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INVESTIGATION OF INFLUENCE OF MODELING FIDELITIES ON SUPPLY CHAIN DYNAMICS

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ABSTRACT

In this paper, a three-echelon supply chain model is analyzed to determine strategies to reduce the supply chain system dynamics. Uniqueness of this research stems from the use of multiple models with varying degrees of detail representing the same supply chain. The significance of a detailed supply chain model on the quality of result is made clear. Factors employed to build an abstract to a detailed model include: transportation and production delay, demand at the retailer, and production and transportation capacity. It is shown that the system dynamics itself varies with increasing detail in the model. In addition, it is examined to see if a strategy found effective in improving the system dynamics with an abstract model is effective with a detailed model. It is established that the strategy found to be the most effective on an abstract model is not always the best strategy for the real supply chain.

1 INTRODUCTION

In today's competitive world, the success of an industry is contingent upon the management of its supply chain. Traditionally, the various business units along the supply chain operate independently. These units have their own objectives, and they are often conflicting (Ganeshan and Harrison 1995). This calls for a strategy to coordinate the various business units within the supply chain for effective management. The strategy seeking to integrate business processes over multiple firms, rather than a single firm has been a common thread in any definition of supply chain management (Houlihan 1985, Cooper, Lambert and Pagh 1997, Lambert, Cooper and Pagh 1998). The decision levels in a supply chain have been categorized into strategic, tactical and operational levels, in the areas of location, production, inventory and transportation (Ganeshan and Harrison 1995).

The analysis of various supply chain strategies and the implementation of the most effective strategy is dependent upon the model that represents the supply chain characteristics (Ramakrishnan and Wysk 2002). The modeling approaches followed for representing the supply chain can be classified into five broad classes: (i) Network design, (ii) Mixed-Integer Programming optimization, (iii) Stochastic programming, (iv) Heuristic methods and (v) Simulation based methods (Dong 2001). Among the methods presented above, simulation provides a practical basis for representing complex interdependencies between organizations, and help realistically analyze the performance tradeoffs associated with different organizational decision-making assumptions (Swaminathan, Smith and Sadeh 1994). Simulation is used to comprehensively model and analyze the dynamic behavior of supply chain systems. Simulation can evaluate the effectiveness of new policies before implementation. Researchers have used simulation models of a supply chain to study different aspects of the supply chain such as the instability of the chain (Bhaskaran 1998), the performance effects of operational factors (Beamon and Chen 2001), demand amplification effects (Wikner, Towill and Naim 1991) etc.

The objective for modeling and analyzing the supply chain may be to realize tangible goals such as minimize total cost, boost output, lower per unit cost, reduce lead time, decrease the system dynamics, etc (Ayers 2001) or intangible goals like synchronize the requirements of the customers with flow of materials from suppliers, increase customer service, build competitive advantage for the supply chain, etc (Cooper, Lambert and Pagh 1997).

The purpose of supply chain modeling in this research is two fold: (i) to analyze the supply chain dynamics and to identify strategies to minimize the dynamics; (ii) to illustrate the significant effect of the fidelity of the model representing the supply chain. The next section will provide a background on the study of supply chain dynamics carried out over the years. The section on research objective will yield further insights into the purpose of this paper. An explanation of the supply chain reference model is presented next, followed by the explanation of the experimental settings. Based on the experimental results, conclusions are presented.

2 LITERATURE REVIEW

Industrial dynamics is defined as "the investigation of the information-feedback characteristics of industrial activity to show how organizational structure, amplification and time delays interact to influence the success of an enterprise" (Forrester 1961). The dynamics within a supply chain can thus be attributed to the delays and amplifications in the flow of information (about demand) across the system. It has been observed that a multi-echelon distribution system with cascading inventories and ordering procedures amplify the disturbances (i.e., demand) occurring at the retailer echelon as one move along the chain towards the factory (Wikner, Towill and Naim 1991). Lee, Padmanabhan and Whang (1997) defined this phenomenon as the demand amplification effect or the bullwhip effect. Such distortion of information leads to excessive inventory throughout the system, poor product forecasts, insufficient or excessive capacities, product unavailability, and higher costs (Lee, Padmanabhan and Whang 1997). In this paper, the terms demand amplification, bullwhip effect, and dynamics will be used interchangeably.

