentiation of P1 and P2 is eliminated insides the product. Therefore the production process after implementing this strategy changes as follow:

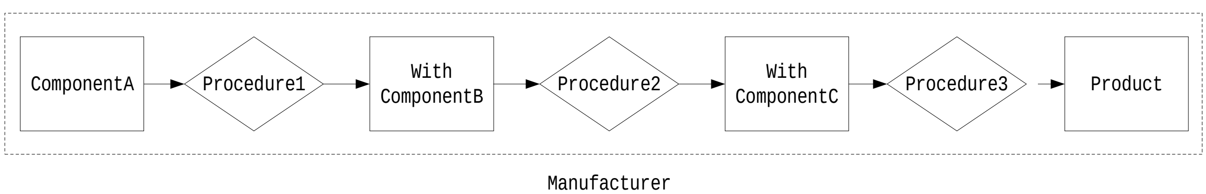

Figure 4-3: Production process after form postponement in the plant. A standardized component B is used to take place of component B1 and component B2 in the production.

In this case the difference between two products are completely eliminated, so the production for common intermediate products, i.e. the differentiation point, is fully postponed to the end of the process. Therefore only material stock and end product stock are considered here. The producing time for this new component remains the same as before. Therefore, the benefit of this strategy comes from reducing the safety stock.

To implement *time postponement*, we consider changing the production sequence of the product in the plant so that the general components, i.e. component A and C, can be integrated into the product before integrating component B1 (B2) to differentiate product 1 and 2. Consequently, the sequence of procedure2 and procedure3 exchanges simultaneously, as shown in Figure 4-5. One-time fix cost during redesigning may be reasonably ignored when the future product quantity after such redesign is sufficiently large. This strategy helps the manufacturer to move the stock point to the general unfinished product, rather than the final products, to gain risk-pooling benefit in inventory management. Since the differentiation point in this case has been postponed after procedure3, the inventory for common intermediated products is delayed as well.

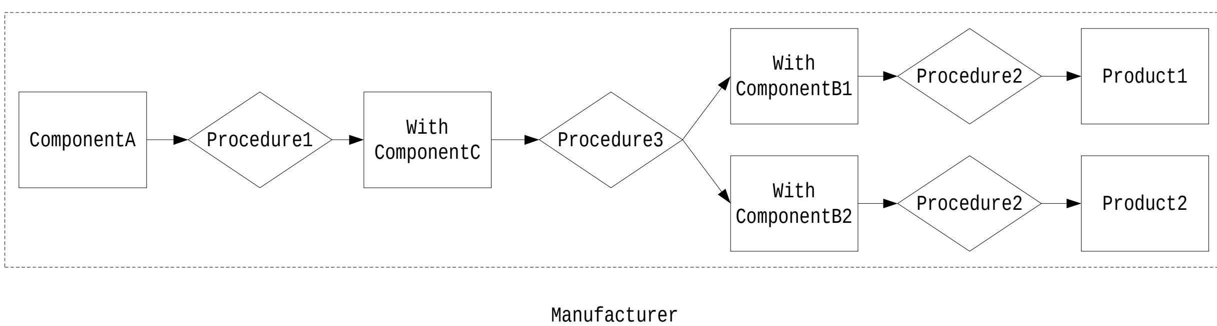

Figure 4-4: Production process after time postponement in the plant. The sequence of procedure2 and procedure3 is reversed.

To implement *place postponement*, we consider delaying the procedures with component B1 (B2) and component C from the plant to the retailer (or distribution center), i.e. let the retailer carries out procedure2 and procedure3, as shown in Figure 4-6. If these delayed operations do not require professional equipment, labor or technology strictly, one-time investment may close to zero. In this case, the stock for intermediated products will move to the retailer site where the differentiation work starts.

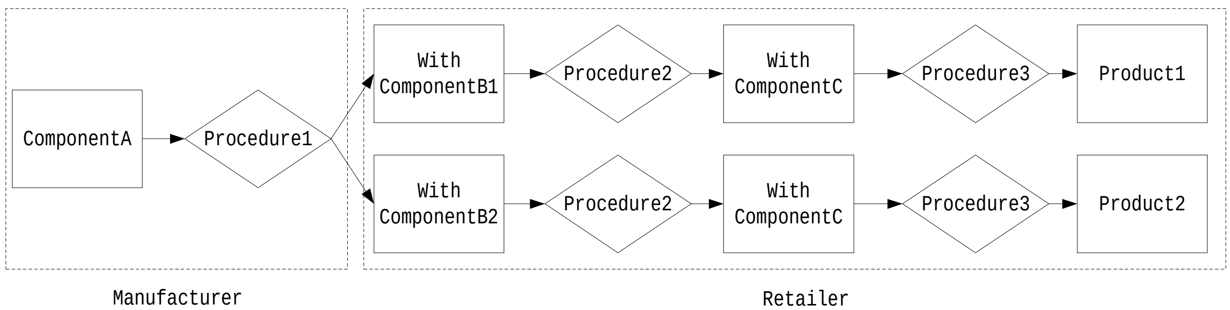

Figure 4-5: Production process after place postponement. Procedure with component A is carried out in the plant while the remaining procedures are carried out in the downstream site.

4.3.1. Combined postponement design

Due to the complexity of product design, various postponement strategies sometimes are applied simultaneously in practice. For example, HP designed two postponement strategies together to delay the supply difference of its Deskjet printers, which was different from the single postponement approach applied on its LaserJet printers. Initially, HP manufactured its Deskjet-Plus printers in its Washington Division and shipped the printers to three distribution centers (DC) in North America, Europe and Fast East respectively. Depending on the regional demand, different power supply modules had to be installed in the printers to accommodate local voltage, frequency and plug conventions. Therefore HP redesigned the printer so that the power module could be added as a simple plug-in, manufactured generic Deskjet-Plus printers, i.e. without particular power supply module, in the U.S. plant and later localized them in oversea distribution centers, based on observed regional demand conditions there. To implement such a DC-localization policy, HP made some design changes to the product so that the power supply module would be the last component added on and such addition was a simple plug-in. Then the power supply was assembled at DC. By restructuring its printer production process in this fashion, HP maintained the same service level with an *18%* reduction in inventory (Lee et al., 1993).

Therefore this study would be more practical if we can understand how the combined postponement strategies in supply chains are influenced by information strategies. As an extension to experimental design, we also modeled the combined postponement cases and believed these settings would extend the extant of this study and generalize the results from previous design.

First, we choose above HP Deskjet case as the example of combined approach of time and place postponement, and put it into the model we developed. To implement this combined postponement, we consider reversing the sequence of procedure 2 and 3, then delaying the procedures with component B1 (B2) from the plant to the retailer (or distribution center), i.e. let the retailer carries out procedure2 finally while the plant carries out procedures 1 and 3 first. Other settings keep unchanged. As a result, the production process after implementing this combined strategy changes as follow:

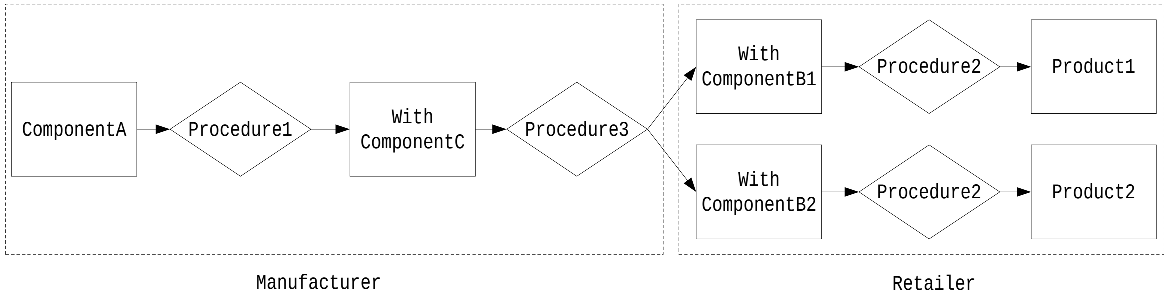

Figure 4-6: Production process after combined time and place postponement. Procedure with components A and C are carried out in the plant while the remaining procedures are carried out in the downstream site.

Production localization becomes prevalent in today world, which usually helps companies increase response time to a local customer's order, avoid duties, reduce transportation and labor costs and achieve a positive market value of maintaining a local-manufacturing presence. With the product standardization at the plant, we can find that such localization is in fact a combination of form and place postponement. Still take HP's generic printer with universal power supply as example. Its final assemble activities, such as manual packaging, can be delayed to the local distribution centers since the manual and other packaging stuffs can be supplied by local suppliers to save costs of inventory, transportation, material, duties, et cetera, and to increase network agility (Feitzinger and Lee, 1997). We define it as the combined postponement case 2, which is in fact a combination of form and place postponement approach, to distinguish it from the previous case.

To implement this combined postponement, we consider replace component B1 and B2 with a universal component B, then delaying the procedures with component C from the plant to the retailer (or distribution center), i.e. let the retailer carries out procedure3 finally while the plant carries out procedures 1 and 2 first. All other settings keep unchanged. As a result, the production process after implementing this strategy changes as follow:

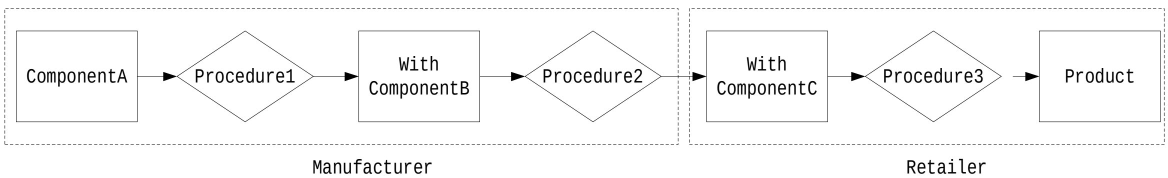

Figure 4-7: Production process after combined form and place postponement. Procedure with components A and B are carried out in the plant while the remaining procedures are carried out in the downstream site.

Note that there are few examples of combining form and time postponement in practice, which is quire reasonable: Since form postponement has already delayed the product differentiation to the latest possible point, changing the sequence of production process does not have much contribution to supply chain improvement. Therefore in this extension, we are not going to analyze it.

4.4. Experiment Design For Information Sharing Strategies

OIS is the basic form for supply chain to collaborate with each other, i.e. no other information received by the supplier except orders from immediate downstream organization. In this case, each tier in the chain uses the history of customer's order quantity as the demand information to estimate the future mean demand and demand variance. These estimated values will be used to adjust the order-up-to *S* level in inventory and finally affect the order decision.

When sharing demand information in a supply chain, each tier is aware of end market demand for the products and uses such information to forecast the future demand. Consequently the optimal *S* level is directly affected by this information.

When the supplier shares its shipment information with the manufacturer, the manufacturer is aware of its coming shipment. Hence it can easily infer the proportion of demand filled within next L_i days and uses the real coming shipment quantity instead of its unfulfilled order quantity having placed to the supplier to adjust its order decision. However its forecasting quality and optimal *S* level is not improved and keeps the same as that in OIS. Also note that in our study, we only consider the SIS between the manufacturer and the supplier.

The demand forecasting methods, *S* level and order decision of supply chain members with different information sharing strategies are summarized in Table 4-1, Table 4-2 and Table 4-3, respectively. We can find that by replaying the order quantity with the real demand, the demand forecasting equation and *S* level calculation in DIS is different from the other two, while the order decision in SIS is different from the other two by replacing the unfulfilled order quantity with the real shipment in the way.

Information Sharing Strategies	Demand Forecasting Equation
Order-IS	$\hat{d}_{i,t} = \sum_{j=1}^{n} o_{i,t-j} / n$, $\hat{\sigma}_{i,t}^{2} = \sum_{j=1}^{n} \left(\hat{d}_{i,t} - o_{i,t-j} \right)^2 \Big/ (n-1)$
Demand-IS	$\hat{d}_{t} = \sum_{j=1}^{n} d_{t-j} / n$, $\hat{\sigma}_{t}^{2} = \sum_{j=1}^{n} \left(\hat{d}_{t} - d_{t-j} \right)^2 \Big/ (n-1)$
Shipment-IS	$\hat{d}_{i,t} = \sum_{j=1}^{n} o_{i,t-j} / n$, $\hat{\sigma}_{i,t}^{2} = \sum_{j=1}^{n} \left(\hat{d}_{i,t} - o_{i,t-j} \right)^2 \Big/ (n-1)$

Table 4-1: Demand forecasting equations used in various information sharing strategies.

Information Sharing Strategies	Order-up-to Level
Order-IS	$S_{i,t} = L_i \cdot \sum_{j=1}^{n} o_{i,t-j} / n + z_i \sqrt{\sum_{j=1}^{n} \left(\sum_{j=1}^{n} o_{i,t-j} \Big/ n - o_{i,t-j} \right)^2 \cdot L_i \Big/ (n-1)}$
Demand-IS	$S_{i,t} = L_i \cdot \sum_{j=1}^{n} d_{t-j} / n + z_i \sqrt{\sum_{j=1}^{n} \left(\sum_{j=1}^{n} d_{t-j} \Big/ n - d_{t-j} \right)^2 \cdot L_i \Big/ (n-1)}$
Shipment-IS	$S_{i,t} = L_i \cdot \sum_{j=1}^{n} o_{i,t-j} / n + z_i \sqrt{\sum_{j=1}^{n} \left(\sum_{j=1}^{n} o_{i,t-j} \Big/ n - o_{i,t-j} \right)^2 \cdot L_i \Big/ (n-1)}$

Table 4-2: S levels used in various information sharing strategies.

Information Sharing Strategies	Order Decision
Order-IS	$Q_{i,t} \mid r_{i,t} = \left[0, S_{i,t} - \sum_{1}^{L_i - 1} Q_{i,t-i} - r_{i,t} \right]^{+}$
Demand-IS	$Q_{i,t} \mid r_{i,t} = \left[0, S_{i,t} - \sum_{1}^{L_i - 1} Q_{i,t-i} - r_{i,t} \right]^{+}$
Shipment-IS	$Q_{i,t} \mid r_{i,t} = \left[0, S_{i,t} - \sum_{1}^{L_i - 1} y_{i,t+i} - r_{i,t} \right]^{+}$

Table 4-3: Order decisions equations used in various information sharing strategies.

4.5. Validation Of The Simulation Models

We must validate the model first before analyzing. Although it is impossible to find out a complete same model as the real-world problem, we can concentrate on validating the insights we have gained or will gain from the simulation (Shannon, 1975). If a model is "valid", then the decisions made by the model should be applicable to those in the real world.

There are two main aspects of validation: validating whether the model behaves in the same fashion as the real-world case, and validating whether the inferences drawn from the experiments using the model are valid. Based on this view, Shannon (1975) introduced several methods to validate the simulation model. First, the researcher must ascertain that the model has face validity and the results of the model appear to be reasonable. Then the researcher should test the assumptions and the input-output transformation respectively which require statistical tests, such as analysis on mean, variance, regression and so on. In order to achieve this, following model validation analyses are employed, after clearly understanding of the logic and the structure of supply chain systems presented in the previous sections. The whole construction process of simulation model follows Law and Kelton (1991), as shown in Figure 3-5. Although Law and Kelton (1991) pointed out that it was not a must for the simulation research contains all the ten stages, the stages might not be taken in the stated order and the simulation study was not a sequential process, this flow diagram provides a good guideline for us to construct our simulation model in this study.

4.5.1. Simulation tool: GPSS/World

GPSS, the General Purpose Simulation System, is one of the worlds' most popular languages in computer simulation, firstly developed by Geoffrey Gordon at IBM in the early 1960's. It provides a rich basis for modern simulation environments. Moreover, GPSS deeply influences many other simulation languages that now rely on derivations of GPSS concepts.

GPSS/World, maintained by Minuteman Software, is a direct descendent of GPSS/PC, an early implementation of GPSS for personal computers which was introduced in 1984. GPSS/World is primarily intended to be an extension of simulation environment for GPSS/PC users, enhanced by an embedded programming language PLUS, Programming Language Under Simulation. It brings all the simulation primitives up to the user interface, and makes it easy to visualize and manipulate simulations. As a result, simulations can be developed, tested, and understood more quickly than ever before in GPSS/World environment. All transactions in the simulation can be saved at any time in any state, with detailed descriptive statistics. Its nature allows the internal mechanisms of models to be revealed and captured. Its interactivity allows one to explore and manipulate simulations. Its pre-developed simulation validity technology makes experiment convenient to be warmed-up and repeated. Its built-in data analysis facility can calculate confidence intervals and an analysis of variance easily. In this study, we model the entities in a linear supply chain network consisting of one retailer, one manufacturer and one supplier. Each of the entities perform tasks like receiving orders, receiving shipment from its supplier, fulfilling orders, calculating inventories, forecasting demands, placing orders to its supplier and producing products. The combination behavior of each entity composed a complex environment.

4.5.2. Statistical analysis for model validity

Since GPSS is a stable simulation system that provides detailed transaction reports for post analysis, we focus our internal validation on whether the simulation model correctly represents the supply chain. Considering a multiple-tier linear supply chain structure which consists of a retailer (R), a manufacturer (M) and a supplier (S), if we set the safety stock factor at upper tiers, i.e. M and S, extremely high in the chain, say *8*, then M can be viewed as an ultimately source to R which has unlimited supplying capability. As a result, R reverts to a basic single-stage case in operations research. It can be calculated that when $z>7$, the tier's expected stock-out probability, i.e. $1-\Phi(z)$ where $\Phi(\cdot)$ is the standardized normal cumulative distribution, is below *1E-12* which can be safely ignored. Since such inventory management case that has been well studied in operations research, we can compare the simulation result with theoretical values under such situation.

We evaluate the fill rate and the inventory level of each product at retailer's side while varying demand variance and lead-time between the retailer and its supplier. Other indexes, such as inventory cost, can be inferred from these two indexes. The theoretic values are shown in Table 4-4, where (x, y) indicates the combination of demand standard deviation *STD* (σ) and leadtime value *LT* (L). For example, *(10,3)* stands for the situation: *STD* as *10%* of the mean and leadtime in between as *3* periods.

Condition (STD, LT)	Fill rate (P1, P2)	Average Inventory (P1, P2)
(10,3)	0.996	28.5
(10,6)	0.994	40.4
(10,9)	0.993	49.5
(30,3)	0.989	85.7
(30,6)	0.984	121.2
(30,9)	0.981	148.5
(50,3)	0.981	142.8
(50,6)	0.974	202.0
(50,9)	0.968	247.5

Table 4-4: Theoretical value of service level and inventory level at the retailer's side

The simulation runs *2,000* periods for each condition and the average value of these indexes, shown as $X_i\ Y_i$, is calculated. If one computer period simulates one-hour (or one-day) in the real world, the whole *2000* will represent one-year (or eight-year) activities in a supply chain. Therefore, a *2000*-period running should be enough to provide the stable performance of a supply chain. We get a data set of these indexes: $(X_1 ... X_{15}), (Y_1 ... Y_{15})$ for each condition, with *15* times replication, with each replication using a different random seed. The replication here is designed to provide the statistical significance of the simulation results. Then *t*-test, via SPSS (SPSS Inc.) is used to evaluate whether the simulation results fit with theoretic values. The confidence interval is *95%* and H_0: $E(X_i) = \bar{X}$, $E(Y_i) = \bar{Y}$. The significances are shown as follows

Condition (STD, LT)	Sig. Test of Service level (P1)	Sig. Test of AVG Inventory (P1)	Sig. Test of Service level (P2)	Sig. Test of AVG Inventory (P2)
(10,3)	0.172	0.260	0.407	0.162
(10,6)	0.186	0.346	0.505	0.382
(10,9)	0.726	0.611	0.743	0.451
(30,3)	0.801	0.706	0.645	0.509
(30,6)	0.128	0.265	0.237	0.558
(30,9)	0.126	0.233	0.182	0.434
(50,3)	0.663	0.801	0.754	0.526
(50,6)	0.275	0.086	0.356	0.178
(50,9)	0.341	0.296	0.713	0.180

Table 4-5: Significances between the simulation result and theocratic result.

From the result, we cannot find statistical difference between simulation result and theoretical values based on *5%* significance test. Meanwhile, *95%* confidence intervals of the difference of the data, i.e., the confidence interval of $\left(E(X_i)-\bar{X}\right)$, all cover zero.

4.5.3. Statistical analysis for steady-state parameters

To promise a probabilistically stable simulation result, we design two simulation processes to examine whether total repeat time and running length of each time will influence the simulation result in experiments. Design1 is to repeat the experiment *15*, *25*, and *35* times, each time the simulation continuously runs *2,000* periods with a unique random number seed; Design2 is to vary the running period of each experiment, i.e. each experiment repeats *15* times. Each time the experiment respectively runs for *2,000*, *3,000* and *4,000* periods (increasing by *1000* periods each time) with a unique random number seed. We employ an ANOVA (Analysis of variance) test to examine whether these different treatments make system performances different in the simulation given a *95%* confidence. If not, we infer that performance has become steady in the treatment of *15*-repeat-of-*2000*-period and no need to increase simulation length or replication number. In this statistic test, the fill rate and the inventory level of products or components at each tier are chosen as the measurement. The result indicates that neither a longer simulation length nor more replications significantly change the result from a *2000*-period and *15*-repeat scenario, shown as follows:

Tier	Product	Design1		Design2	
		Fill rate	Inventory Level	Fill rate	Inventory Level
Retailer	Product1	0.254	0.900	0.755	0.588
	Product2	0.989	0.751	0.977	0.926
Manufacturer	Product1	0.172	0.316	0.472	0.947
	Product2	0.944	0.940	0.971	0.909
Supplier	Component1	0.966	0.948	0.951	0.914
	Component2	0.948	0.443	0.914	0.850
	Component3	0.181	0.536	0.891	0.949
	Component4	0.536	0.919	0.949	0.569

Table 4-6: ANOVA test of different simulation scenarios under a 95% confidence. Service level / Inventory Level: ANOVA test for comparing the simulated service level /inventory level of product x under different simulation scenario: different replications (Design1) and cycle length (Design2).

We also use the Replication/Deletion approach to improve the estimates of the steady-state mean of the performances. We divide *2000* periods into *20* intervals, each containing *100* periods. The replication time is *15*. We calculate the system performances in three ways: calculating the number based on all time periods during the simulation (*d=0*); deleting the first *100*-period simulation data and calculating the number based on the remaining 1900 periods (*d=1*); and ignoring the first *200*-period data in the calculation (*d=2*) and go on if necessary. ANOVA test is carried out with *95%* confidence level in SPSS to examine whether measurements are different significantly under such three treatments. In this way, we can determine whether the "warm-up" period has significantly impact to the simulation output. Result, shown in Table, indicates that there are no significant difference under different treatments when *d=0, d=1* and *d=2*. Therefore, the system becomes steady enough quickly (may due to our setting that the initial stock, including both on hand and in-transit, is close to the order-up-to level and the system stores *200*-period demand data in history at the very beginning of each experiment) and the effect of "warm-up" period can be ignored.

Tier	Product	Service level	Inventory Level
Retailer	Product1	0.920	0.462
	Product2	0.984	0.640
Manufacturer	Product1	0.975	0.943
	Product2	0.989	0.996
Supplier	Component1	0.945	0.973
	Component2	0.973	0.973
	Component3	0.995	0.976
	Component4	0.976	0.991

Table 4-7: ANOVA test of simulation scenarios with different "warm-up" period under a 95% confidence. Service level / Inventory Level: ANOVA significance of the simulated service level / inventory level of product x under different "warm-up" period.

CHAPTER 5 RESULTS ANALYSIS

This chapter is organized as follows: In section 5.1, we present the general observation of the simulation results, and the table of statistical significance on service level, fill rate, inventory cost, order leadtime, absolute percent error of service level and dynamics effect in the supply chain network. Section 5.2 carries out the sensitivity analysis of various system parameters, including demand correlation over time, demand variance, production leadtime and target service level. In Section 5.3, we summarize the experiment results. In Section 5.4, we summarize our work and discuss the managerial implication of this study, its strengths and limitations respectively.

To study the impact of information-shared postponement strategies on supply chain performance under various informative environments, ANOVA tests were performed to examine the significant performance changes of a certain postponement strategy (no, form, time and place postponement respectively) under OIS, DIS and SIS respectively. Simulation results from each informative setting were compared with each other by ANOVA to find the significant differences among these groups. If such significance was found, i.e., the overall *F*-test demonstrated that at least one difference existed, the multiple comparison procedure was used to assess which groups' data differed significantly from others.

However, before doing so, a test of homogeneity of variances of group data was computed to examine whether the dependent variables, i.e. the performance indices in this study, had the same variance in each group. The reason was that in ANOVA test, within-group mean square was the equal-weight average of group variances taking group sizes into account. When groups differed widely in variances, this average was a poor summary measure. In this study, *5%* significance level of Levene's test of homogeneity of variance was used, i.e. the null hypothesis that the groups had equal variances was set as *5%* level.

The failure to meet the assumption of homogeneity of variances, even for moderate departures, is not fatal to ANOVA as it is a relatively robust test, particularly when groups are of equal sample size (Box, 1954). The result of Levene (1960)'s test is mainly used as a guide to choose post multi-comparison procedures. In this study, Tukey's honestly significant difference (HSD) test (Tukey, 1993) was used when the assumption of the homogeneity of variance was met and Games-Howell (Games and Howell, 1976) method was used when such an assumption was not met. The Tukey method is designed for the variance homogeneity situation and is a conservative post-hoc test (that is "without a priori hypotheses", a method used for exploring differences in group samples), which is most likely to accept the null hypothesis of no group differences. It is preferred when the number of groups is large and all pair-wise comparisons are being tested. Besides, Games-Howell method is designed for unequal or unknown variances.

In calculation, each experiment will test one combination of four different postponement environments with three different informative environments that requires *15* repeats * *2000* computer-simulated periods. Therefore there are *12* combinational tests using *12*15*2000* computer-simulated periods. Combined *1* basic experiment with *18* sensitivity experiments, altogether, there are *19* experiments to test *19*12* combinations, using a total of *19*12*15*2000*, i.e. *6.84* millions, computer-simulated periods.

5.1. Service And Cost performances

Firstly the performances change, including service level (SL), fill rate (FR), order leadtime (OLT), absolute percent error of service level (APESL), dynamics effect (DE) and inventory cost (IC), in a supply chain without postponement were studied. In this form, the simulation experiment was simplified to study the value of information sharing strategies in a supply chain. Then, its result was used as the benchmark to judge the information value in postponement environment in the latter sections. In this study we defined the SL, FR and APESL at the chain level were the average value of three tiers' performances on these indexes, OLT and IC at the chain level were the sum of three tiers' performances on these indexes, and DE at the chain level was the product of three tiers' DE, which also equaled to the ratio of supplier's order variance to the market demand variance.

5.1.1. General observations

Firstly we conducted the significant tests to get a brief idea about how supply chain performances change with various available information in the particular postponement environment, including no postponement, form postponement, time postponement and place postponement. The result of significant tests on performances differences in a no-postponement environment was presented in Table 5-1 (The relationship in each cell pointed out the value difference of performances among strategies. For example, O>D in the "Inventory Cost" column pointed out that the inventory cost in OIS was larger than in DIS which meant the DIS helped the supply chain to reduce inventory cost).

Information Impact on No-Postponement Case

No-Postponement	Service Level	Fill Rate	Order Leadtime	Absolute Percent Error of Service Level	Dynamic Effect	Inventory Cost
Retailer	0	0	0	0	D>O, S	0
Manufacturer	S>O>D	S>O>D	D>O, S	D>O, S	O, D>S	O, S>D
Supplier	O>S>D	O>S>D	D>S>O	D>S>O	O>S>D	O>S>D
Supply Chain	O, S>D	O, S>D	D>O, S	D>O, S	O>D>S	O>S>D

Table 5-1: 95% confidence of the mean difference of chain member's performance among Order-IS, Demand-IS and Shipment-IS without postponement. O: Order-IS; D: Demand-IS; S: Shipment-IS. (D>S means the performance value under Demand-IS is significantly larger than that under Shipment-IS in the column. D>S>O equals D>S, D>O and S>O, while D>S, O equals D>S and D>O only; 0 means no such significant mean difference in various informative environments).

First of all, results showed that the performances at the retailer's site did not have significant changes with various information strategies, which was quite natural: the retailer was at the front tier of the market so it would not face any demand distortion. As a result, it could not directly benefit from the information sharing. Because of its close-to-optimal *S* level, own safety stock and high target service level promised by its supplier, the shipment uncertainty would not influence it significantly either (A similar observation was drawn by Zhang et al., 2002a,b). All indexes showed that the retailer performed stably under various informative environments, except DE: it was interesting to find that DE in DIS was about *12%* larger than that in OIS. We will explain it in the latter section.

The impacts of different information sharing strategies showed their significance at upstream organizations in the chain. At manufacturer site, SIS improved its service level and fill rate, but did not change its inventory cost. It was another story in DIS: DIS significantly reduced inventory cost as well as its promised service level. As shown in the Table 5-1, tiers with DIS had smaller inventory cost, lower service level, lower fill rate, longer order leadtime and higher absolute percent error of service level than that with the other two information strategies. It is because that we were studying a decentralized supply chain in which orders still existed between tiers. As the *S* level and the forecasted future demand at all tiers in a chain was calculated by using the end market demand, DIS drove upper tiers to keep fewer stocks than other ISS and successfully cut down the inventory cost by targeting at satisfying the end market demand. However the order from downstream was different from, usually larger than, the real demand, tiers' service to their immediate customer would worsen: insufficient inventory caused a drop in service level and fill rate, and consequently an increasing order leadtime to its immediate customer. Note that although the service performances were lower with DIS then with other information strategies in upper tiers, DIS performed the same as the other strategies did at the first tier of the chain, i.e. the retailer.

At the supplier level, we found that DIS performed similarly as what it did at the manufacturer level: reducing both the inventory cost and service level at the supplier tier. SIS had some changes in its performances: Comparing to DIS, its service performances were better while its inventory cost was higher. However, its service performances became worse, while its cost performance became better, than OIS. As Zhang et al. (2002b) analyzed, there was still a cost-benefit tradeoff in its inventory management to the sender of shipment information: When the target service level was high, less shipment uncertainty occurred and customer's ordering was less affected by this uncertainty. As a result, a "noise" of ordering variance or a misunderstanding of the feedback from shared information, caused by manufacturer's order adjusting in SIS, may aggravate demand forecast error at the supplier side and made its service performance worse.

Then we considered the whole supply chain performances. It was shown that SIS performed equivalently with OIS on service but generated less cost, while DIS reduced inventory cost most but provided worse service. Based on this observation, we found that SIS dominated, or was superior to, OIS in a supply chain without postponement, while DIS might conditionally dominate OIS, or even SIS, depending on particular service-cost balance in this decentralized supply chain. Note that in this study we borrow the economic term "dominate" to express the situation that one strategy is superior to another one in both the service and cost performances. If one is superior to another in service performances but worse in cost performances or vice versa, we use the term tradeoff to describe the situation.

Then we returned to understand the dynamic effect along the supply chain in this case. First of all, the information distortion was clearly shown at the supply chain level: OIS caused the largest bullwhip effect while SIS caused the smallest in this case. However, such relationship did not keep consistent along the chain: DE in SIS was larger at the supplier tier but smaller at the manufacturer tier, which showed that although the timely order adjusting benefited the manufacturer, it might, in return, become a noise to the supplier and aggravate supplier's demand forecast error. In another word, the information sender might misunderstand the feedback from the information receiver. At the retailer tier, we found DE in DIS was the largest. If we analyzed the tier separately, theoretically speaking, bullwhip effect should not occur at the front tier so DE at the retailer tier should be equal among various informative environments. However because now the retailer behaved as a member in a chain, its own performance would be influenced by other members: As its upstream partner could not promise a *100%* service level, desired shipment was not always equal to the real shipment. Such shipment fluctuating, or shipment uncertainty, would influence retailer's order decision to adjust such gap and consequently increased its order variance. Therefore higher shipment uncertainty would cause a larger demand distortion. Since the service level at the manufacturer in DIS was lower in this case, retailer's order variance became larger than the other environments.

Information Impact on Form-Postponement Case

Next we studied the significant performance differences in a form-postponement environment under various informative environments, as shown in Table 5-2. Comparing with no-postponement case, the major change in form postponement was the combination of two products into one product. Therefore, the performance differences from information strategies should follow similarly rules as in no-postponement case. Comparing Table 5-1 with Table 5-2, there were only one difference: retailer's DE in SIS became same as in OIS which did not conflict with the observation we draw in the previous case.

Form-Postponement	Service Level	Fill Rate	Order Leadtime	Absolute Percent Error of Service Level	Dynamic Effect	Inventory Cost
Retailer	0	0	0	0	D>O, S	0
Manufacturer	S>O>D	S>O>D	D>O, S	D>O, S	O, D>S	O, S>D
Supplier	O>S>D	O>S>D	D>S>O	D>S>O	O>S>D	O>S>D
Supply Chain	O, S>D	O, S>D	D>O, S	D>O, S	O>D>S	O>S>D

Table 5-2: 95% confidence of the mean difference of chain member's performance among Order-IS, Demand-IS and Shipment-IS with form postponement. O: Order-IS; D: Demand-IS; S: Shipment-IS. (D>S means the performance value under Demand-IS is significantly larger than that under Shipment-IS in the column. D>S>O equals D>S, D>O and S>O, while D>S, O equals D>S and D>O only; 0 means no such significant mean difference in various informative environments).

<u>Information Impact on Time-Postponement Case</u>

Then we studied the significant performances changes in a time-postponement environment, as shown in Table 5-3. Generally speaking, the observations about the service performances at all tiers in time-postponement was almost the same as the previous two cases, expect the trend that OIS and SIS became close in some measurement which in fact did not affect the observations we draw before.

However, compared with previous cases, there were two main differences in supply chain performances: one was that the dynamic effects in SIS at the manufacturer tier and the supply chain level became larger than the other two strategies, the other was the inventory cost in SIS at the supplier tier and the chain level became larger than the other two strategies. The reason might be one: SIS caused the supplier to build up more stocks because of the increasing order variance from the manufacturer. As we knew, in time-postponement the differentiation point was delayed, therefore the inventory position to store the semi-finished products was moved downwards and the leadtime between the manufacturer and the supplier in fact increased. As a result, the "noise" of ordering variance from the manufacturer, caused by adjusting orders in SIS, might aggravate demand forecast error at the supplier side. In return, the supplier set up a higher level of safety stock to resist the fluctuating order variance. This result indicated that SIS might not be a good strategy in time postponement since the longer leadtime between the manufacturer and the supplier caused unnecessary misunderstanding of the feedback from shared shipment information and the loss from such misunderstanding behavior might overcome the information receiver's benefit from the shared information. Although the manufacturer still benefited from shipment information, the overall performances in a supply chain were reduced. DIS still showed its significant impact on reducing inventory cost and there was a consistent trade-off between cost and service inside the supply chain.

Time-Postponement	Service Level	Fill Rate	Order Leadtime	Absolute Percent Error of Service Level	Dynamic Effect	Inventory Cost
Retailer	0	0	0	0	D>O, S	0
Manufacturer	S>O>D	S>O>D	D>O, S	D>O, S	S>O, D	O, S>D
Supplier	O, S>D	O>S>D	D>O, S	D>O, S	O, S>D	S>O>D
Supply Chain	O, S>D	O, S>D	D>O, S	D>O, S	S>O>D	S>O>D

Table 5-3: 95% confidence of the mean difference of chain member's performance among Order-IS, Demand-IS and Shipment-IS with time postponement. O: Order-IS; D: Demand-IS; S: Shipment-IS. (D>S means the performance value under Demand-IS is significantly larger than that under Shipment-IS in the column. D>S>O equals D>S, D>O and S>O, while D>S, O equals D>S and D>O only; 0 means no such significant mean difference in various informative environments).

<u>Information Impact on Place-Postponement Case</u>

Finally we analyzed the supply chain performances of various information strategies in place postponement case, as shown in Table 5-4. Most of the relationships among three information strategies were the same as the first case. However the significant differences between SIS and OIS tended to weaken, i.e. the manufacturer still benefited from SIS but the total supply chain performance became close to OIS. DIS still showed its significant impact on reducing inventory cost and typical tradeoff between cost and service in a chain. Furthermore retailer's inventory cost was reduced in DIS, which could be viewed as an advantage of using DIS in place postponement: Because the production was partly moved to the retailer site in place postponement, retailer held extra inventory of components. With DIS available, these component stocks could be significantly reduced.