Forrester (1961) had described a three-echelon supply chain model and analyzed the impact of demand variations. He derived a detailed non-linear model of the supply chain to simulate "what-if" scenarios. Wikner, Towill and Naim (1991) and Towill (1991) simplified Forrester's model and facilitated greater level of analysis of the dynamics. Later, Towill and Del Vecchio (1994) defined supply chain as a series of demand amplifiers and applied filter theory to the study of dynamics. Further, Lee, Padmanabhan and Whang (1997) have developed stochastic mathematical models describing the bullwhip effect. In their research the authors identify four major causes to the bullwhip effect (demand signal processing, order batching, price fluctuations, rationing and shortage gaming) and show how these causes contribute to the effect. Recently, Riddalls and Bennett (2002) have investigated the use of pure delays in modeling real systems and shown the transient inability to supply all that is demanded as an influential source of demand variations.

3 RESEARCH OBJECTIVE

This research aims to: (i) Study the effect of demand amplification across the supply chain, (ii) Identify strategies to minimize the dynamics, and (iii) Exemplify the importance of a detail and realistic supply chain model on the quality of results obtained.

The supply chain models developed by other researchers (presented in the Literature Review section) are studied. The different strategies identified by the researchers to minimize the dynamics are observed. Common features among some of these supply chain models are:

- Aggregation of several activities of the supply chain into a single deterministic delay. For example, the entire manufacturing process is represented as a point delay; the transportation activities are represented as point delays.
- The absence of specific emphasis on the transportation systems.
- The demand variations occurring at the retailer level are fixed at step increase. Strategies are identified to minimize the dynamics that occur due to the step increase in demand.
- The transportation and production capacities are assumed infinite. The resources are also assumed to be instantaneously available.
- Accurate information is assumed to be available at the right place at the right time.

The supply chain model developed using such assumptions does not provide a purposeful insight into the operations of the actual supply chain. The strategies identified using such abstract and inaccurate models to reduce system dynamics are not necessarily the best solution for the supply chain. Should not the best strategy for reducing the dynamics of the actual supply chain be identified using an accurate model of the supply chain? This provided us the motivation to study the impact of the level of accurateness of a model of the supply chain on the system dynamics.

To realize our objectives, an exemplary decentralized supply chain is considered. In decentralized control, each individual player in the supply chain makes decisions based on locally available information (Lee and Billington 1993). Multiple simulation models in varying degrees of detail (from an abstract model to a highly detailed model) are built to represent the same supply chain. The dynamics of the models are analyzed for different demand patterns. A set of strategies are then plugged in to these model and the best one for that supply chain model is determined. The best strategy for each model across demand patterns are then evaluated against each other.

4 EXPERIMENT SETTINGS

4.1 Sample Supply Chain

A three-echelon supply chain consisting of a Retailer, Distributor and a Manufacturer is considered. The retailer / distributor linkage and the distributor / manufacturer linkage are serviced by independent transportation systems. The customer place orders to and receives goods from the retailer. The retailer place orders to and receives goods from the distributor. The distributor, in turn, place orders to and receives goods from the manufacturer. The manufacturer then orders and produces the goods in its shop floor. These three players operate in a decentralized fashion. Only a single product is handled by the supply chain. The internal working of each player is described in the following section.

4.2 Modeling Assumptions

The following assumptions and policies are adhered to build the supply chain models:

4.2.1 Inventory Policies

- The desired inventory level for all the three players is 0 units.
- When a sales order is placed on a player, the corresponding number of goods is deducted from the inventory of that player (to reflect the sale). Similarly, when goods arrive, they are added to the inventory of that player (to reflect delivery and stocking).
- When a sales order is received, the player checks its current inventory. If there is sufficient inventory to cover the order then the required goods are immediately dispatched. If there is not sufficient inventory to cover the order, the quantity available in hand is dispatched and the rest of the order is fulfilled eventually. Transportation costs are ignored.
- Shortages are represented as negative inventory.
- Costs for holding inventory (per unit per week) are arbitrarily determined as follows: Retailer: \$0.50; Distributor: \$0.75; Factory: \$1.00
- The shortage costs are assumed to be ten times as large as the holding cost (per unit per week) for each player.

4.2.2 Delays Assumptions

- The accounting and purchasing delays, that is, the difference in the time of sale and the time that sale is reflected in an order sent out to obtain a replacement is zero for all players.
- The mail delay, that is, the difference in the time an order is issued by the buyer and the time the same order is received by the seller is zero between all players.
- The information transmission delay, that is, the time taken to transmit any information (other than orders) from one player to another is zero between all players.
- The transportation and production delays are represented as zero, constant or a statistical distribution depending on the fidelity of the supply chain model.