Place-Postponement	Service Level	Fill Rate	Order Leadtime	Absolute Percent Error of Service Level	Dynamic Effect	Inventory Cost
Retailer	0	0	0	0	D>O, S	O, S>D
Manufacturer	S>O>D	S>O>D	D>O, S	D>O, S	O>S	O, S>D
Supplier	O, S>D	O>S>D	D>O, S	D>O, S	O>S>D	O, S>D
Supply Chain	O, S>D	O, S>D	D>O, S	D>O, S	O>D	O, S>D

Table 5-4: 95% confidence of the mean difference of chain member's performance among Order-IS, Demand-IS and Shipment-IS with place postponement. O: Order-IS; D: Demand-IS; S: Shipment-IS. (D>S means the performance value under Demand-IS is significantly larger than that under Shipment-IS in the column. D>S>O equals D>S, D>O and S>O, while D>S, O equals D>S and D>O only; 0 means no such significant mean difference in various informative environments).

We found several common and different behaviors of the supply chain and its members in various informative environments given different postponement strategies. DIS showed its significant impact on reducing inventory cost and the typical tradeoff between cost and service in a chain across postponement strategies. Also, the bullwhips effect in DIS was always smaller than that in OIS at the chain level, although at the front tier its DE was larger than the other two strategies. Additionally, DIS significantly reduced the inventory cost at the retailer tier in place postponement, which indicated to be a good choice for place postponement in a supply chain. SIS performed differently across situations: in no-postponement and form-postponement case, it dominated the OIS by both the service and cost performances, but in time-postponement and place-postponement case, such significant benefit was weakened. Furthermore, although SIS always benefited the manufacturer, the supplier's performances became worsen simultaneously because of the misunderstanding of the feedback on the shared information in some situations, which consequently worsened the whole supply chain performances.

In summary, DIS significantly reduced supply chain's inventory while SIS improved the manufacturer's service level and fill rate in all information environments. However, the order leadtime at the manufacturer was not significantly reduced by SIS. The reason may be the relatively small reduction time was not a significant change to the large value of total leadtime. By analyzing DE in above tables, it was clear that DIS reduced the supply chain's dynamic effect although it increased DE at the retailer site. Although SIS reduced the supply chain's DE in no-postponement and form-postponement situation, such reduction did not appear in time postponement and place postponement.

<u>Postponement Impact on Information Cases</u>

Then we analyzed how could various postponement perform given a specific information environment. As shown in Table 5-5, it was clear that no matter what information environment it was, the supply chain's inventory cost was significantly reduced by three postponement strategies: form, time and place.

With DIS and SIS available, form postponement always reduced the inventory cost most but the reduction by time postponement and place postponement did not follow a constant trend. However, it was found that in OIS, the inventory cost reduction enabled by form postponement was larger than that by time postponement and no postponement but whether such reduction was larger than that by place postponement was not clear.

Inventory Cost	Order information Sharing	Demand Information Sharing	Shipment Information Sharing
Retailer	F<N, T<P	F<N, T<P	F<N, T<P
Manufacturer	P<F<T<N	P<F<T<N	P<F, T<N
Supplier	F, P<N<T	F<N, P<T	F<N, P<T
Supply Chain	F<T<N; P<N	F<P<T<N	F<P, T<N

Table 5-5: 95% confidence of the mean difference of chain member's inventory cost among No-Postponement, Form-Postponement, Time-Postponement and Place-Postponement in Order-IS, Demand-IS and Shipment-IS respectively. N: No-Postponement; F: Form-Postponement; T: Time-Postponement; P: Place-Postponement. Comma is used to separate the variables with insignificantly-different values while semicolon is use to separate two relations (e.g. T, P<F; T<N means T<F, P<F and T<N)

Because the differentiation point in time postponement was moved closer to the retailer, the leadtime in between was reduced and consequently the demand uncertainty in the leadtime was reduced as well. Naturally the safety stock at the manufacturer was reduced. Given a fixed total leadtime in a supply chain, the differentiation point moving closer to the market meant a longer leadtime between the supplier and the manufacturer. As a result, more safety stock was set up at the supplier site to resist the increased demand uncertainty in the leadtime. As shown in Table 5-5, the inventory cost at the supplier site in time postponement was increased while such cost at the manufacturer site was reduced, compared with the no-postponement situation. It was also obvious that the retailer's inventory cost increased by place postponement because the additional production had been carried out at the retailer site, and consequently the manufacturer's inventory cost was reduced greatly.

5.1.2. Detailed performances

To get a whole picture of how different informative environments affect postponement implementation, the comparison of service and cost performances of all supply chain members was made. Also we presented the performance differences of various information strategies using data in OIS as the benchmark.

<u>Service Level Analysis</u>

As shown in Figure 5-1 and Table 5-6, although information strategies provided a close service level at the retailer's tier, the service at upper tiers changed significantly. In DIS, the service level reduced more as tiers moved upwards, sometimes even reached *10%* reduction at the supplier tier, while the average supply chain service reduced around *4%* to *5%*. It was because of the decentralized structure in this study in which orders were still available between tiers. Although SIS significantly improved the service level at the manufacturer tier, such improvement was not above *0.5%*, mainly because the initial *95%* target service did not contain much space for improvement, and the overall service level between SIS and OIS was close. The manufacturer's service level improvement in the place postponement was the largest. Note that in the table the cell with grey background means that the value inside is not significantly different from the value in OIS.

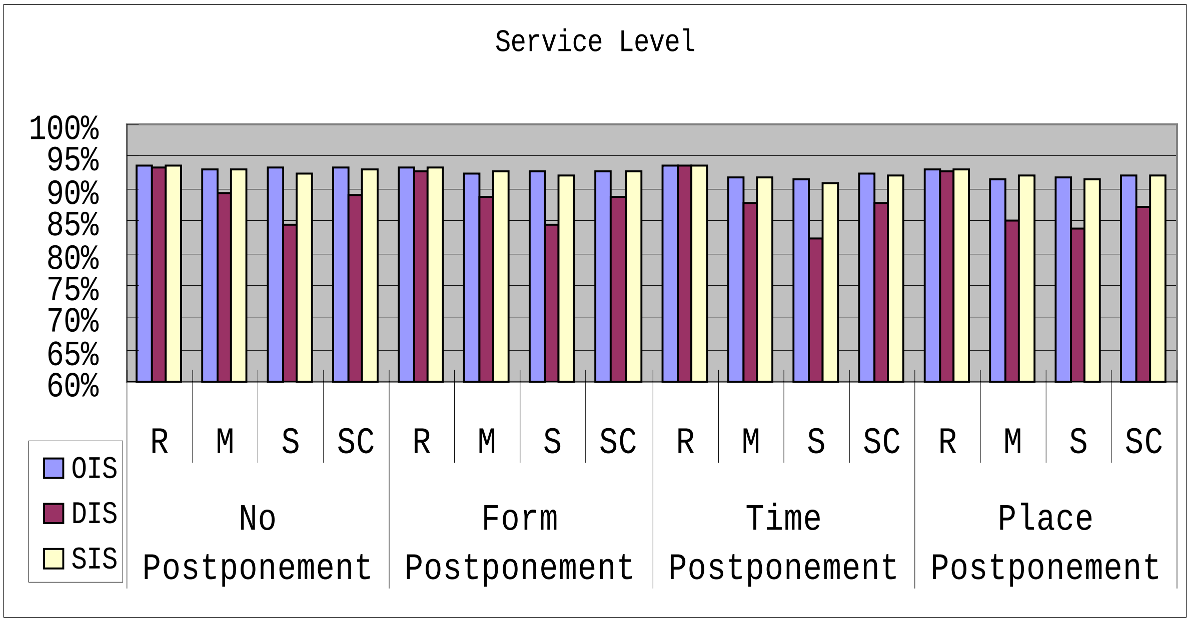

Figure 5-1: The service level of information-shared postponement in a supply chain. R: retailer, M: manufacturer, S: supplier, SC: the supply chain level. OIS: Order-IS, DIS: Demand-IS, SIS: Shipment-IS.

Service Level		Retailer	Manufacturer	Supplier	Supply Chain Level
No Postponement	DIS	-0.3%	-3.8%	-9.3%	-4.5%
	SIS	0.0%	0.1%	-0.9%	-0.3%
Form Postponement	DIS	-0.5%	-4.1%	-8.7%	-4.4%
	SIS	0.0%	0.1%	-0.7%	-0.2%
Time Postponement	DIS	-0.3%	-4.2%	-10.2%	-4.9%
	SIS	0.0%	0.1%	-0.7%	-0.2%
Place Postponement	DIS	-0.4%	-7.2%	-8.6%	-5.4%
	SIS	0.0%	0.4%	-0.5%	0.0%

Table 5-6: Percentage difference of service level under various information strategies in a supply chain, using data in Order-IS as the benchmark. The cell with grey background means the value inside is not significantly different from the value in Order-IS at 95% confidence.

Fill Rate Analysis

Then we analyzed the fill rate in Table 5-7, which showed a similar behavior as service level: information strategies provided a close fill rate at the retailer's tier; DIS reduced the fill rate at upstream organization and performed worst with the place postponement; SIS improved the fill rate less than *0.5%*, although significant, at the manufacturer tier. The reason might be the high target fill rate did not leave much space for improvement. The manufacturer's fill rate improvement in the place postponement was the largest. There were also some differences: the reduction in fill rate in DIS became smaller, i.e. *4%* to *6%* at the supplier while around *2%* overall. The supplier's fill rate in SIS reduced more, which had reached above 1%. Because of the different changing rate between service level and fill rate, it was clear that the result of backlog cost measured by units of sale loss should be different from that measured by chance of sale loss, which was another reason that we did not count backlog cost in this study.

Fill Rate		Retailer	Manufacturer	Supplier	Supply Chain Level
No Postponement	DIS	-0.2%	-2.0%	-4.2%	-2.1%
	SIS	0.0%	0.2%	-1.6%	-0.5%
Form Postponement	DIS	-0.1%	-1.7%	-3.5%	-1.8%
	SIS	0.0%	0.1%	-1.7%	-0.5%
Time Postponement	DIS	-0.1%	-1.6%	-5.8%	-2.5%
	SIS	0.0%	0.3%	-1.6%	-0.5%
Place Postponement	DIS	-0.2%	-3.9%	-4.2%	-2.8%
	SIS	0.0%	0.4%	-1.4%	-0.4%

Table 5-7: Percentage difference of fill rate under various information strategies in a supply chain, using data in Order-IS as the benchmark. The cell with grey background means the value inside is not significantly different from the value in Order-IS.

Order Lead Time Analysis

Another service index is the order leadtime, which measures the leadtime in response to customers' orders. The result in Table 5-8 showed that information strategies did not affect retailer's order leadtime at all. However DIS increased the leadtime at upstream organization for about *1%*. However the experiment result showed that SIS did not affect the order leadtime at the manufacturer.

Order Leadtime		Retailer	Manufacturer	Supplier	Supply Chain Level
No Postponement	DIS	0.3%	0.6%	1.4%	1.0%
	SIS	0.0%	0.2%	0.1%	0.1%
Form Postponement	DIS	0.4%	0.6%	1.3%	0.9%
	SIS	0.0%	0.0%	0.1%	0.0%
Time Postponement	DIS	0.2%	0.6%	1.5%	1.0%
	SIS	0.0%	0.3%	0.1%	0.0%
Place Postponement	DIS	0.4%	1.1%	1.3%	1.1%
	SIS	0.0%	-0.1%	0.1%	0.0%

Table 5-8: Percentage difference of order leadtime under various information strategies in a supply chain, using data in Order-IS as the benchmark. The cell with grey background means the value inside is not significantly different from the value in Order-IS.

Inventory Cost Analysis

The important cost index is inventory cost. As shown in Figure 5-2, DIS reduced inventory cost greatly at upper tiers. At the manufacturer tier, it reduced inventory cost from *16%* to *24%*, while such reduction increased to *37%* to *50%* at the supplier site. The average reduction over the supply chain was around *20%* to *30%*. Furthermore, DIS reduced retailer's cost by *6%* in place postponement. Considering the maintained service level, DIS was retailer's dominating strategy with place postponement in a chain. Furthermore, it was clear that DIS provided more benefit in form postponement environment but less in time and place postponement, compared with a supply chain without any postponements. The result of inventory cost differences is summarized in Table 5-9. Considering the service performance together with the inventory cost here, if the service performances are not critical to upper tiers, the upper tiers can benefit a great cost reduction from DIS. Even if the suppliers shares out part of its benefit from cost reduction to the downstream organization, e.g. the retailer, the whole supply chain cost reduction is still significant. Because the retailer did not have any significant loss in service and cost performance, it is reasonable to design such a performance scheme: by providing DIS, the tiers relaxes its requirement on supplier's service level but asks for redistribution of the benefit from cost reduction.

SIS did not reduce the inventory cost as much as DIS did. It reduced the inventory cost at the supplier tier, from *8%* to *12%*, which resulted in *3%* to *5%* cost reduction over the chain in no postponement and form postponement situation. Since the service level and fill rate were maintained at the supply chain level simultaneously, SIS could be viewed as a pure benefit to the supply chain in those two situations. However it did not show any significant effect in place postponement case. Considering its unchanged service performances simultaneously, SIS could not be convinced as a good choice of information strategy with place postponement if the investment cost in SIS was considered. Furthermore, resulting in increased cost and unimproved service, SIS even worsened the supply chain performance in time postponement. Therefore the supply chain should use SIS only in no-postponement and form-postponement situation.

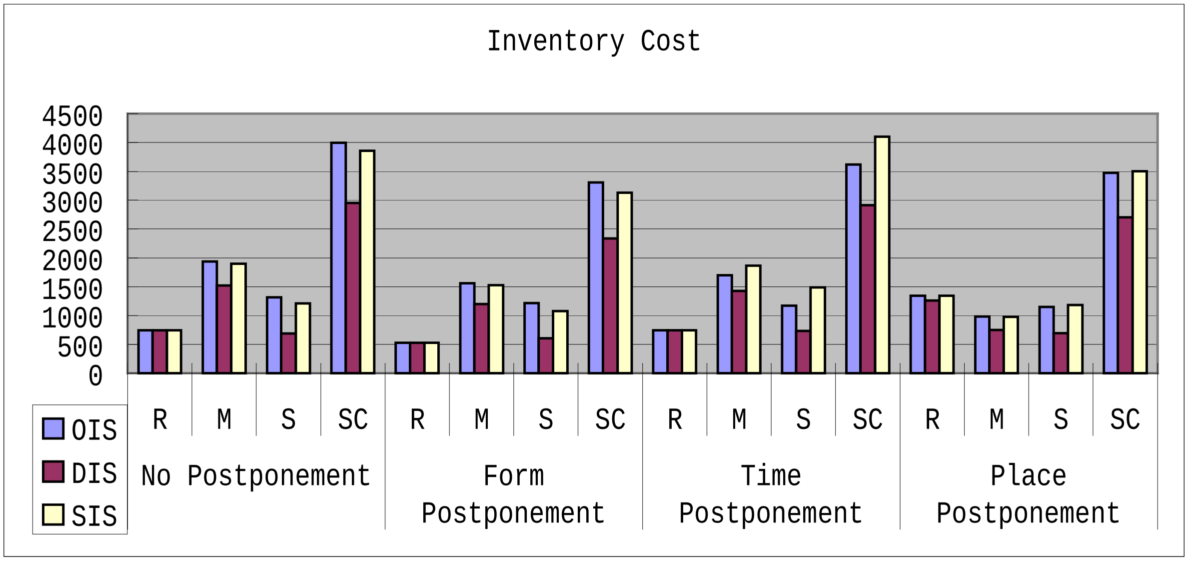

Figure 5-2: The inventory cost of information-shared postponement in a supply chain. R: retailer, M: manufacturer, S: supplier, SC: the supply chain level. OIS: Order-IS, DIS: Demand-IS, SIS: Shipment-IS.

Inventory Cost		Retailer	Manufacturer	Supplier	Supply Chain Level
No Postponement	DIS	0.3%	-21.4%	-47.8%	-26.1%
	SIS	0.0%	0.2%	-8.0%	-3.5%
Form Postponement	DIS	0.3%	-23.4%	-49.9%	-29.4%
	SIS	0.0%	-2.3%	-11.6%	-5.3%
Time Postponement	DIS	0.3%	-16.0%	-37.2%	-19.5%
	SIS	0.0%	0.3%	26.8%	13.2%
Place Postponement	DIS	-6.4%	-23.5%	-39.8%	-22.3%
	SIS	0.0%	-0.4%	2.8%	0.8%

Table 5-9: Percentage difference of inventory cost under various information strategies in a supply chain, using data in Order-IS as the benchmark. The cell with grey

background means the value inside is not significantly different from the value in Order-IS.

Dynamic Effect Analysis

Studying the bullwhip effect provided an in-depth understanding of how the supply chain re-acted to the demand fluctuation. As shown in Table 5-10, in all postponement cases DIS reduced the demand distortion at upper tiers in a chain and consequently the bullwhip effect at the chain level was always significantly smaller than in OIS, with the reduction ranges from *11%* to *22%*. In another word, DIS provided a constant stabilizing effect in a supply chain. However, SIS did not behave consistently in the way of reducing bullwhip effect. In a no-postponement and form-postponement case, SIS reduced the bullwhip effect most for about *40%*. In place postponement, such stabilizing effect was less significant, i.e. the reduction reduced to *9%*. In time postponement, SIS even increased the bullwhip effect by *8%*. The trends are summarized in Figure 5-3. By analyzing these data, it was clear that the dynamic effect did not obtain a clear link with the service or cost performance in a supply chain, i.e. although the supply chain performance became better when DE was reduced, a greater reduction in DE did not promise a better service level or more cost reduction. Furthermore, with DE reduced the supply chain performances changed differently between DIS and SIS. Therefore DE is not a suitable independent measurement to evaluate supply chain performance although it is good to demonstrate the demand distortion process along supply chains.