4.2.3 Ordering Policy and Forecasting Methods

- All three players follow a periodic inventory review policy with a review period of 1 week.
- Order quantity is calculated using the following formulae (Sterman 1989, Riddalls and Bennett 2002) for all the players: MAX (O(t), 0); where:

$$O(t)=\underbrace{\hat{L}(t)}_{\text{Expected demand}}+\alpha_i\underbrace{[\bar{i}(t)-i(t)]}_{\text{Inventory discrepancy}}+\alpha_{WIP}\underbrace{\left[\hat{h}.\hat{L}(t)-\int_{t-h}^{t}O(s)ds\right]}_{\text{Order in pipeline/ work in progress term}}. \quad (1)$$

  In Equation (1), $\bar{i}(t)$ represents the desired inventory level and i(t) represent the current inventory. The integral quantity in the work in progress (WIP) term denotes the current WIP. The desired WIP is the product of expected production (delivery) delay ($\hat{h}$) and the desired throughput (taken to be equal to the expected demand). αi and αWIP denote the proportion of the inventory discrepancy and the WIP respectively (Riddalls and Bennett 2002).
- αi = 1 and αWIP = 1 for all the players in the supply chain models with zero and constant transportation delay. For models with time varying transportation delays, αi = 1 and αWIP = 0.8. Riddalls and Bennett (2002) indicate that this is reasonable since inventory discrepancies are much more immediately apparent to managers than any variance in what is on order. The low value of αWIP can be attributed to many factors from an inability to track goods on a production line or in transit, to the effect of information delays and inaccuracies.
- The expected demand (in all players) is forecasted using exponential smoothing method with an arbitrary smoothing factor of 0.2.
- Order cancellations are not permitted.

4.2.4 Demand and Costing

- Initial demand, at the retailer, is held constant at 1000 units / week.
- The total cost of the supply chain is calculated as the sum of inventory holding cost and shortage cost for all the three players.

4.3 Experimental Factors

Based on the work of other researchers (refer to the Literature Review section) and the preliminary tests conducted, four different factors are considered in this research. They are:

- *Transportation and Production Delays*: These delays are the difference in the time an order in placed and the time when the goods are received (order is fulfilled). Transportation delay exists between the Retailer and Distributor (R-D) and Distributor and Manufacturer (D-M). Production delay exists only at the Manufacturer where the goods are produced.

- Demand at Retailer: Different demand patterns are applied at the retailer level of the supply chain. The demand is represented in units/week.
- Production Capacity: The total number of units produced per week by the manufacturer is varied.
- Transportation Capacity: The total number of units transported per week between the different players is varied.

The above factors are differentiated into various levels, as shown in Table 1. Combination of these factors will help build from abstract supply chain models to detailed ones.

4.4 Strategies to Reduce Dynamics

The demand amplification effect on each of the simulation model built is analyzed. Various strategies can then be employed to reduce the amplification effect. The strategies used in this research are described in this section.

4.4.1 Inventory Levels Determination

This strategy is considered to exploit the stabilizing effects, if any, of inventory on the supply chain dynamics. Optimum inventory level at the minimum cost is identified for each player. The objective selected is to minimize the maximum order generated by the manufacturer. Using this as the only objective, it is observed during the trial runs that though the dynamics is minimized to the lowest possible, the inventory levels identified are not always of the least cost. Thus, it is determined to again optimize the sup-