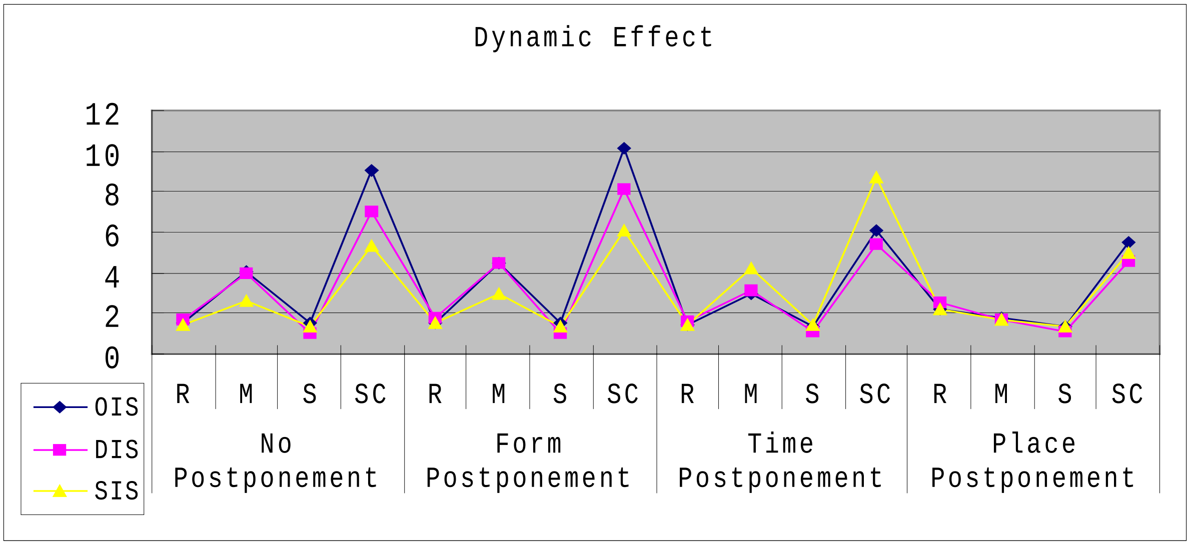

Figure 5-3: The service level of information-shared postponement in a supply chain. R: retailer, M: manufacturer, S: supplier, SC: the supply chain level. OIS: Order-IS, DIS: Demand-IS, SIS: Shipment-IS.

Dynamic Effect		Retailer	Manufacturer	Supplier	Supply Chain Level
No Postponement	OIS	1.49	4.03	1.50	9.01
	DIS	1.67	4.00	1.04	6.99
	SIS	1.48	2.63	1.36	5.31
Form Postponement	OIS	1.51	4.45	1.49	10.18
	DIS	1.74	4.48	1.04	8.15
	SIS	1.50	2.92	1.37	6.05
Time Postponement	OIS	1.45	2.99	1.38	6.05
	DIS	1.63	3.11	1.06	5.40
	SIS	1.45	3.21	1.40	6.52
Place Postponement	OIS	2.23	1.77	1.37	5.46
	DIS	2.51	1.69	1.07	4.55
	SIS	2.20	1.67	1.34	4.97

Table 5-10: The value of dynamic effect under various information strategies in a supply chain.

APESL Analysis

Studying the absolute percent error of service level provided an in-depth understanding of the service reliability affected by information sharing strategies. As shown in Table 5-11, information strategies affected the service reliability insignificantly at the retailer tier in all postponement cases. However such service fluctuation increased at upper tiers in a chain when DIS was available, ranging from *6%* to *14%*, and consequently the worsened such service control at the chain level. SIS performed similarly as OIS did at upper tier as well and the service fluctuation was varied from *2%* to *4%*. Therefore SIS and OIS supported a relatively stable service in the supply chain. Since APESL increased largely at upper tiers in DIS, the down tiers should ensure that the upper tiers has set a high target service level before it relaxes the service requirement.

Absolute Percent Error of Service Level		Retailer	Manufacturer	Supplier	Supply Chain Level
No Postponement	OIS	1.4%	2.1%	2.0%	1.8%
	DIS	1.8%	5.9%	11.1%	6.3%
	SIS	1.5%	2.0%	2.9%	2.1%
Form Postponement	OIS	1.9%	2.7%	2.5%	2.4%
	DIS	2.4%	6.6%	11.0%	6.7%
	SIS	1.9%	2.6%	3.2%	2.6%
Time Postponement	OIS	1.4%	3.5%	3.6%	2.8%
	DIS	1.6%	7.6%	13.5%	7.6%
	SIS	1.4%	3.5%	4.3%	3.1%
Place Postponement	OIS	2.0%	3.6%	3.3%	3.0%
	DIS	2.4%	10.6%	11.6%	8.2%
	SIS	2.0%	3.2%	3.8%	3.0%

Table 5-11: The value of absolute percent error of service level under various information strategies in a supply chain implementing a particular postponement strategy.

In summary, from the significance analysis and numerical analysis of supply chain's performance in various information environments, we find that it is a beneficial combination of SIS and no/form postponement in a supply chain while DIS is good for place postponement. When DIS is available, the supply chain members can relax its requirement for supplier's actual service performance, after confirming that the target service level at supplier site is already high, and ask for benefit redistribution from cost reduction. This performance measurement scheme is beneficial to all supply chain members in DIS. Although DE can demonstrate the demand distortion process along supply chains, it is not a suitable measurement to evaluate supply chain performance independently. Table 5-12 summarizes the significant impacts of information sharing strategies on postponement based on simulation results. Note that in the table, service level is used to represent supply chain's service performance.

Information Value / Postponement	DIS	SIS
Form	Cost: - (most)	Cost: -
	Service: -	Service: +
Time	Cost: -	Cost: +
	Service: -	Service: +
Place	Cost: -	Cost: ?
	Service: -	Service: + (most)

Table 5-12: The summary of information value on postponement in a supply chain based on simulation results. Cost: the cost performance in a supply chain; Service: the service performance in a supply chain; +: significant positive influence by information; -: significant negative influence by information; (most): significant influence by information which is the largest compared with other environments; ?: unclear / insignificant influence by information.

5.2. Sensitivity Analysis

The service and cost performance of different combined strategies were well studied in the previous sections. In this section, a further consideration about the impact of system parameters, including the impact of demand variance and demand correlation over time in the market, the impact of different manufacturing lead-time proportion along a supply chain, and the impact of various service levels that the supply chain members may target at, was added. This in-depth study provided a comprehensive understanding of the supply chain dynamics in various environments.

In this section, the standard deviation σ of market demand, which the retailer faced, was set as *10* and *50* respectively, to represent the low and the high demand variances a supply chain may deal with. The demand correlation coefficient ρ was varied from *–0.8* to *0.8*, with an interval of *0.2*, to represent the changing correlation, either negative or positive, of product demand across time. The production lead-time *L* change to *3* and *12* respectively, to represent different production lead-time proportions of the total lead-time that was measured from the time raw material was available to the time the finished product was delivered to the end customer throughout a supply chain. The target service level α at each tier in a supply chain was set as *90%* and *99%* respectively to represent the low and high service qualities the supply chain member may offer to its customers. Table 5-13 summaries the experimental settings in basic experiment and sensitivity analyses. Each experiment tested the combination of four different postponement environments with three different informative environments and each environment required *15* repeat * *2000* computer simulated periods. Therefore, altogether, there were *18* sensitivity experiments to test *18*12* environments using a total of *18*12*15*2000* computer-simulated period.

System Parameters	Value in Basic Experiment	Values in Sensitivity Experiment	# of Sensitivity Experiments
ρ	*0*	*-0.8, -0.6 -0.4, -0.2, 0.2, 0.4,0.6, 0.8*	*8*
σ	*30*	*10, 50*	*2*
L	*6*	*3, 9*	*2*
α (z_1, z_2, z_3)	*95% (z=1.65)*	*90% (z=1.22), 99% (z=2.32)*	6

Table 5-13: The summary of experimental settings in sensitivity analysis

5.2.1. The impact of demand correlation across time

In this section, we analyzed the performances of information-shared postponement strategies with trended demand to answer the question: would the value of information-shared postponement strategies changed in a supply chain with different demand trends. In our example, the demand process for products follow a AR(1) process without seasonality. In the basic experiment, we set the demand correlation coefficient $\rho = 0$ to represent the no-trend demand. In current sensitivity analysis, we varied ρ from *–0.8* to *0.8*, with an interval of *0.2*, to represent the changing correlation, either negative or positive, of product demand across time. Given these trend correlations, the average demand would become *56%, 63% 71%, 83%, 125%, 166%, 250%* and *500%* (please referring appendix for proof) of the original demand quantity respectively. Because of extremely large data set, we would only list the results of service level, fill rate and inventory cost in the table.

First we study the situations that the demand trend was positive, i.e. the demand was increasing as time passed. The result details are shown in Appendix Table A-1. With DIS available, the inventory cost reduction increased between *12%* and *15%* in a supply chain, comparing with the no-trend situation. It was also shown that the reduction of dynamic effect increased as the correlation coefficient became larger. However the reduction of service level and fill rate simultaneously increased about *5%-8%* and 3%-5% respectively. A trade-off still existed here, e.g. when demand was highly positive correlated with time, was a *40%* reduction in inventory cost worthy of *10%* reduction in service level that could motivate the supply chain to use DIS? When using SIS the inventory cost reduced *7%-55%* more than the no-trend situation, depending on the postponement type. Furthermore, the service level and fill rate at the supply chain level increased about *3%* and *2%* more than the no-trend situation respectively. These results suggested that the value of SIS positively relates to the positive demand trend and such value is a pure benefit to the supply chain.

Another significant finding is that the demand correlation variable changed the conclusion on SIS value in the basic experiment. In another word, it was an opposite conclusion about the shipment information value in the sensitivity study when adding the consideration about demand correlation: In time and place postponement case, when the demand correlation was high, e.g. above *0.4*, the supply chain's inventory cost decreased significantly while the service level and the fill rate increased compared to the OIS situation, although in the basic experiment SIS was viewed as dominated strategy to DIS and OIS in those two postponement cases. Therefore SIS dominated OIS in all postponement cases when the demand correlation became positively high. Also we could found when ρ was high, say above *0.4*, the inventory cost reduction by SIS in all postponement cases was close to, and sometimes even higher than, that by DIS while the supply chain's service performances by SIS was significantly larger than those by DIS. Therefore SIS conditionally dominates DIS when the demand correlation was positively high. We also found that the information value of both DIS and SIS on reducing the bullwhip effect in a supply chain was increasing as ρ increased, except the case of place postponement with SIS. In summary, SIS was more suitable to postponements than the other two information strategies when demand correlation over time increased.

When the demand was negatively correlated over time, supply chain's service level and fill rate improved as the demand coefficient negatively increased. As shown in Appendix Table A-2, the service performances became equivalent to the performances under OIS when the coefficient was negatively high enough, for example, below *–0.6*. Although its value on inventory cost reduction decreased simultaneously, i.e. from *20%-30%* to *11%-12%*, such reduction still existed. In another word, DIS still helped the supply chain reduce the inventory cost around *11%-12%* when the demand correlation became extremely low. Therefore in all postponement cases, the value of DIS to the supply chain was not a trade-off any more and DIS dominated OIS when demand coefficient was negatively high. Also we found the changes of bullwhip effect reduction enabled by DIS is not significant in this situation.

In such a negative demand correlation situation, SIS behaved totally different from what it did in the positive correlation one, i.e. its impact on the supply chain, either on the service level, the fill rate, or the inventory cost, disappeared quickly. As shown in Appendix Table A-2, when the demand correlation was negatively high enough, supply chain's service and cost performances was not significantly different between SIS and OIS. Furthermore, the bullwhip effect reduction enabled by SIS decreased in this situation. Therefore it was obvious that DIS dominates the other two strategies when the demand coefficient was negatively high.

By analyzing the inventory cost reduction in this sensitivity study, it was clear that the inventory cost reduction ratio in DIS increased as the demand correlation coefficient increased. Although the service improvement ratio in SIS increased when the positive demand correlation increased, such ratio did not changed when the demand correlation became negative.

5.2.2. The impact of demand variance

In this experiment, the standard deviation of market demand, which the retailer faced, was set as *10* and *50* respectively to represent the low and the high demand variances a supply chain might deal with. Together with the value of *30* in the basic case that represented the moderate demand variance, this experiment showed how demand fluctuating affected the performance of the combined strategies in a supply chain. To simplify our analysis, we focus on service level, fill rate, inventory cost and dynamic effect. The result is summarized in Appendix Table A-3. One general observation was that the retailer's service and cost performances in various information-shared postponement environments did not change with the demand fluctuating, i.e. in all situations the retailer's performances were stable. However the other tiers, and consequently the whole supply chain, were affected by the changed demand variance.

When the demand fluctuating increased, the supply chain that used DIS faced a 1% less reduction in service level, a 1% more reduction in fill rate and a 7% less reduction in inventory cost. There is a clear trend of decreasing cost reduction with increasing demand variance. Since the cost-benefit tradeoff still existed between the reduction of service and inventory cost, it was not clear to say whether the supply chain benefit more from DIS as the demand variance increased or vice versa.

When the supply chain using SIS, most of the service and cost indexes for tiers did not have significant change as the demand variance increased, except a *9%* significant cost increase in time postponement. First of all, this result showed that the demand variance did not have a significant influence on SIS value in most of environments. Second, SIS was not a suitable strategy with time postponement, particularly when the demand variance increased.

When studying the impact of demand variance on DE along the supply chain, we found that the DIS reduced more bullwhip effect as the demand variance became higher and vice versa. Furthermore, in no-postponement and form-postponement situation, DE in SIS was not influenced by the changes of demand variance. However when demand variance became low, the bullwhip effect of the supply chain that used SIS reduced *40%* and *15%* in the time and place postponement situation respectively.

In summary, the changes of demand variance influenced DIS performance in a supply chain although the cost-benefit tradeoff to use this strategy still existed. However the impact of SIS on the supply chain was not affected much by this variance change in most environments.

5.2.3. The impact of production leadtime

In this experiment, the production lead-time was changed to *3* and *9* respectively to represent different production lead-time proportions of the total lead-time which was from the time the raw material available to the time the finished product was delivered to the end customer throughout a supply chain. In the basic case, the total production time was set as *6* while the total delivery time was *18*, which represented a moderate production-time-proportion supply chain and the production time covered *25%* of the total product cycle time in a supply chain. When the production time was increased to *3* and *9* respectively, such a proportion simultaneously changed to about *14%* and *33%*, which represented the low and the high production-time-proportion supply chains in this study. In practice, manufacturing-oriented industries, in which production activities take much of the total lead-time, and logistic-oriented industries, in which delivering activities take much of the total lead-time, are two typical types of industry. By changing production time, this experiment analyzed the value of information-shared postponement strategies in different types of industries.

The result is summarized in Appendix Table A-4. One general observation was that the information impact on retailer's service and cost performances in various postponement environments did not change with the product leadtime, i.e. in all situations the retailer's performances were stably changed with information strategies. However, with the changed production leadtime, DIS' value on inventory cost reduction varied from *20%* to *33%* in the supply chain level while tiers' service level and fill rate did not have significant changes. Because the inventory cost reduction sometimes became lower but sometimes become higher with the increasing of the production leadtime, the benefit of DIS in various postponement environments in a supply chain was affected by the production leadtime in a nonlinear manner.

In the SIS case, with the increasing production leadtime, the impact of information on tiers' service level and fill rate did not significantly change. However the inventory cost reduction varied in an unclear manner, i.e. the inventory cost sometimes increased and sometimes decreased as the production leadtime increased: In the time and place postponement situation, either the longer or the shorter product time made the inventory cost reduction significantly more than in the moderate leadtime while in no postponement and form postponement situation a moderate leadtime helped SIS perform well.

Therefore it was clear that the benefit of SIS in various postponement environments in a supply chain was associated with the leadtime (or the ratio of production leadtime to the total leadtime), but the trend of such impact could not be clearly shown here.

The inconstant performance with the leadtime changes motivated us to consider the factor beyond information sharing strategies. Li et al. (2001) analyzed the impact of leadtime distribution, which was defined as varying the leadtime between each tier while keeping the total leadtime of the whole supply chain, on a multi-tier supply chain. One finding in their study was that given a fixed total leadtime across the supply chain, different leadtime distribution influenced the bullwhip effect and inventory cost differently. In this study, the leadtime distributions in various postponement strategies were different from each other due to the process redesign: as the product differentiation point was delayed and moved to the downstream organization, the leadtime between tiers were changed accordingly. As a result, the changed leadtime distribution might influence the supply chains more than the changed leadtime length did and caused the supply chain behaved inconsistently.

5.2.4. The impact of service level

In this section, the target service level at each tier in a supply chain was set as *90%* and *99%* respectively to represent the low and high service qualities that the supply chain member may offer to its customers. Note that to provide a clear and comparable result, each time only one tier might vary its service to either *90%* or *99%* while the other two tiers maintained their original value at *95%*.

In Appendix Table A-5, when the retailer's target service level varied from a low level, i.e. *90%*, to a high level, i.e. *99%*, the actual service level and the fill rate in a supply chain using DIS did not significantly change, although there was a slight decreasing in inventory cost reduction. The dynamic effect did not changed with the service level either. In general, the value of DIS in the supply chain did not change significantly with the retailer's target service level in all postponement situations. Similar conclusion can be drawn when judging the SIS value. This observation is quite natural since the front tier's service level should not directly affect upstream performances except by the order decision. As the lowest service level tested here was already *90%*, the influence of retailer's order decision on other members should be relatively insignificant. Therefore, it was clear that a front tier's service level did not have significant impact on information value in a supply chain with different postponement implementations.

When the manufacturer's target service level varied from a low level, i.e. *90%*, to a high level, i.e. *99%*, the inventory cost reduction in the supply chain using DIS reduced for *8%* at most, with a *1%-2%* improvement in service: As the manufacturer's target service level improved, more safety inventory was required which counteracted part influence from information distortion. Therefore the impact of DIS on inventory reduction and service reduction decreased. In SIS, the supply chain's service performances were not significantly influenced by manufacturer's target service level but the inventory cost reduction decreased in no-postponement and form-postponement case when the service level increased. The dynamic effect did not show a consistent behavior with the changing manufacturer's service level. The result is summarized in Appendix Table A-6.

When the supplier's target service level varied from a low level, i.e. *90%*, to a high level, i.e. *99%*, the inventory cost reduction in the supply chain that utilized DIS changed slightly while the supply chain's service level and fill rate increased *2%* and *1%* respectively. Similarly in SIS the supply chain's service and cost performances changed slightly with supplier's target service level. Overall, we did not observe a clear impact of target service level on the information value in a supply chain under current setting. The reason may be the high inventory level we tested: even given the *90%* as the target service, the actual fill rate reached about *95%*. Considering the *99%* actual fill rate given by *99%* target service, the improvement caused by target service level was quite limited. We also set the *80%* as the target service and ran it in experiment. The result showed that the tier could actually achieve a fill rate around *92%*. Because an over *90%* service level and fill rate is common in modern industry, it is less useful for us to test the situations of below-*90%* service level. The result is summarized in Appendix Table A-7.