Table 1: Experimental factor and levels

Factor	Level	Description
Transportation and Production Delays	Zero	The transportation and production delays are Zero (0).
	Constant	The transportation and production delays are constant. • Transportation delay in R-D sector is 2 weeks. • Transportation delay in D-M sector is 3 weeks. • Production delay in Manufacturer is 6 weeks.
	Distribution	The delays are modeled as a discrete distribution function. • Transportation delay in R-D sector is 2 weeks for 80% of time; 3 weeks for 15% of time; 4 weeks for 5% of time. • Transportation delay in D-M sector is 3 weeks for 85% of time, and 4 weeks for 15% of time. • Production delay in Manufacturer is 6 weeks for 90% of time; 7 weeks for 5% of time; 8 weeks for 5% of time.
	Detailed Production	Each machine involved in production is modeled individually. That is, the shop floor is represented in detail. The transportation delays follow the same distribution as above.
	Detailed Production and Transportation	Each machine involved in production is modeled individually, as above. Each transporter involved in transportation system is also modeled individually.
Demand at Retailer	Constant	Demand is held constant at 1000 units/week.
	Step Increase	The demand is increased at week zero by 10% to 1100 units/week and held.
	Cyclic Fluctuation	The demand varies sinusoidal between 900 and 1100 units/week over a period of 1 year.
	Random Variations	There is a random variation in demand. This is modeled as a normal distribution, with mean of 1000 units/week and std. dev. of 100.
Production Capacity	Infinite Capacity	The manufacturer can produce infinite units in any week.
	Finite Capacity	The manufacturer can produce a maximum of 1250 units/week (25% more than the average demand/week). For this option, the production delay is assumed to be constant at 6 weeks.
Transportation Capacity	Infinite Capacity	Infinite quantity of good can be transported by each transportation link in a week.
	Finite capacity	A maximum of 1250 units/week can be transported in each of the transportation links (25% more than the average demand/week).

ply chain model with the objective to minimize cost and with the requirement that the dynamics must be maintained at the lowest possible level established in the first optimization run.

4.4.2 Lead Time Reduction

This strategy is employed to verify the effectiveness of reduced lead time between players on the supply chain dynamics. When the delay factor is at level Zero, this strategy is ignored. When the delay factor is Constant Delays, the lead times are reduced by 1 week for all players. For the Distribution Delays factor, the lead times are made more efficient as follow:

- Transportation delay in R-D sector is 2 weeks for 95% of time, and 3 weeks for 5% of the time.
- Transportation delay in D-M sector is 3 weeks for 95% of the time, 4 weeks for 5% of the time.
- Production delay in Manufacturer is 6 weeks for 98% of the time, and 7 weeks for 2% of the time.

The desired inventory levels identified with strategy 1 are used when testing this strategy.

4.4.3 Access to Point of Sale (PoS) Data I

The availability of the actual retailer sales information to the manufacturer is evaluated in this strategy. The manufacturer obtains the current week's actual sales data from the retailer. The manufacturer accounts for this PoS information (25%) and the sales orders (25%) received from the distributor in the orders dispatched to the shop floor. The desired inventory levels identified with strategy 1 are used when testing this strategy.

4.4.4 Access to Point of Sale (PoS) Data II

This strategy is an augmentation to the previous strategy. The extension reflects in the plan by which the manufacturer sends only the quantity of goods it deems as sufficient to the distributor. The excess good ordered by the distributor is instructed to be ignored. The desired inventory levels identified with strategy 1 are used when testing this strategy.

4.4.5 Vendor Managed Inventory (VMI)

Using this strategy, the option of using VMI between the manufacturer and the distributor is evaluated. The manufacturer will maintain the inventory of the distributor based on the actual sales information of the distributor.

5 RESULTS

A full factorial combination of the experimental factors and the different strategies bring the total number of supply chain models to be analyzed to 480. Based on the feedback acquired from the preliminary runs the total number of models built is narrowed down to 216. All the supply chain models are built using Arena^{TM} simulation package (Kelton, Sadowski and Sadowski 2001). To determine optimum inventory level, the optimization package OptQuest for Arena^{TM} (OptQuest for Arena 2000) is used. In this research, the effect of randomness in the simulation models is not considered. That is, the results presented are based on a single replication of the simulation models, and consideration of multiple replications is left for future research.

All the different supply chain models have been simulated. Initially, the base case supply chain models are simulated to measure the actual demand variations. The base case model represents the supply chain model built based on all the assumptions stated and with any combination of the experimental factors. There is no dynamics reduction strategy applied in the base case supply chain models. The demand amplification effect in six base case supply chain models are illustrated in Figure 1 through Figure 6. The output of the most abstract model is presented in Figure 1 and that of the detailed model is presented in Figure 6, with increasing level of detail. For all six cases, the pattern of demand at the retailer is random variation. The actual sales at the retailer and the quantity ordered by the manufacturer are shown in the figures.

The most abstract supply chain model with zero transportation and production delay, and infinite transportation and production capacity (Figure 1), shows the maximum quantity ordered by the manufacturer is for 1305 units (30.5% more than the average demand of 1000 units/week) and the minimum order is for 82 units (91.8% less than the average demand).

The next supply chain model with constant transportation and production delay, and infinite transportation and production capacity (Figure 2), shows the maximum quantity ordered by the manufacturer is for 2823 units (182.3% more than the average demand) and the minimum order is for 0 units (100% less than the average demand).

The next supply chain model with distribution based transportation and production delay, and infinite transportation and production capacity (Figure 3), shows the maximum quantity ordered by the manufacturer is for 3383 units (238.3% more than the average demand) and the minimum order is for 0 units (100% less than the average demand).

The next supply chain model with distribution based transportation and production delay, and finite transportation capacity and infinite production capacity (Figure 4), shows the maximum quantity ordered by the manufacturer is for 3488 units (248.8% more than the average demand) and the minimum order is for 0 units (100% less than the average demand).

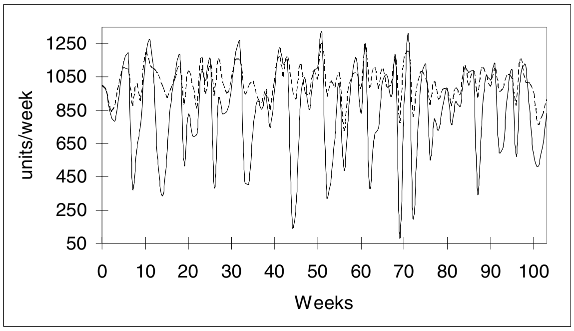

Figure 1: Demand amplification effect for supply chain model with zero delays, and infinite capacities

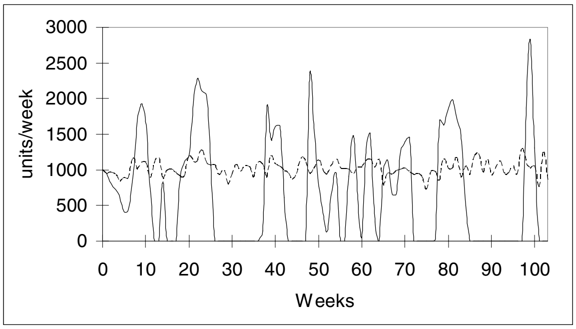

Figure 2: Demand amplification effect for supply chain model with constant delays, and infinite capacities

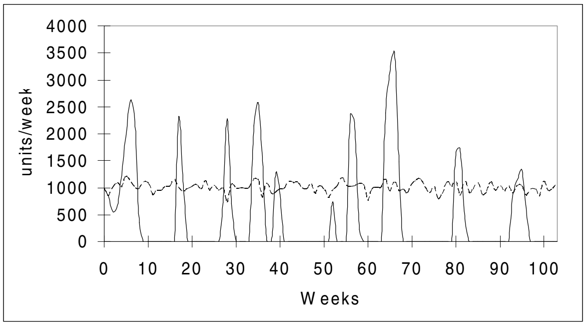

Figure 3: Demand amplification effect for supply chain model with distribution based delays, finite transportation capacity and infinite production capacity

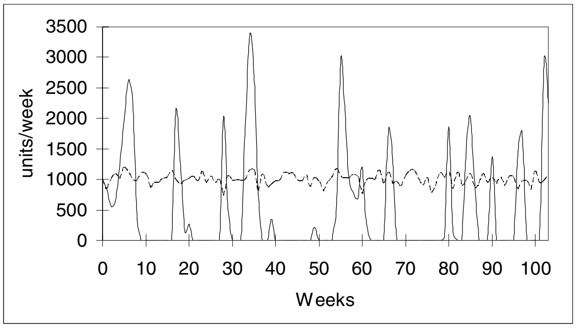

Figure 4: Demand amplification effect for supply chain model with distribution based delays, and infinite capacities

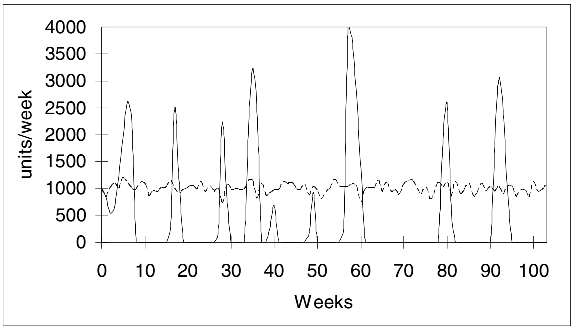

Figure 5: Demand amplification effect for supply chain model with distribution based delays, and finite transportation and production capacity