In summary, we did not observe a significant impact of target service level on the information value in a supply chain. The reason may come from the high service level we targeted at in the experiment. This result suggests that a critical service requirement to the upper tiers in a supply chain may be unnecessary, which enhances the rationality of the measurement scheme we designed in section 5.1.2.

Table 5-14 summarizes the significant impacts of four system parameters, including demand correlation, demand variance, production leadtime, and tier's target service level, on the supply chain performance based on simulation results. Note that in the table, service level is used to represent supply chain's service performance.

System factors / Postpone	Demand Correlation (ρ)		Demand Variance (σ)		Production Leadtime (L)		Target Service Level (α)	
	DIS	SIS	DIS	SIS	DIS	SIS	DIS	SIS
Form	Cost +	Cost +	Cost **-**	Cost **?**	Cost -	Cost **?**	Cost **?**	Cost **?**
	Service **-**	Service **+**	Service +	Service **?**	Service **?**	Service **?**	Service **?**	Service **?**
Time	Cost +	Cost +	Cost **-**	Cost -	Cost **?**	Cost **?**	Cost **?**	Cost **?**
	Service -	Service **+**	Service +	Service **?**	Service **?**	Service ?	Service **?**	Service **?**
Place	Cost +	Cost +	Cost **-**	Cost -	Cost **?**	Cost **?**	Cost **?**	Cost **?**
	Service -	Service **+**	Service +	Service **?**	Service **?**	Service **?**	Service **?**	Service **?**

Table 5-14: The summary of deducible significant impacts of system parameters on the supply chain performance. Cost: the cost reduction ratio in a supply chain; Service: the service improvement ratio in a supply chain; +: deducible positive influence; -: deducible positive influence; ?: unclear/insignificant influence.

5.3. Extended Analysis Of Combined Postponement Cases

The significant performance differences in the combined case 1, i.e. time and place postponement, under various informative environments were shown in Table 5-15. First of all, results showed that the performance changes at the retailer's site were the same as the result of place-postponement case in previous study, i.e. DIS helped the front tier to reduce its inventory cost most but increased its dynamic effect simultaneously. At the upstream organizations, SIS showed its significant impact on service improvement while DIS helped sites to keep lower inventory cost.

Combined Postponement Case 1	Service Level	Fill Rate	Order Lead Time	Absolute Percent Error of Service Level	Dynamic Effect	Inventory Cost
Retailer	0	0	0	0	D>O, S	O, S>D
Manufacturer	S>O>D	S>O>D	D>O, S	D>O, S	O>D, S	O, S>D
Supplier	O, S>D	O, S>D	D>O, S	D>O, S	O>S>D	O, S>D
Supply Chain	S>O>D	O>S>D	D>O, S	D>O, S	O>D>S	O, S>D

Table 5-15: 95% confidence of the mean difference of chain member's performance among Order-IS, Demand-IS and Shipment-IS in combined postponement case 1, i.e. time and place. O: Order-IS; D: Demand-IS; S: Shipment-IS. (D>S means the performance value under Demand-IS is significantly larger than that under Shipment-IS in the column. D>S>O equals D>S, D>O and S>O, while D>S, O equals D>S and D>O only; 0 means no such significant mean difference in various informative environments).

Then we considered the whole supply chain performances. It was shown that SIS performed better than OIS at service level improvement and dynamic effect reduction, while DIS performed better than OIS at inventory cost reduction and dynamic effect reduction. However, SIS did not provide itself as an efficient approach on supply chain cost reduction while DIS could not perform well on supply chain service maintaining. Based on this observation, we found that the influence of SIS and DIS on supply chain management tended to be strengthened in this combined case, i.e. the typical tradeoff between cost and service under these two information environments became more obvious in a chain.

Then we studied the significant performance differences in the combined case 2, i.e. form and place postponement, under various informative environments, as shown in Table 5-16. Comparing with previous postponement case 1, the major change in form postponement was the standardizing two products into one product, instead of changing the produce sequence. Therefore, the performance differences from information strategies should follow similarly rules as case1.

Combined Postponement Case 2	Service Level	Fill Rate	Order Lead Time	Absolute Percent Error of Service Level	Dynamic Effect	Inventory Cost
Retailer	0	0	0	0	D>O, S	O, S>D
Manufacturer	S>O>D	S>O>D	D>O>S	D>O, S	O, D>S	O>S>D
Supplier	O, S>D	O, S>D	D>O, S	D>O, S	O, S>D	O, S>D
Supply Chain	S>O>D	S>O>D	D>O, S	D>O, S	O>D>S	O>S>D

Table 5-16: 95% confidence of the mean difference of chain member's performance among Order-IS, Demand-IS and Shipment-IS in combined postponement case 2, i.e. form and place. O: Order-IS; D: Demand-IS; S: Shipment-IS. (D>S means the performance value under Demand-IS is significantly larger than that under Shipment-IS in the column. D>S>O equals D>S, D>O and S>O, while D>S, O equals D>S and D>O only; 0 means no such significant mean difference in various informative environments).

However, comparing Table 5-15 with Table 5-16, there were two main differences in supply chain performance: one was that the overall fill rate at the chain level in SIS became significantly grater than the other two strategies, the other was the inventory cost in SIS at the chain level became significantly smaller than OIS, although it was still larger than DIS. Therefore it was obvious that SIS dominated OIS by both the service and cost performance while DIS still showed its significant impact on reducing inventory cost.

In summary, as the supply chain implemented combined postponement approach, the benefit from utilizing demand information and shipment information became more significant: DIS largely reduced supply chain's inventory cost and dynamic effect, while SIS improved chain's service level, reduced its dynamic effect and inventory cost. From numerical result analysis, we also found that the ratios of supply chain's service improvement and cost reduction, enabled by different information strategies, became greater than previous cases that only implemented one postponement at a time, which showed an increasing information value as supply chain applied more postponement approaches. These findings extend the extant of this study and generalize the results from previous analysis.

5.4. Summary And Implication

We carried out various experiments to study the value of information sharing strategies in postponement environments in a supply chain. Six measurements, including service level, fill rate, order leadtime, absolute error of service level, dynamic effect and inventory cost, were applied to under the supply chain behaviors. In this section, we summarize our work and discuss its managerial implication, strength and limitation, respectively.

5.4.1. Summary

Motivated by the common and different impacts of information sharing strategy and postponement strategy on a supply chain's inventory and production management, we studied the information-shared postponement in supply chains. In this study, we defined three postponement strategies: form, time and place, based on three characteristics of production/process in the supply chain which describe the basic essence of postponement, i.e. product design, process design and place design. A no-postponement case was added for comparison purpose. From the view of channel focus, we defined two different information sharing strategies at operational level based on the purpose and the channel focus on information sharing strategies: demand information sharing and shipment information sharing. An order information sharing case, i.e. only orders were available between any two tiers in a supply chain, was added for comparison purpose.

To simplify our analysis, we focused on the information impact on each postponement situation in a supply chain. As a result, the performances of supply chain members, as well as the overall chain performances, were examined with different information sharing strategies. By statistical significance test, the supply chain's general behaviors of implementing different information-shared postponement strategies were presented, which was the first phase of the whole picture. Then the comparisons of service and cost performances of all supply chain members among different information sharing strategies were carried out to indicate how different information strategies collaborate with postponement strategies.

Results showed that DIS helped organizations reduce inventory cost. However, choosing DIS was a typical tradeoff between cost and service in a chain across postponement strategies in a supply chain. The bullwhip effect in DIS was always smaller than that in OIS. Additionally, DIS significantly reduced the inventory cost at the retailer tier in place postponement, indicating that it was probably a good choice to place postponement.

SIS performed differently across situations: in no-postponement and form-postponement case, it dominated OIS on both the service and cost performances, but in time-postponement and place-postponement case, such significant benefit was weakened. Furthermore, although SIS always benefited the manufacturer, the supplier's performances became worse in some cases because of the misunderstanding of the feedback on the shared information. Results also showed that the performances at the retailer's site did not have significant changes in most information-shared postponement environments. We also found that although DE could demonstrate the demand distortion process along supply chains, it was not a suitable measurement to evaluate supply chain performance independently.

Postponement strategies could reduce the supply chain inventory cost. However, form postponement reduced the inventory cost most in DIS and SIS while place postponement played equivalently well as form postponement did in OIS. Because the differentiation point in time postponement was moved closer to the retailer, the inventory cost at the supplier site increased while such cost at the manufacturer site decreased. In place postponement, the retailer's inventory cost increased while the manufacturer's inventory cost decreased greatly.

Then a further consideration about the impact of system parameters, including the impact of demand variance and demand correlation over time in the market, the impact of different production leadtime, and the impact of various target service levels that the supply chain members may set, were added. This in-depth study provided a comprehensive understanding of the supply chain dynamics, and its sensitivity, in various environments.

Results suggested that the value of SIS positively correlated to the demand trend: the inventory cost reduction and the service improvement increased when the demand correlation increased. When the demand correlation was low, SIS dominated OIS only in no-postponement and form-postponement environment while its performances in time-postponement and place-postponement was worse than the benchmark. However, when the demand correlation became high, the supply chain's inventory cost decreased significantly, while the service level and the fill rate became greater than OIS situation. Therefore, SIS dominated OIS in all postponement cases when the demand correlation was positively high. Also, SIS conditionally dominated DIS when the demand correlation was positively high: The inventory cost reduction by SIS in all postponement cases was equal or higher than that by DIS while the service improvement by SIS was larger than those by DIS. Furthermore, DIS dominated both OIS and SIS when demand coefficient was negatively high enough. We also found that DIS enlarged the inventory cost reduction when the demand variance decreased.

However, we did not observe a significant impact of target service level on the information value in a supply chain. The reason might come from the high service level we targeted at in the experiment. This result suggested that a critical service requirement to the upper tiers in a supply chain might be unnecessary. Although leadtime showed a significant impact on information value in a supply chain, such impact was in an inconstant manner, which motivated us to consider the impact of leadtime distribution instead of leadtime length.

5.4.2. Discussion and implication

In highly competitive markets, the use of information technologies in intra-organizational and inter-organizational systems is changing the business landscape in fundamental ways and showing its significant impact on leveraging inventory, connecting business partners, and cost-effectively fulfilling orders across multiple distribution channels. There are two challenges that are involved in achieving an efficient supply chain management: one is the increasing proliferation of product variety which adds the difficulty in facilitating the smooth and efficient flow of products down the value-added chain at the least cost. The other is demand distortion that causes the supply chain more difficult to match supply with market demand properly. For companies seeking to develop or manage their business with customers effectively, their success in overcoming these two challenges largely depends on their ability of utilizing proper information to fit with their operations and to integrate partners into a tightly coupled supply chain.

With the front tier in a supply chain sharing out its real sell through data, upstream partners can improve demand forecasts and develop better production plans to decrease the overage and underage costs. The drawback of this policy is that the members may experience more stock-out. The reason is that the upstream partners cannot promptly respond to demand fluctuating with their safety stock. Even when they find the increase in the incoming order rate is larger than the real change in the end market, they fail to recognize retailer's needs to adjust its inventory and supply line, which undermines the relationships among the partners. Furthermore, the physical leadtime existing among supply chain organizations delays the adjusted supply from upstream suppliers.

Another important information in supply chains is when and how much the goods will appear "on their doorstep", i.e. the information of available-to-promise (ATP). Due to suppliers' imperfect service on transportation and production, members' orders could not always be satisfied on time with perfect product quality. Therefore, to them, accuracy and high quality on arrival shipping quantity is valuable to make better inventory and production decisions. In this study, we also analyzed the effect of supplier's shipment information on supply chain's performance. It is found that SIS helps downstream organizations improve their decision quality. Consequently their inventory cost is reduced and overall performance of the supply chain is improved. However, sometimes a "noise" of ordering variance, i.e. a misunderstanding of the feedback from shared information, caused by order adjusting from information receiver in SIS, may aggravate demand forecast error at the information sender and worsen the organization' service performance.

Influence on Supply Chain Performances and Managerial Suggestion

Based on experimental analysis, one general finding is that various information strategies perform differently on performance measures. A managerial implication is that managers should choose suitable information sharing strategies according to the characteristic of their postponement types and system environments. For example, those organizations that concern about inventory cost may choose DIS while other "mission critical" organizations that are more sensitive to service other than cost may find SIS more suitable to them.

When implementing different postponement strategies, the performance of tiers in a chain is usually affected differently. For example, the place postponement strategy increases the cost at the lower tier where takes over part of the production activities but reduces the cost occurs at upper tiers. Similarly, upper tiers' inventory cost increases by implementing time postponement strategies (Similar observation includes Dong and Lee, 2002). Therefore, organizations that implement postponement strategies should consider these cost-change issues in supply chains.

With available information, different target service level at upper tiers does not show a significant influence on the cost reduction in the supply chain, which means that a critical service requirement to the upper tiers in a supply chain may be unnecessary. Because of the significant cost reduction from the information, the supply chain members can relax its requirement for supplier's service performance and, in return, ask for benefit redistribution from cost reduction, such as a lower purchasing price. This performance measurement scheme can benefit all supply chain members. Another important implication from this result is that the service at upstream partners may not be as critical as we thought to be. If a minimum acceptable service can be promised, say *90%* in this study, the front tier's performance to serve the market can be satisfied with the help of information sharing mechanism in the supply chain. Based on this finding, organizations obtain more flexibility to choose its suppliers and IT becomes a more important input to their supplier-choose decision. If the supplier can satisfy the IT requirement to communicate with the front tier efficiently and properly utilize the valuable information from its partners, it should perform as well as other suppliers with higher service standard. On the other hand, if the supplier ignores the importance of information but focuses only on the service providing, it may afford unnecessary high cost and lose market share. From this point of view, well-utilized information technology can directly improve company's productivity and competition competence in the market. Other empirical evidences (e.g. Dedrick, 2003) in economic study support this observation.

Feasibility of Information Collaboration and Managerial Suggestions

The feasibility of implementing information-shared postponement strategies in a supply chain is another important consideration in practice. One important finding in this study is that the benefit from information-shared postponement strategies is not equally contributed to all tiers in a supply chain. It is usually the information receiver that gains more benefit than the information sender does. For example, in DIS, the front tier that shares out the market demand information does not enjoy any significant benefit in most information-shared postponement environments, while upstream organizations optimize their inventory and reduce cost via this information. Similarly in SIS, downstream organizations utilize the shipment information shared from the upstream partner to adjust their order decision and to improve their service performance, while the information sender cannot improve its performance by sharing out the information. The different result to supply chain members may cause barriers to information sharing because it is difficult for participants to collaborate tightly in a supply chain if anyone cannot benefit from the collaboration.

A managerial implication drawn from this result is that part of the benefits gained by information receivers should be redistributed to the information sender so that the information sender is more willing to keep sharing out the valuable information to improve supply chain performance. The analyses of the different roles that tiers act in information sharing strategies, in postponement strategies and in the sensitivity of tier's target service level show that the benefit redistribution may become an important issue in supply chain management. For example, supply chain members can lower down the unit price of its products that are supplying to their downstream partners as a pay for shared market demand from downstream. Furthermore, if price is an order winner (APICS, 2002) in a highly competitive industry, the lower price can result in a higher competition competence. On the other hand, if the information of shipment availability becomes an order qualifier (APICS, 2002) in the market, organizations are forced to provide ATP information to their customers as a basic requirement to enter the market, which, in fact, is quite common in practice. Another possibility to break through this barrier is the availability of an organization that holds a strong bargaining power in the chain. These big organizations that control the main resources in the chain, like Intel and Wal-Mart, can push its upstream and downstream partners to behave collaboratively before allowing them entering the market. For example, Intel and Wal-Mart usually set EDI as the pre-requisite to do business with, which make information sharing for inter-organizational collaboration possible.

Construction fee of inter-organizational information system (IS) is another important consideration for a realistic information sharing mechanism. Sharing information is not free. To share information timely and efficiently, IT technologies, such as EDI and Internet-based technologies, are essential and important to support this goal. As we have found out that some tiers may not benefit from the information they provide, a satisfactory share of the IS construction fee is necessary to integrate them into the supply chain management. Therefore, before IS construction, the whole supply chain should be clear about the benefit each tier may earn if information is available, through the similar approach used in this study.

One point in IS development and integration is the infrastructure design and investment. As Client/Server is the popular and common-used framework in the information system, the investment in information systems that are held as servers is greater than the other client members. Therefore the benefit each member can earn should be considered as an input of the IS design to determine the server location and investment afforded. The organizations that benefit significantly from the information should afford more investment in IS infrastructure. After all these consideration above, the information sharing mechanism becomes more realistic.

To enable information sharing, the information systems of the participating enterprises must be integrated as well. However the initial capital investment may be large. If an enterprise already has an information system, system integration may become a problem. An organization with a strong bargaining power, like Wal-Mart, may demand its suppliers to use a compatible information system while an organization with weak bargaining power usually has to satisfy various IT requirements from different major customers. Furthermore complete demand information visibility requires the information systems of all the enterprises in the supply chain to be integrated, while sharing shipment data only requires a two-tier integration that is more feasible.

Impact of Market and Industry Environment and Managerial Suggestions

The characteristics of market and industry also influence the efficiency of utilizing information. One suggestion from this study is that the suitable information sharing strategies should be used in markets with different demand patterns. There are several factors that influence the demand patterns. First of all, different product nature causes different demand patterns. For example, Fisher (1997) classified the products into functional products, which had low demand variation and stable requirement, and innovative products, which had shorter life cycle and larger demand variation. Second, demand patterns of product change along the product life cycle that usually include four stages: introduction, growth, maturity and decline. Finally, product characteristics, such as functionalities, determine the product nature and appeal different supply chain performance.

With postponement implementation, the product nature can be changed, which usually result in the demand pattern change. Therefore, supply chain managers should choose suitable information sharing strategies according to the characteristic of their postponement types and market environments. For example, if the supply chain manager faces a no-trend demand process, DIS is a good choice to place postponement while SIS performs well in no-postponement and form-postponement situation. Whether DIS or OIS is better for time postponement is a case-to-case cost-service trade off. However in a market with an increasing trend on product demand, SIS becomes a dominating strategy for manager to consider in all postponement-type supply chain, regardless the centrality of the supply chain itself. When the market demand turns to decrease, DIS is the choice.

Furthermore, when the trends are unpredictable, OIS is still a choice to avoid the loss from wrongly manipulating the demand/order variance by information sharing strategies. For example, the longer leadtime between the manufacturer and the supplier may cause unnecessary misunderstanding of the feedback from shared shipment information and the loss from such misunderstanding behavior may overcome the benefit one tier may obtain from the shared information. Furthermore, previous research suggested that the results might be amplified when more tiers were involved (Tan and Wang, 2001). As OIS is comparatively less sensitive to demand fluctuation, managers may choose this strategy, particularly in the case that that the investment on information sharing and collaboration is greater than the additional benefit from using other information strategies.

It is obvious that the core point in information sharing is the total collaboration among participating enterprises to accomplish collective targets. To achieve a satisfying collaboration, well understandings among participants enabled by sharing information and knowledge is the foundation. For example, there is a need to understand specific trading partner attribute in a supply chain and information meanings of each transaction. However the relationships among participants in supply chain management may be long-term and stable, as well as short-term and temporary. If the supply chain alliance is temporary, the information and knowledge sharing mechanism should be open enough to absorb new participants, to make new alliance and to share information quickly (Zhang and Zhang, 2004). One possible solution is developing consortium-based and open standards for information sharing mechanism cross industries so that any participant in a supply chain can "speak the same language" to share timely information efficiently. For example, RosettaNet maintains a successful consortium-based standard of open e-business process, developed by more than 400 of the worlds' leading IT companies (Morris, 2002). It utilizes XML-based dialogues between trading partners to communicate core business processes and information, including administration, product introduction, order management, inventory management, marketing information management, service and support and so on. By providing such a transmission standard and platform environment in the industry, information sharing mechanism becomes more feasible and efficient in supply chain management.

Since the capital investment in information infrastructure development depends on the technology level as well as many other issues discussed in the previous sections, this thesis does not consider the information cost. However the cost saving and service improvement, enabled by information sharing, can be used as a benchmark to evaluate information system investment. From this perspective, this study provides a practical and general approach for organizations to evaluate their IT investment on IS construction and supply chain collaboration.

5.4.3. Strength and limitation of the simulation system

Simulation can solve complicated real-world problem with wide scope and scalability (Law and Kelton, 1991) and is an effective way to improve modeling (Galliers and Land, 1987). Since simulation is built on mathematical or logical model, there are few barriers between simulation implementation and models. By simulation, computers are used to evaluate a model numerically, and data are gathered in order to estimate the desired true characteristics of the model and to find out how accurate the logic / analytical model fits the real situation. The simulation system is also very flexible. It can be used to model various types of supply chains by specifying the proper combination of supply chain members with particular properties.

Simulation system is a powerful tool to study the dynamic supply chain network since it enables a detailed review of the inner-workings in real time that is not seen in the high level analytical models (Shannon et al., 1980). The supply chain is a complex system involving may business organizations and processes of varying levels of granularity and inter-related relationship. These entities and processes relationships do not remain constant but change over time as they response to each other and to the environment. Mathematical and analytical approaches usually study only few specific aspects of the supply chain in isolation, e.g. only the performances about one tier in a supply chain is analyzed, or only one or two performances is measured in a chain. As we discussed in the previous sections, researches show that the locally optimized performances in one stage does not promise an improvement in the whole supply chain, sometimes even worsen it. Therefore analyzing a single stage under few performances cannot provide a full and correct picture of the whole chain changes. For example, Dong and Lee (2002) argued that the inventory removed at a certain place in a supply chain might be transferred to another place in the chain when changing the channel structure, which meant other members' cost and service were influenced as well. In this case, analyzing one member's performances was definitely not enough. Simulations, on the other hand, can simulate the actual behaviors of the real world enterprises thoroughly crossing the whole chain, so that we can better understand the supply chain complexity as well as its adaptive behavior. The complexity is kept manageable by modeling the business organizations in terms of simple entities and the supply chain as a combination of these entities. Furthermore, in computer simulation it is easy to trace the intermediate behaviors of the system during its execution, which is very useful in understanding the behavior of a supply chain

One main constraint is that the simulation cannot provide a general understanding of the variable impact in the system. Because simulation evaluates a model numerically, theoretically speaking, any specific data sets to simulate the system variables cannot cover all possible points and scopes the variables may reach. Even when the sensitivity study is carried out, the system only roughly show you how the system behaves at these key points but not a full picture on how the system changes with the variables. Therefore, the simulation result faces a generalization problem. On the other hand, mathematical analytical tools, e.g. calculus, can clearly and convincingly describe such changes in a model. Another constraint of the simulation system is it is usually unable to provide optimal solutions. The value of simulation systems is not the preciseness of the result, but to give users an idea of the outcome in "what-if" scenarios.

CHAPTER 6 CONCLUSION AND FUTURE DIRECTION

In this chapter, we conclude the purpose, the experiment and the result of this study, with a summary of future studies.

6.1. Conclusion

The goal of this thesis is to study the impact of information sharing on supply chains that implement different types of postponements. We compared the performances in supply chains with different available information to discover how information strategies influence the effectiveness of postponement strategies. In this study, we defined four different types of postponement situations, i.e. form, time, and place, together with a no-postponement case for comparison purpose, after categorizing postponement strategies. Then three types of information strategies are chosen from perspective of decision-making utilization and channel focus, they are order information sharing, demand information sharing and shipment information sharing. Altogether six measurements, including service level, fill rate, order leadtime, absolute error of service level, dynamic effect and inventory cost, are applied to the supply chain performances.

This study was carried out via simulation. A simulation system was developed via GPSS to model a three-tier linear supply chain network consisting of a retailer, a manufacturer and a supplier. This setting represents a typical production-inventory system. We designed the chain as a decentralized type that is more common than a centralized type in practice. However our analysis can be simply extend to cover a centralized supply chain. The behaviors of the chain members were periodically activated, observed and recorded for statistical analysis of the impact of various information sharing strategies and postponement strategies in a supply chain network. Sensitivity analyses on four system variables, i.e. demand correlation, demand variance, production leadtime and service level, were carried out for in-depth understanding of the managerial implications of such combined effects. ANOVA tests were used to examine the significance of results.

This study provided a detailed analysis of the correlations of postponement and information sharing strategies on supply chain performance and illustrated clearly how these two strategies would affect the benefit of inter-organizational collaboration. Results showed that different information sharing strategies did not perform equally well on all performance measures. Managers should choose suitable information sharing strategies according to the characteristic of their postponement types and system environments. If the supply chain faces a no-trend demand process, demand information sharing is a good choice for place postponement while shipment information sharing performs well in no-postponement and form-postponement situation. Whether demand information sharing or order information sharing is better for time postponement is a case-to-case cost-service tradeoff.

The benefits of information-shared postponement strategies are significantly influenced by the trended demand. In a market with an increasing trend on product demand, shipment information sharing becomes a dominating strategy for manager to consider in all postponement-type supply chain, regardless the centrality of the supply chain. When the market demand turns to decrease, demand information sharing is the choice.

Furthermore, the benefits from information-shared postponement strategies are not equally contributed to all tiers in a supply chain. For example, the front tier does not enjoy significant benefits in most information-shared postponement environments while the information provider cannot improve, sometimes even reduces, its performances by sharing out its shipment information. These "unfair" treat may become a barrier for the tier to share its information in a supply chain. In practice, sometimes the organizations in a supply chain may have different incentives to optimize its performances locally and may be wary of the possibility of other partners abusing information to reap more benefit. As a result, it is valuable to find out the beneficial way to share the minimum amount of necessary information with partners during information systems construction or collaboration negotiation. This study can help organizations achieve this goal.

Information sharing in supply chain network is an important ingredient in coordinating the activities between strategic partners while postponement strategy effectively increases a supply chain's responsiveness to increasing product variations and shortening product life cycle. We believe our research will contribute greatly to the supply chain management research and real life applications.

6.2. Future Direction

1. In our study, only one type of information sharing strategy is used throughout the entire supply chain at any one time. The recommendation to use a hybrid information sharing may lead to greater improvements in performances. Knowing the behavior of strategies under each demand pattern, we can suggest a good combination of information strategies.

2. In this study, only one forecasting method is used through out the supply chain, i.e. a simple moving average. However a proper forecasting method that can largely reduce estimate error is a benefit to the organizations without information coordination. Because both information sharing strategies and postponement strategies partly reduces the demand distortion, a better forecasting choice may influence, probably weaken, the value of information and postponement. It will be valuable to analyze how information-shared postponement strategies perform with the forecasting accuracy in a supply chain. To do so, more demand patterns and forecasting methods should be introduced into this model.

3. A linear supply chain structure is analyzed in this model. However other types of the chain structure, such as convergent structure, i.e. a number of suppliers converge to a relatively small distribution network, and divergent structure, i.e. a numbers of suppliers diverge to a relatively large distribution network, may influence the effectiveness of information-shared postponement strategies in a supply chain. Product structure and characteristics partially determine the supply chain structure: Complex products that comprise a large number of parts in industries like aerospace, automotive and other

machinery naturally require many suppliers to supply those components respectively. These products usually require professional maintenance in a few distribution centers. Consumer products, on the other hand, are usually simple in product structure and easy to be stored. Therefore a relatively small number of suppliers are required but a divergent distribution network is necessary to sell the products economically and fast to the customers. These different structures will affect the chain performance. For example, a risk pooling effect on aggregating demand is expected in the distribution channel of a divergent supply chain while the value of shipment information may increase in a convergent supply chain. By analyzing the impact of supply chain structure on the information-shared postponement strategies, our model more thoroughly simulates and solves the supply chain problems in real-world practice.

4. We assume in this study that each tier in the supply chain has no capacity limitation on their production and inventory, or the production and inventory plans rarely reach their upper capacity limitation, while such capacity limitation sometimes exists in practice. Therefore it is valuable to analyze the impact of capacity limitation on information-shared postponement as an extension.

5. The supply chain we simulate is a decentralized one without a unique centralized decision maker. Although the chain members share some degree of information in between, they still make their inventory / production decisions locally to optimize their individual objective function, which results in a sub-optimal supply chain management. On the contrary, by system coordination, a centralized decision maker can optimize the

chain-wide performances instead of any single tier in the chain. In this study such benefit is not thoroughly studied. Therefore we are encouraged to consider detailed system coordination approaches, such as using centralized multi-echelon order decision to replace orders between tiers, in a supply chain to quantify the expected cost-benefit of implementing postponement strategies.

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APPENDICES:

Proof1: $E\left(\lim_{t->\infty}\frac{1}{t}\sum D_t\right)=\frac{1}{1-\rho}u$ where $D_t = u + \rho D_{t-1} + \varepsilon_t$, $u > 0$, $|\rho| < 1$ and ε_t follows normal-distributed IID $(0, \sigma^2)$

Lemma1: $\lim_{t->\infty} x_t = A \Rightarrow \lim_{t->\infty}\frac{1}{t}\sum x_t = A$.

When $|x_t - A| < \frac{\varepsilon}{2}\forall t > N_1$ (N_1 is a natural number and ε is positive), $\left|\frac{(x_1 - A) + ...(x_{N_1} - A)}{t}\right| < \frac{\varepsilon}{2}\forall t > N_2$ (N_2 is a natural number). Let $N = \max\{N_1, N_2\}$, so

$$\left|\frac{x_1 + ...x_t}{t} - A\right| \le \left|\frac{(x_1 - A) + ...(x_{N_1} - A)}{t}\right| + \left|\frac{(x_{N_1+1} - A) + ...(x_t - A)}{t}\right| < \frac{\varepsilon}{2} + \frac{t\varepsilon}{2t} = \varepsilon\forall t > N$$

Therefore $E\left(\lim_{t->\infty}\frac{1}{t}\sum D_t\right) = E\left(\lim_{t->\infty} D_t\right) = E\left[\lim_{t->\infty}\left(\sum_{t=1}^{\infty}\rho^{t-1}\right)\cdot u\right] = \frac{u}{1-\rho}$

Note: Due to the complicated experimental designs and tests, the simulation code, including the configuration files and data analysis programs, contains thousands of lines, which is too long for this appendix. Therefore the source code will be provided only upon request.

Performances	Information Sharing	Demand Correlation	No Postponement				Form Postponement				Time Postponement				Place Postponement			
			R	M	S	SC	R	M	S	SC	R	M	S	SC	R	M	S	SC
Service Level	Demand-IS	0	-0.3%	-3.8%	-9.3%	-4.5%	-0.5%	-4.1%	-8.7%	-4.4%	-0.3%	-4.3%	-10.2%	-4.9%	-0.4%	-7.2%	-8.6%	-5.4%
		0.2	-0.8%	-6.3%	-12.7%	-6.6%	-0.9%	-6.9%	-11.5%	-6.4%	-0.7%	-6.3%	-13.2%	-6.7%	-1.0%	-10.0%	-11.3%	-7.4%
		0.4	-1.6%	-8.9%	-15.3%	-8.7%	-1.8%	-9.8%	-14.1%	-8.6%	-1.2%	-7.9%	-14.7%	-7.9%	-1.8%	-12.5%	-13.6%	-9.3%
		0.6	-2.7%	-11.6%	-17.8%	-10.9%	-2.6%	-12.2%	-16.1%	-10.5%	-1.7%	-9.2%	-16.2%	-9.1%	-2.9%	-14.4%	-15.7%	-11.1%
		0.8	-3.8%	-13.9%	-20.3%	-13.0%	-4.0%	-14.9%	-18.7%	-12.8%	-2.2%	-10.4%	-17.1%	-10.1%	-4.1%	-16.3%	-17.5%	-12.9%
	Shipment-IS	0	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.4%	-0.5%	0.0%
		0.2	0.0%	0.3%	0.2%	0.2%	0.2%	0.6%	0.5%	0.4%	0.0%	0.2%	1.5%	0.6%	0.1%	1.5%	1.6%	1.1%
		0.4	0.2%	0.9%	1.8%	1.0%	0.1%	1.0%	2.1%	1.1%	0.2%	0.6%	3.8%	1.5%	-0.1%	2.0%	4.1%	2.0%
		0.6	0.0%	0.6%	3.7%	1.5%	0.0%	1.0%	4.3%	1.9%	0.3%	0.9%	6.3%	2.5%	-0.1%	2.5%	6.2%	2.9%
		0.8	0.2%	1.0%	6.1%	2.5%	0.2%	1.3%	6.6%	2.9%	0.6%	1.1%	7.9%	3.3%	-0.1%	2.1%	7.7%	3.3%
Fill Rate	Demand-IS	0	-0.2%	-2.0%	-4.2%	-2.1%	-0.1%	-1.7%	-3.5%	-1.8%	-0.1%	-1.6%	-5.8%	-2.5%	-0.2%	-3.9%	-4.2%	-2.8%
		0.2	-0.5%	-3.6%	-6.5%	-3.5%	-0.5%	-3.2%	-5.2%	-2.9%	-0.4%	-2.6%	-8.2%	-3.7%	-0.5%	-5.9%	-6.0%	-4.1%
		0.4	-1.1%	-5.5%	-8.6%	-5.0%	-0.8%	-4.8%	-6.9%	-4.1%	-0.8%	-3.8%	-9.9%	-4.7%	-1.0%	-8.1%	-8.0%	-5.6%
		0.6	-2.1%	-7.4%	-10.7%	-6.7%	-1.5%	-6.6%	-8.7%	-5.6%	-1.3%	-4.6%	-11.3%	-5.6%	-1.7%	-9.8%	-9.9%	-7.0%
		0.8	-3.3%	-9.0%	-12.9%	-8.4%	-2.3%	-8.0%	-10.1%	-6.8%	-1.8%	-5.0%	-11.7%	-6.1%	-2.7%	-11.5%	-11.4%	-8.4%
	Shipment-IS	0	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.1%	-1.7%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.4%	-1.4%	-0.4%
		0.2	0.1%	0.3%	-1.1%	-0.3%	0.2%	0.5%	-1.2%	-0.2%	0.0%	0.1%	-0.3%	-0.1%	0.1%	1.4%	-0.1%	0.4%
		0.4	0.1%	0.6%	-0.1%	0.2%	0.1%	0.7%	-0.1%	0.3%	0.1%	0.5%	1.6%	0.7%	0.0%	1.9%	1.7%	1.2%
		0.6	-0.1%	0.5%	1.4%	0.6%	-0.1%	0.4%	1.6%	0.6%	0.3%	1.0%	3.7%	1.6%	0.1%	2.7%	3.5%	2.1%
		0.8	0.0%	0.9%	3.5%	1.4%	0.0%	0.9%	4.0%	1.6%	0.7%	1.6%	5.6%	2.6%	0.2%	3.0%	4.9%	2.7%
Inventory Cost	Demand-IS	0	0.3%	-21.4%	-47.8%	-26.1%	0.3%	-23.4%	-49.9%	-29.4%	0.3%	-16.0%	-37.2%	-19.5%	-6.4%	-23.5%	-39.8%	-22.3%
		0.2	0.9%	-26.4%	-57.0%	-33.7%	1.5%	-29.8%	-60.8%	-38.8%	0.7%	-18.5%	-46.4%	-25.3%	-7.3%	-26.0%	-48.9%	-28.0%
		0.4	2.8%	-27.4%	-66.2%	-39.4%	4.1%	-29.3%	-70.1%	-43.7%	1.3%	-17.2%	-61.8%	-31.5%	-3.9%	-21.8%	-64.1%	-31.9%
		0.6	5.6%	-23.8%	-73.2%	-40.3%	6.2%	-28.1%	-75.5%	-43.8%	3.0%	-13.9%	-74.3%	-34.0%	-0.1%	-20.2%	-76.6%	-34.2%
		0.8	8.2%	-19.9%	-76.9%	-40.5%	9.4%	-28.6%	-78.2%	-43.9%	5.9%	-12.3%	-80.0%	-34.5%	2.8%	-18.6%	-82.1%	-34.4%
	Shipment-IS	0	0.0%	-1.7%	-8.0%	-3.5%	0.0%	-2.3%	-11.6%	-5.3%	0.0%	9.5%	26.8%	13.2%	0.0%	-0.4%	2.8%	0.8%
		0.2	-0.2%	-6.0%	-10.9%	-6.9%	-0.4%	-7.9%	-16.6%	-10.6%	-0.1%	8.2%	33.0%	15.6%	-2.9%	-10.9%	1.8%	-3.7%
		0.4	-1.1%	-18.0%	-17.1%	-16.0%	-1.5%	-27.5%	-28.6%	-26.0%	-0.7%	-10.5%	19.2%	0.8%	-20.1%	-34.1%	-13.1%	-23.0%
		0.6	-4.4%	-40.9%	-28.8%	-34.1%	-6.1%	-49.7%	-37.9%	-42.9%	-2.0%	-18.1%	13.8%	-6.6%	-39.1%	-57.5%	-36.3%	-45.9%
		0.8	-11.2%	-57.9%	-41.1%	-49.8%	-13.4%	-60.8%	-43.6%	-52.7%	-4.5%	-30.3%	-2.2%	-20.2%	-49.1%	-63.3%	-45.9%	-54.3%

Table A-1: The supply chain performances with different positive demand correlation across time. R: retailer, M: manufacturer, S: supplier, SC: supply chain level. The percentage values in the cells are the difference from the benchmark: the Order-IS situation.