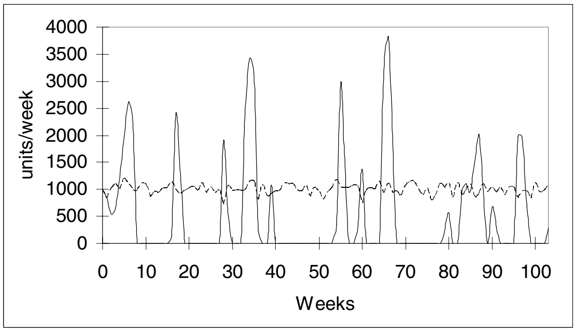

Figure 6: Demand amplification effect for supply chain model with distribution based delays, and infinite transportation capacity and finite production capacity

LEGEND: ----- Actual sales at retailer; ——— Quantity ordered by manufacturer

The next supply chain model with distribution based transportation and production delay, and infinite transportation capacity and finite production capacity (Figure 5), shows the maximum quantity ordered by the manufacturer is for 3822 units (282.2% more than the average demand) and the minimum order is for 0 units (100% less than the average demand).

The fairly detailed supply chain model with distribution based transportation and production delay, and finite transportation and production capacity (Figure 6), shows the maximum quantity ordered by the manufacturer is for

3997 units (299.7% more than the average demand) and the minimum order is for 0 units (100% less than the average demand).

This clearly shows the basic problem (demand amplification) for which the solution (strategy to reduce the amplification) is sought for is itself greatly dependent on the type of model used to represent the supply chain. In other words, dynamics along the supply chain is caused not only due to demand variations but also due to unavoidable time delays, inability of the supplier to fulfill the quantity ordered, inability of the transporter to deliver the goods on time, inability of the transporter to transport all of the order quantity, etc. Now, it remains to be seen if a strategy found effective with an abstract supply chain model is also effective with a detailed supply chain model. The effects of applying the strategies Inventory level determination, Lead time reduction, Access to PoS I and Access to PoS II on supply chain models with three demand patterns (constant, cyclic fluctuations and random variations) is summarized in Figure 7, 8 and 9. The effectiveness of a strategy is measured by the maximum variation produced at the manufacturer in response to the demand at the retailer. The maximum variation or range is measured as the difference between the maximum and minimum order quantities generated by the manufacturer. These ranges are plotted for supply chain models with different fidelities under each of the strategy.

Figure 7 shows the effect of the strategies on the supply chain models in response to the step increase in demand at retailer. It is evident that for the most abstract model of the supply chain, the strategy Access to PoS II produces the least the variations. However, for the supply chain models with higher fidelities both Lead time reduction and Access to PoS II are found to be the best strategies.

Figure 8 shows the effect of the strategies on the supply chain models in response to cyclic fluctuations in demand at retailer. The result indicates that for all the supply chain models, Lead time reduction is the best strategy.

Figure 9 shows the effect of the strategies on the supply chain models in response to random variations in demand at retailer. It is found that for all the supply chain models, Access to PoS II is the best strategy. In fact, Lead time reduction is the worst strategy for this supply chain model.

6 CONCLUSION

A three-echelon supply chain is modeled in varying degrees of detail. The dynamics along the supply chain due to demand variations at the retailer level is analyzed. Several strategies are identified to reduce the dynamics. These strategies are tested out on supply chain models with varying levels of detail. Two key conclusions are drawn in the course of this research. First, the dynamics occurring due to the demand variations at the retailer also depends on the capacity of the players, varying delivery and production times, forecasting methods etc. Second, the strategy found effective on an abstract model of the supply chain is not always the best strategy for the real supply chain.

The most suitable and effective strategy can be exactly identified by using a simulation model completely representing the actual supply chain. However, building such an exhaustive supply chain model is a daunting task. The next stage of research will concern itself with determining the ideal level of detail that can be incorporated into a simulation model. The level of aggregation required in the various aspects of the supply chain (e.g., should the entire manufacturing process be represented as a single delay or should individual machines be represented in the simulation model) will be investigated.