Performances	Information Sharing	Demand Correlation	No Postponement				Form Postponement				Time Postponement				Place Postponement			
			R	M	S	SC	R	M	S	SC	R	M	S	SC	R	M	S	SC
Service Level	Demand-IS	0	-0.3%	-3.8%	-9.3%	-4.5%	-0.5%	-4.1%	-8.7%	-4.4%	-0.3%	-4.3%	-10.2%	-4.9%	-0.4%	-7.2%	-8.6%	-5.4%
		-0.2	-0.1%	-2.2%	-6.1%	-2.8%	-0.1%	-2.3%	-6.0%	-2.8%	-0.1%	-2.8%	-7.0%	-3.3%	-0.2%	-4.6%	-5.9%	-3.6%
		-0.4	0.0%	-1.0%	-3.5%	-1.5%	0.0%	-1.1%	-3.7%	-1.6%	0.0%	-1.6%	-4.4%	-2.0%	-0.1%	-2.5%	-3.6%	-2.1%
		-0.6	0.0%	-0.4%	-1.9%	-0.8%	0.0%	-0.4%	-1.8%	-0.7%	0.0%	-0.7%	-2.4%	-1.0%	0.0%	-1.3%	-1.9%	-1.1%
		-0.8	0.0%	-0.2%	-0.8%	-0.3%	0.0%	-0.1%	-0.5%	-0.2%	0.0%	-0.3%	-1.2%	-0.5%	0.0%	-0.6%	-1.0%	-0.5%
	Shipment-IS	0	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.4%	-0.5%	0.0%
		-0.2	0.0%	0.0%	-0.9%	-0.3%	0.0%	0.0%	-0.8%	-0.2%	0.0%	0.0%	-1.0%	-0.3%	0.0%	0.1%	-0.9%	-0.2%
		-0.4	0.0%	0.0%	-0.5%	-0.2%	0.0%	0.0%	-0.6%	-0.2%	0.0%	0.0%	-0.9%	-0.3%	0.0%	0.0%	-0.7%	-0.2%
		-0.6	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.0%	-0.6%	-0.2%	0.0%	0.0%	-0.4%	-0.1%
		-0.8	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.0%	-0.6%	-0.2%	0.0%	0.0%	-0.5%	-0.2%
Fill Rate	Demand-IS	0	-0.2%	-2.0%	-4.2%	-2.1%	-0.1%	-1.7%	-3.5%	-1.8%	-0.1%	-1.6%	-5.8%	-2.5%	-0.2%	-3.9%	-4.2%	-2.8%
		-0.2	-0.1%	-0.9%	-2.5%	-1.1%	0.0%	-0.8%	-2.1%	-1.0%	0.0%	-0.9%	-3.5%	-1.5%	-0.1%	-2.2%	-2.5%	-1.6%
		-0.4	0.0%	-0.3%	-1.2%	-0.5%	0.0%	-0.2%	-1.1%	-0.4%	0.0%	-0.4%	-2.0%	-0.8%	0.0%	-1.0%	-1.3%	-0.8%
		-0.6	0.0%	-0.1%	-0.5%	-0.2%	0.0%	-0.1%	-0.4%	-0.2%	0.0%	-0.2%	-1.0%	-0.4%	0.0%	-0.5%	-0.6%	-0.4%
		-0.8	0.0%	0.0%	-0.2%	-0.1%	0.0%	0.0%	-0.1%	0.0%	0.0%	0.0%	-0.5%	-0.2%	0.0%	-0.2%	-0.3%	-0.2%
	Shipment-IS	0	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.1%	-1.7%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.4%	-1.4%	-0.4%
		-0.2	0.0%	0.0%	-1.1%	-0.4%	0.0%	0.0%	-1.2%	-0.4%	0.0%	0.0%	-1.4%	-0.5%	0.0%	0.1%	-1.2%	-0.4%
		-0.4	0.0%	0.0%	-0.6%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.0%	-1.0%	-0.3%	0.0%	0.0%	-0.7%	-0.2%
		-0.6	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.0%	-0.3%	-0.1%	0.0%	0.0%	-0.6%	-0.2%	0.0%	0.0%	-0.5%	-0.2%
		-0.8	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.0%	-0.6%	-0.2%	0.0%	0.0%	-0.5%	-0.2%
Inventory Cost	Demand-IS	0	0.3%	-21.4%	-47.8%	-26.1%	0.3%	-23.4%	-49.9%	-29.4%	0.3%	-16.0%	-37.2%	-19.5%	-6.4%	-23.5%	-39.8%	-22.3%
		-0.2	0.1%	-17.3%	-39.2%	-20.2%	0.1%	-19.0%	-41.4%	-23.1%	0.1%	-15.9%	-32.1%	-17.1%	-5.5%	-20.3%	-33.2%	-18.2%
		-0.4	0.0%	-14.3%	-31.7%	-15.9%	0.0%	-15.4%	-33.3%	-17.9%	0.0%	-15.1%	-28.6%	-15.4%	-4.9%	-18.2%	-28.6%	-15.6%
		-0.6	0.0%	-12.0%	-26.3%	-13.0%	0.0%	-13.3%	-27.5%	-14.7%	0.0%	-13.7%	-25.6%	-13.6%	-4.5%	-16.6%	-25.6%	-13.9%
		-0.8	0.0%	-10.0%	-22.3%	-10.8%	0.0%	-11.3%	-22.6%	-12.1%	0.0%	-11.9%	-22.7%	-11.8%	-3.8%	-14.9%	-22.9%	-12.2%
	Shipment-IS	0	0.0%	-1.7%	-8.0%	-3.5%	0.0%	-2.3%	-11.6%	-5.3%	0.0%	9.5%	26.8%	13.2%	0.0%	-0.4%	2.8%	0.8%
		-0.2	0.0%	-0.7%	-5.4%	-2.0%	0.0%	-1.0%	-8.0%	-3.2%	0.0%	4.1%	12.5%	5.7%	0.0%	0.4%	0.5%	0.3%
		-0.4	0.0%	-0.3%	-2.8%	-0.9%	0.0%	-0.3%	-4.2%	-1.5%	0.0%	1.9%	4.7%	2.2%	0.0%	0.2%	-0.5%	-0.1%
		-0.6	0.0%	-0.1%	-1.2%	-0.4%	0.0%	-0.1%	-1.7%	-0.5%	0.0%	1.1%	2.3%	1.2%	0.0%	0.1%	-0.5%	-0.1%
		-0.8	0.0%	0.0%	-0.5%	-0.1%	0.0%	0.0%	-0.5%	-0.2%	0.0%	1.0%	2.1%	1.0%	0.0%	0.2%	-0.1%	0.0%

Table A-2: The supply chain performances with different negative demand correlation across time. R: retailer, M: manufacturer, S: supplier, SC: supply chain level. The percentage values in the cells are the difference from the benchmark: the Order-IS situation.

Performances	Information Sharing	Demand Standard Deviation	No Postponement				Form Postponement				Time Postponement				Place Postponement			
			R	M	S	SC	R	M	S	SC	R	M	S	SC	R	M	S	SC
Service Level	Demand-IS	10	-0.4%	-4.2%	-10.3%	-5.0%	-0.5%	-4.2%	-9.6%	-4.7%	-0.3%	-4.6%	-11.1%	-5.3%	-0.4%	-7.8%	-9.7%	-6.0%
		30	-0.3%	-3.8%	-9.3%	-4.5%	-0.5%	-4.1%	-8.7%	-4.4%	-0.3%	-4.3%	-10.2%	-4.9%	-0.4%	-7.2%	-8.6%	-5.4%
		50	-0.2%	-3.4%	-8.0%	-3.9%	-0.4%	-3.8%	-7.6%	-3.9%	-0.2%	-3.5%	-8.6%	-4.1%	-0.3%	-6.2%	-7.4%	-4.6%
	Shipment-IS	10	0.0%	0.1%	-0.5%	-0.1%	0.0%	0.1%	-0.3%	0.0%	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.6%	-0.3%	0.1%
		30	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.4%	-0.5%	0.0%
		50	0.0%	0.1%	-1.1%	-0.3%	0.0%	0.1%	-1.0%	-0.3%	0.0%	0.1%	-0.1%	0.0%	0.0%	0.6%	-0.5%	0.0%
Fill Rate	Demand-IS	10	-0.1%	-1.0%	-2.3%	-1.1%	0.0%	-0.8%	-1.8%	-0.9%	-0.1%	-0.8%	-3.4%	-1.4%	-0.1%	-2.3%	-2.4%	-1.6%
		30	-0.2%	-2.0%	-4.2%	-2.1%	-0.1%	-1.7%	-3.5%	-1.8%	-0.1%	-1.6%	-5.8%	-2.5%	-0.2%	-3.9%	-4.2%	-2.8%
		50	-0.2%	-2.1%	-4.5%	-2.3%	-0.2%	-2.0%	-4.0%	-2.1%	-0.1%	-1.7%	-5.8%	-2.5%	-0.2%	-4.1%	-4.4%	-2.9%
	Shipment-IS	10	0.0%	0.1%	-1.1%	-0.4%	0.0%	0.0%	-1.1%	-0.4%	0.0%	0.0%	-1.7%	-0.6%	0.0%	0.3%	-1.4%	-0.3%
		30	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.1%	-1.7%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.4%	-1.4%	-0.4%
		50	0.0%	0.0%	-1.8%	-0.6%	0.0%	0.1%	-1.8%	-0.6%	0.0%	0.1%	-1.1%	-0.3%	0.0%	0.5%	-1.3%	-0.3%
Inventory Cost	Demand-IS	10	0.2%	-26.0%	-52.3%	-30.4%	0.2%	-27.5%	-54.2%	-33.4%	0.1%	-23.5%	-42.5%	-25.2%	-7.5%	-28.3%	-44.3%	-26.0%
		30	0.3%	-21.4%	-47.8%	-26.1%	0.3%	-23.4%	-49.9%	-29.4%	0.3%	-16.0%	-37.2%	-19.5%	-6.4%	-23.5%	-39.8%	-22.3%
		50	0.5%	-18.4%	-45.9%	-23.7%	0.5%	-20.1%	-47.4%	-26.6%	0.5%	-13.0%	-37.0%	-17.9%	-5.3%	-20.4%	-38.3%	-20.4%
	Shipment-IS	10	0.0%	-1.7%	-8.7%	-3.8%	0.0%	-1.7%	-11.9%	-5.4%	0.0%	0.2%	17.6%	6.0%	0.0%	-1.8%	0.6%	-0.3%
		30	0.0%	-1.7%	-8.0%	-3.5%	0.0%	-2.3%	-11.6%	-5.3%	0.0%	9.5%	26.8%	13.2%	0.0%	-0.4%	2.8%	0.8%
		50	0.0%	-1.1%	-6.5%	-2.7%	0.0%	-3.0%	-11.9%	-5.7%	0.0%	17.3%	32.7%	18.7%	-0.2%	1.3%	5.0%	1.9%
Dynamic Effect	Demand-IS	10	17.2%	12.6%	-30.5%	-8.4%	18.6%	14.5%	-29.6%	-4.4%	17.7%	20.3%	-24.8%	6.4%	24.8%	-3.3%	-22.7%	-6.7%
		30	12.4%	-0.6%	-30.3%	-22.4%	15.5%	0.7%	-30.3%	-19.9%	12.7%	4.0%	-23.4%	-10.7%	12.8%	-4.4%	-22.0%	-16.6%
		50	8.4%	-7.7%	-30.3%	-30.2%	12.1%	-3.6%	-30.5%	-24.9%	8.3%	-5.4%	-23.6%	-21.7%	5.5%	-6.7%	-21.8%	-23.0%
	Shipment-IS	10	-1.0%	-35.2%	-8.2%	-41.1%	-0.9%	-36.1%	-7.9%	-41.6%	-0.2%	15.7%	-2.8%	12.3%	-3.9%	-11.4%	-3.9%	-18.2%
		30	-0.5%	-34.6%	-9.3%	-41.1%	-0.6%	-34.4%	-8.0%	-40.6%	0.1%	40.6%	1.5%	43.6%	-1.2%	-5.5%	-2.3%	-9.1%
		50	-0.2%	-33.7%	-9.9%	-40.4%	-0.3%	-34.8%	-9.5%	-41.2%	-0.1%	48.1%	2.8%	52.1%	-2.0%	0.1%	-1.6%	-3.5%

Table A-3: The supply chain performances with different demand variance. R: retailer, M: manufacturer, S: supplier, SC: supply chain level. The percentage values in the cells are the difference from the benchmark: the Order-IS situation.

Performances	Information Sharing	Production Lead Time	No Postponement				Form Postponement				Time Postponement				Place Postponement			
			R	M	S	SC	R	M	S	SC	R	M	S	SC	R	M	S	SC
Service Level	Demand-IS	3	-0.2%	-4.1%	-9.4%	-4.5%	-0.5%	-4.2%	-9.6%	-4.7%	-0.3%	-4.6%	-11.1%	-5.3%	-0.4%	-7.8%	-9.7%	-6.0%
		6	-0.3%	-3.8%	-9.3%	-4.5%	-0.5%	-4.1%	-8.7%	-4.4%	-0.3%	-4.3%	-10.2%	-4.9%	-0.4%	-7.2%	-8.6%	-5.4%
		9	-0.4%	-4.1%	-8.5%	-4.3%	-0.4%	-4.4%	-8.3%	-4.4%	-0.3%	-4.2%	-9.6%	-4.7%	-0.3%	-7.3%	-8.8%	-5.5%
	Shipment-IS	3	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.1%	-0.3%	0.0%	0.0%	0.0%	-0.4%	-0.1%	0.0%	0.6%	-0.3%	0.1%
		6	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.4%	-0.5%	0.0%
		9	0.0%	0.0%	-0.5%	-0.1%	0.0%	0.0%	-0.2%	-0.1%	0.0%	0.0%	-0.8%	-0.3%	0.0%	0.3%	-0.7%	-0.1%
Fill Rate	Demand-IS	3	-0.1%	-1.6%	-4.8%	-2.2%	0.0%	-0.8%	-1.8%	-0.9%	-0.1%	-0.8%	-3.4%	-1.4%	-0.1%	-2.3%	-2.4%	-1.6%
		6	-0.2%	-2.0%	-4.2%	-2.1%	-0.1%	-1.7%	-3.5%	-1.8%	-0.1%	-1.6%	-5.8%	-2.5%	-0.2%	-3.9%	-4.2%	-2.8%
		9	-0.2%	-2.2%	-3.8%	-2.1%	-0.2%	-2.2%	-3.4%	-1.9%	-0.1%	-1.7%	-4.9%	-2.2%	-0.2%	-3.8%	-4.0%	-2.6%
	Shipment-IS	3	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.0%	-1.1%	-0.4%	0.0%	0.0%	-1.7%	-0.6%	0.0%	0.3%	-1.4%	-0.3%
		6	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.1%	-1.7%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.4%	-1.4%	-0.4%
		9	0.0%	0.1%	-1.4%	-0.4%	0.0%	0.0%	-1.3%	-0.4%	0.0%	0.0%	-1.7%	-0.6%	0.0%	0.2%	-1.6%	-0.4%
Inventory Cost	Demand-IS	3	0.3%	-18.1%	-41.0%	-22.0%	0.2%	-27.5%	-54.2%	-33.4%	0.1%	-23.5%	-42.5%	-25.2%	-7.5%	-28.3%	-44.3%	-26.0%
		6	0.3%	-21.4%	-47.8%	-26.1%	0.3%	-23.4%	-49.9%	-29.4%	0.3%	-16.0%	-37.2%	-19.5%	-6.4%	-23.5%	-39.8%	-22.3%
		9	0.4%	-18.9%	-37.5%	-20.2%	0.3%	-20.8%	-38.7%	-22.6%	0.3%	-19.3%	-39.5%	-21.6%	-6.1%	-28.4%	-45.0%	-25.1%
	Shipment-IS	3	0.0%	2.4%	6.6%	3.3%	0.0%	-1.7%	-11.9%	-5.4%	0.0%	0.2%	17.6%	6.0%	0.0%	-1.8%	0.6%	-0.3%
		6	0.0%	-1.7%	-8.0%	-3.5%	0.0%	-2.3%	-11.6%	-5.3%	0.0%	9.5%	26.8%	13.2%	0.0%	-0.4%	2.8%	0.8%
		9	0.0%	-0.6%	2.7%	0.4%	0.0%	-0.8%	1.7%	0.1%	0.0%	2.0%	10.9%	4.3%	-0.1%	-3.0%	-6.3%	-3.0%
Dynamic Effect	Demand-IS	3	12.3%	2.4%	-25.3%	-14.1%	18.6%	14.5%	-29.6%	-4.4%	17.7%	20.3%	-24.8%	6.4%	24.8%	-3.3%	-22.7%	-6.7%
		6	12.4%	-0.6%	-30.3%	-22.4%	15.5%	0.7%	-30.3%	-19.9%	12.7%	4.0%	-23.4%	-10.7%	12.8%	-4.4%	-22.0%	-16.6%
		9	14.2%	-7.1%	-19.7%	-14.8%	19.5%	-6.3%	-20.5%	-11.0%	12.4%	2.7%	-25.4%	-13.8%	25.9%	-11.9%	-30.1%	-22.5%
	Shipment-IS	3	-0.3%	-2.1%	-2.9%	-5.1%	-0.9%	-36.1%	-7.9%	-41.6%	-0.2%	15.7%	-2.8%	12.3%	-3.9%	-11.4%	-3.9%	-18.2%
		6	-0.5%	-34.6%	-9.3%	-41.1%	-0.6%	-34.4%	-8.0%	-40.6%	0.1%	40.6%	1.5%	43.6%	-1.2%	-5.5%	-2.3%	-9.1%
		9	-0.7%	-3.4%	-2.7%	-6.6%	-1.1%	-4.5%	-2.9%	-8.3%	-0.2%	-4.0%	-3.2%	-7.2%	-5.0%	-31.2%	-9.3%	-40.7%

Table A-4: The supply chain performances with different production leadtime. R: retailer, M: manufacturer, S: supplier, SC: supply chain level. The percentage values in the cells are the difference from the benchmark: the Order-IS situation.