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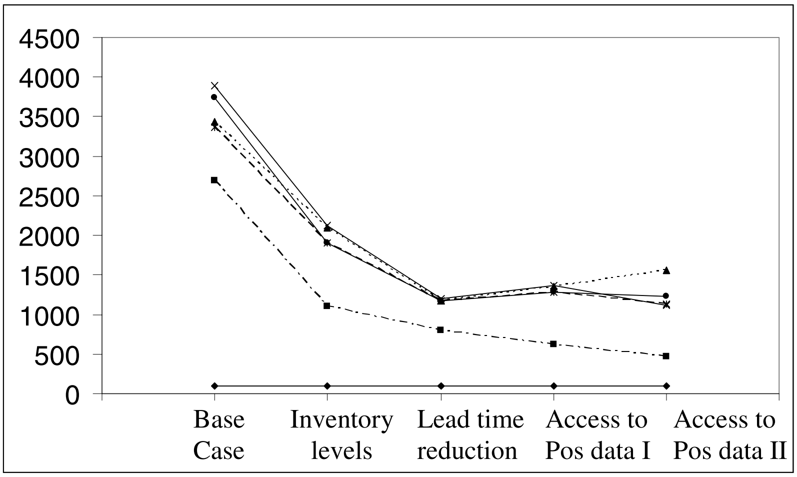

Figure 7: Range (Max – Min) of manufacturing orders generated in response step increase in sales at the retailer

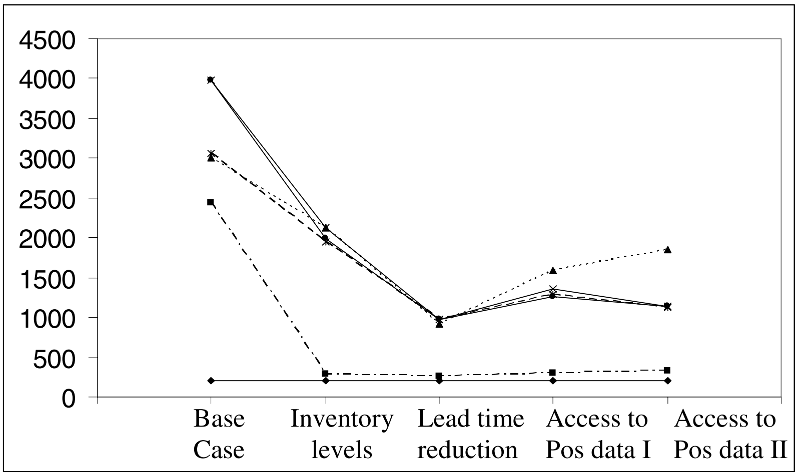

Figure 8: Range (Max – Min) of manufacturing orders generated in response to cyclic fluctuations in sales at the retailer

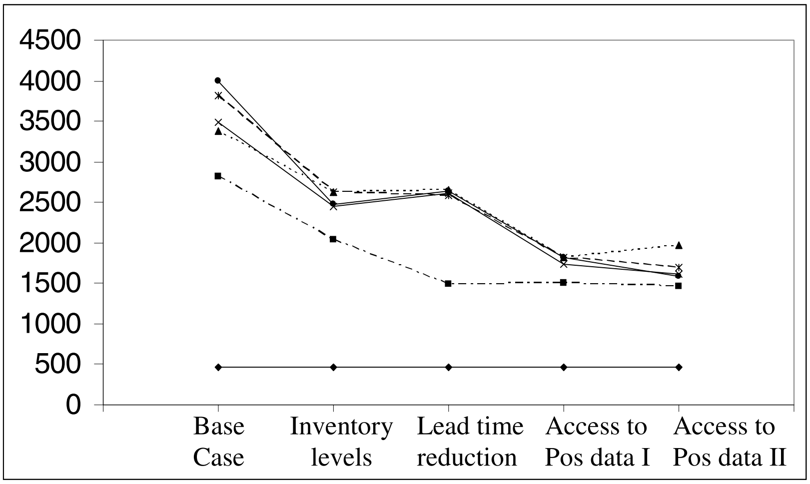

Figure 9: Range (Max – Min) of manufacturing orders generated in response to random variations in sales at the retailer

LEGEND

- —◆— Range of actual sales variation at Retailer
- -■- Range of manufacturing orders for supply chain model with constant delays; infinite capacity
- ··▲·· Range of manufacturing orders for supply chain model with distribution based delays; infinite capacity
- —×— Range of manufacturing orders for supply chain model with distribution based delays; infinite production capacity; finite transportation capacity
- -✱- Range of manufacturing orders for supply chain model with distribution based delays; finite production capacity; infinite transportation capacity
- —●— Range of manufacturing orders for supply chain model with distribution based delays; finite production capacity; finite transportation capacity

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