Performances	Information Sharing	Retailer's Service	No Postponement				Form Postponement				Time Postponement				Place Postponement			
			R	M	S	SC	R	M	S	SC	R	M	S	SC	R	M	S	SC
Service Level	Demand-IS	0.9	-0.4%	-3.8%	-9.2%	-4.6%	-0.5%	-4.2%	-8.7%	-4.6%	-0.3%	-4.2%	-10.1%	-5.0%	-0.6%	-7.1%	-8.6%	-5.5%
		0.95	-0.3%	-3.8%	-9.3%	-4.5%	-0.5%	-4.1%	-8.7%	-4.4%	-0.3%	-4.3%	-10.2%	-4.9%	-0.4%	-7.2%	-8.6%	-5.4%
		0.99	-0.2%	-3.9%	-9.5%	-4.4%	-0.2%	-4.3%	-8.9%	-4.4%	-0.1%	-4.4%	-10.4%	-4.8%	-0.3%	-7.3%	-8.7%	-5.3%
	Shipment-IS	0.9	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.0%	-0.6%	-0.2%	0.0%	0.5%	-0.5%	0.0%
		0.95	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.4%	-0.5%	0.0%
		0.99	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.6%	-0.2%	0.0%	0.0%	-0.6%	-0.2%	0.0%	0.5%	-0.4%	0.0%
Fill Rate	Demand-IS	0.9	-0.2%	-1.9%	-4.2%	-2.1%	-0.2%	-1.7%	-3.6%	-1.8%	-0.2%	-1.5%	-5.7%	-2.5%	-0.3%	-3.8%	-4.2%	-2.8%
		0.95	-0.2%	-2.0%	-4.2%	-2.1%	-0.1%	-1.7%	-3.5%	-1.8%	-0.1%	-1.6%	-5.8%	-2.5%	-0.2%	-3.9%	-4.2%	-2.8%
		0.99	-0.1%	-2.0%	-4.3%	-2.1%	0.0%	-1.8%	-3.7%	-1.8%	-0.1%	-1.6%	-5.9%	-2.5%	-0.1%	-4.0%	-4.3%	-2.8%
	Shipment-IS	0.9	0.0%	0.1%	-1.6%	-0.5%	0.0%	0.1%	-1.7%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.4%	-1.5%	-0.4%
		0.95	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.1%	-1.7%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.4%	-1.4%	-0.4%
		0.99	0.0%	0.1%	-1.6%	-0.5%	0.0%	0.1%	-1.6%	-0.5%	0.0%	0.0%	-1.5%	-0.5%	0.0%	0.4%	-1.4%	-0.3%
Inventory Cost	Demand-IS	0.9	0.5%	-21.2%	-47.5%	-26.9%	0.5%	-23.0%	-49.5%	-30.1%	0.5%	-15.7%	-36.6%	-20.1%	-6.9%	-23.2%	-39.3%	-22.9%
		0.95	0.3%	-21.4%	-47.8%	-26.1%	0.3%	-23.4%	-49.9%	-29.4%	0.3%	-16.0%	-37.2%	-19.5%	-6.4%	-23.5%	-39.8%	-22.3%
		0.99	0.2%	-21.9%	-48.6%	-25.0%	0.1%	-23.9%	-50.8%	-28.4%	0.2%	-16.4%	-37.9%	-18.6%	-5.7%	-23.9%	-40.4%	-21.3%
	Shipment-IS	0.9	0.0%	-1.7%	-8.0%	-3.6%	0.0%	-2.2%	-11.4%	-5.5%	0.1%	9.4%	26.8%	13.7%	0.0%	-0.5%	2.7%	0.8%
		0.95	0.0%	-1.7%	-8.0%	-3.5%	0.0%	-2.3%	-11.6%	-5.3%	0.0%	9.5%	26.8%	13.2%	0.0%	-0.4%	2.8%	0.8%
		0.99	0.0%	-1.9%	-8.3%	-3.4%	0.0%	-2.6%	-12.0%	-5.3%	0.0%	9.7%	26.8%	12.3%	0.0%	-0.3%	2.9%	0.8%
Dynamic Effect	Demand-IS	0.9	12.1%	-0.6%	-30.5%	-22.5%	16.3%	2.1%	-30.5%	-17.5%	12.3%	5.4%	-23.4%	-9.3%	12.9%	-4.5%	-22.0%	-16.0%
		0.95	12.4%	-0.6%	-30.3%	-22.4%	15.5%	0.7%	-30.3%	-19.9%	12.7%	4.0%	-23.4%	-10.7%	12.8%	-4.4%	-22.0%	-16.6%
		0.99	12.7%	-2.0%	-30.8%	-23.5%	16.9%	-0.4%	-31.1%	-19.8%	13.3%	2.9%	-24.1%	-11.6%	12.9%	-5.3%	-22.7%	-17.3%
	Shipment-IS	0.9	-0.5%	-34.7%	-9.6%	-41.2%	-0.6%	-34.0%	-8.0%	-39.6%	0.2%	40.7%	1.8%	43.5%	-1.2%	-6.1%	-2.5%	-9.5%
		0.95	-0.5%	-34.6%	-9.3%	-41.1%	-0.6%	-34.4%	-8.0%	-40.6%	0.1%	40.6%	1.5%	43.6%	-1.2%	-5.5%	-2.3%	-9.1%
		0.99	-0.6%	-35.1%	-9.3%	-41.5%	-0.8%	-35.0%	-8.0%	-40.6%	0.1%	41.5%	1.6%	43.9%	-1.2%	-5.1%	-2.3%	-8.4%

Table A-5: The supply chain performances with different retailer’s service level. R: retailer, M: manufacturer, S: supplier, SC: supply chain level. The percentage values in the cells are the difference from the benchmark: the Order-IS situation.

Performances	Information Sharing	Manufacturer Service	No Postponement				Form Postponement				Time Postponement				Place Postponement			
			R	M	S	SC	R	M	S	SC	R	M	S	SC	R	M	S	SC
Service Level	Demand-IS	0.9	-0.6%	-6.2%	-10.1%	-5.6%	-0.7%	-6.9%	-9.4%	-5.6%	-0.4%	-6.7%	-11.3%	-6.1%	-0.8%	-8.6%	-9.6%	-6.3%
		0.95	-0.3%	-3.8%	-9.3%	-4.5%	-0.5%	-4.1%	-8.7%	-4.4%	-0.3%	-4.3%	-10.2%	-4.9%	-0.4%	-7.2%	-8.6%	-5.4%
		0.99	-0.1%	-1.7%	-8.7%	-3.5%	-0.1%	-1.8%	-8.6%	-3.5%	-0.2%	-2.4%	-9.7%	-4.0%	-0.2%	-6.4%	-8.2%	-4.9%
	Shipment-IS	0.9	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.1%	-0.6%	-0.2%	0.0%	-0.1%	-0.7%	-0.2%	0.0%	0.6%	-0.2%	0.1%
		0.95	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.4%	-0.5%	0.0%
		0.99	0.0%	0.0%	-1.1%	-0.3%	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.3%	-0.9%	-0.2%
Fill Rate	Demand-IS	0.9	-0.3%	-3.4%	-4.9%	-2.8%	-0.3%	-3.1%	-4.1%	-2.5%	-0.2%	-2.6%	-6.5%	-3.1%	-0.4%	-5.0%	-5.1%	-3.5%
		0.95	-0.2%	-2.0%	-4.2%	-2.1%	-0.1%	-1.7%	-3.5%	-1.8%	-0.1%	-1.6%	-5.8%	-2.5%	-0.2%	-3.9%	-4.2%	-2.8%
		0.99	-0.1%	-0.7%	-3.8%	-1.5%	-0.1%	-0.7%	-3.3%	-1.4%	-0.1%	-0.8%	-5.4%	-2.1%	-0.1%	-3.2%	-3.8%	-2.3%
	Shipment-IS	0.9	0.0%	0.1%	-1.4%	-0.5%	0.0%	0.1%	-1.5%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.5%	-1.3%	-0.3%
		0.95	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.1%	-1.7%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.4%	-1.4%	-0.4%
		0.99	0.0%	0.0%	-1.7%	-0.6%	0.0%	0.0%	-1.8%	-0.6%	0.0%	0.0%	-1.7%	-0.6%	0.0%	0.2%	-1.7%	-0.5%
Inventory Cost	Demand-IS	0.9	0.6%	-23.2%	-50.0%	-28.3%	0.6%	-26.1%	-52.7%	-32.4%	0.5%	-15.3%	-37.1%	-19.3%	-5.6%	-24.6%	-41.7%	-24.0%
		0.95	0.3%	-21.4%	-47.8%	-26.1%	0.3%	-23.4%	-49.9%	-29.4%	0.3%	-16.0%	-37.2%	-19.5%	-6.4%	-23.5%	-39.8%	-22.3%
		0.99	0.1%	-17.4%	-43.3%	-21.7%	0.1%	-18.8%	-45.3%	-24.5%	0.1%	-15.6%	-36.4%	-18.8%	-6.3%	-22.2%	-37.9%	-20.0%
	Shipment-IS	0.9	0.0%	-2.4%	-9.0%	-4.3%	0.0%	-3.5%	-13.7%	-7.0%	0.0%	10.3%	25.5%	13.3%	-0.1%	-1.3%	2.8%	0.6%
		0.95	0.0%	-1.7%	-8.0%	-3.5%	0.0%	-2.3%	-11.6%	-5.3%	0.0%	9.5%	26.8%	13.2%	0.0%	-0.4%	2.8%	0.8%
		0.99	0.0%	-0.9%	-4.3%	-1.8%	0.0%	-1.4%	-7.4%	-3.2%	0.0%	9.2%	29.3%	13.6%	0.0%	0.0%	2.5%	0.8%
Dynamic Effect	Demand-IS	0.9	18.8%	-2.7%	-31.7%	-21.0%	23.5%	-3.3%	-32.6%	-19.4%	19.2%	5.2%	-24.2%	-5.0%	16.5%	-7.8%	-23.2%	-17.6%
		0.95	12.4%	-0.6%	-30.3%	-22.4%	15.5%	0.7%	-30.3%	-19.9%	12.7%	4.0%	-23.4%	-10.7%	12.8%	-4.4%	-22.0%	-16.6%
		0.99	5.1%	3.1%	-27.1%	-21.1%	7.2%	8.0%	-27.4%	-15.9%	6.9%	7.3%	-22.6%	-11.2%	10.4%	0.0%	-20.8%	-12.5%
	Shipment-IS	0.9	-0.7%	-35.9%	-9.1%	-42.1%	-1.0%	-37.2%	-8.8%	-43.2%	0.2%	36.2%	1.4%	38.4%	-2.3%	-4.3%	-1.9%	-8.3%
		0.95	-0.5%	-34.6%	-9.3%	-41.1%	-0.6%	-34.4%	-8.0%	-40.6%	0.1%	40.6%	1.5%	43.6%	-1.2%	-5.5%	-2.3%	-9.1%
		0.99	-0.4%	-27.1%	-8.1%	-33.3%	-0.3%	-28.0%	-7.2%	-33.4%	0.3%	50.3%	2.4%	54.4%	-0.8%	-5.8%	-2.6%	-9.0%

Table A-6: The supply chain performances with different manufacturer's service level. R: retailer, M: manufacturer, S: supplier, SC: supply chain level. The percentage values in the cells are the difference from the benchmark: the Order-IS situation.

Performances	Information Sharing	Supplier Service	No Postponement				Form Postponement				Time Postponement				Place Postponement			
			R	M	S	SC	R	M	S	SC	R	M	S	SC	R	M	S	SC
Service Level	Demand-IS	0.9	-0.3%	-4.0%	-12.0%	-5.3%	-0.5%	-4.4%	-11.5%	-5.3%	-0.2%	-4.4%	-12.2%	-5.4%	-0.5%	-7.5%	-11.1%	-6.2%
		0.95	-0.3%	-3.8%	-9.3%	-4.5%	-0.5%	-4.1%	-8.7%	-4.4%	-0.3%	-4.3%	-10.2%	-4.9%	-0.4%	-7.2%	-8.6%	-5.4%
		0.99	-0.3%	-3.7%	-5.4%	-3.2%	-0.4%	-4.0%	-5.2%	-3.2%	-0.3%	-4.1%	-7.1%	-3.8%	-0.4%	-6.7%	-5.4%	-4.2%
	Shipment-IS	0.9	0.0%	0.1%	-1.0%	-0.3%	0.0%	0.2%	-0.7%	-0.2%	0.0%	0.2%	0.7%	0.3%	0.0%	0.8%	0.0%	0.3%
		0.95	0.0%	0.1%	-0.9%	-0.3%	0.0%	0.1%	-0.7%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.4%	-0.5%	0.0%
		0.99	0.0%	0.0%	-0.3%	-0.1%	0.0%	0.0%	-0.3%	-0.1%	0.0%	0.0%	-0.5%	-0.2%	0.0%	0.2%	-0.2%	0.0%
Fill Rate	Demand-IS	0.9	-0.2%	-2.1%	-5.8%	-2.6%	-0.1%	-1.8%	-4.9%	-2.2%	-0.1%	-1.6%	-6.9%	-2.8%	-0.2%	-4.2%	-5.5%	-3.3%
		0.95	-0.2%	-2.0%	-4.2%	-2.1%	-0.1%	-1.7%	-3.5%	-1.8%	-0.1%	-1.6%	-5.8%	-2.5%	-0.2%	-3.9%	-4.2%	-2.8%
		0.99	-0.2%	-1.8%	-2.3%	-1.4%	-0.1%	-1.6%	-2.0%	-1.2%	-0.1%	-1.4%	-3.9%	-1.8%	-0.2%	-3.4%	-2.5%	-2.0%
	Shipment-IS	0.9	0.0%	0.1%	-2.4%	-0.8%	0.0%	0.2%	-2.5%	-0.7%	0.0%	0.1%	-1.4%	-0.4%	0.0%	0.7%	-2.0%	-0.4%
		0.95	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.1%	-1.7%	-0.5%	0.0%	0.0%	-1.6%	-0.5%	0.0%	0.4%	-1.4%	-0.4%
		0.99	0.0%	0.0%	-0.5%	-0.2%	0.0%	0.0%	-0.7%	-0.2%	0.0%	0.0%	-1.0%	-0.3%	0.0%	0.2%	-0.7%	-0.2%
Inventory Cost	Demand-IS	0.9	0.3%	-21.9%	-47.0%	-24.9%	0.3%	-24.6%	-49.7%	-28.7%	0.2%	-19.3%	-38.0%	-20.7%	-6.5%	-24.0%	-39.1%	-21.3%
		0.95	0.3%	-21.4%	-47.8%	-26.1%	0.3%	-23.4%	-49.9%	-29.4%	0.3%	-16.0%	-37.2%	-19.5%	-6.4%	-23.5%	-39.8%	-22.3%
		0.99	0.3%	-20.9%	-46.1%	-26.8%	0.2%	-22.6%	-47.6%	-29.7%	0.2%	-16.9%	-37.9%	-21.6%	-6.5%	-23.6%	-38.9%	-23.4%
	Shipment-IS	0.9	-0.1%	-2.4%	-5.7%	-2.9%	0.0%	-4.7%	-11.5%	-6.1%	-0.1%	7.3%	31.9%	12.8%	-0.3%	-1.6%	7.6%	1.6%
		0.95	0.0%	-1.7%	-8.0%	-3.5%	0.0%	-2.3%	-11.6%	-5.3%	0.0%	9.5%	26.8%	13.2%	0.0%	-0.4%	2.8%	0.8%
		0.99	0.0%	-0.6%	-5.4%	-2.3%	0.0%	-0.9%	-7.2%	-3.4%	0.0%	6.1%	14.7%	8.2%	0.0%	0.3%	0.6%	0.3%
Dynamic Effect	Demand-IS	0.9	13.2%	-5.4%	-27.1%	-21.9%	16.5%	-5.1%	-27.8%	-20.1%	12.5%	-7.8%	-23.0%	-20.1%	12.5%	-6.1%	-20.9%	-16.5%
		0.95	12.4%	-0.6%	-30.3%	-22.4%	15.5%	0.7%	-30.3%	-19.9%	12.7%	4.0%	-23.4%	-10.7%	12.8%	-4.4%	-22.0%	-16.6%
		0.99	11.1%	0.8%	-33.5%	-25.5%	14.5%	7.7%	-33.2%	-17.7%	11.5%	5.3%	-24.7%	-11.6%	11.2%	-4.6%	-22.9%	-18.2%
	Shipment-IS	0.9	-0.9%	-36.6%	-7.5%	-41.9%	-2.1%	-39.5%	-7.9%	-45.4%	-0.9%	30.7%	0.0%	29.6%	-4.3%	-2.2%	-2.3%	-8.5%
		0.95	-0.5%	-34.6%	-9.3%	-41.1%	-0.6%	-34.4%	-8.0%	-40.6%	0.1%	40.6%	1.5%	43.6%	-1.2%	-5.5%	-2.3%	-9.1%
		0.99	-0.1%	-23.8%	-9.2%	-30.8%	-0.1%	-23.3%	-7.8%	-29.4%	0.0%	35.9%	3.3%	40.4%	-0.1%	-1.7%	-1.4%	-3.2%

Table A-7: The supply chain performances with different supplier's service level. R: retailer, M: manufacturer, S: supplier, SC: supply chain level. The percentage values in the cells are the difference from the benchmark: the Order-IS situation.