Supplementary files are available for this work. For more information about accessing these files, follow the link from the Table of Contents to "Reading the Supplementary Files".

Operational Improvements in the Supply Chain: Who Benefits? Who Loses?

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Abstract

This study applies system dynamics simulation to investigate the impact of operational improvements in a supply chain, which is at one of three stages of sharing demand information: the traditional scenario in which no information is shared; vendor managed inventory in which the vendor receives customer demand information to manage warehouse inventory; and collaborative planning, forecasting and replenishment, in which information is shared throughout the supply chain. The impact of five operational improvements, resulting in reduced transit and production lead times, is investigated for each scenario. The impacts are assessed by calculating the average inventory level and inventory variability for each partner in the supply chain. The results of this study indicate that some partners benefit more by certain improvements, whereas others benefit less, and that reduced fluctuations in inventory depend on the type of improvement, the level of supply chain integration, and one's position in the supply chain.

Keywords: supply chain, VMI, CPFR, bullwhip, inventory

Introduction

Effectively managing the supply chain has been a major undertaking of business and industry over the past ten years. As progress is made in integrating the supply chain, new challenges arise and new problems emerge. Because the supply chain is so large and encompasses so many activities, the challenges of effective supply chain management are numerous. The greatest challenge, from the perspective of this study, is to understand how lead time reductions in one part of the chain affect other trading partners. By gaining an understanding of these dynamic relationships, it may be possible to implement policies which can strive to ameliorate the negative impacts and amplify the positive ones. An understanding the system-wide impacts of decisions can help managers anticipate the response throughout the supply chain in order to improve overall system performance.

Many tools have been developed aimed at improving the overall system performance of supply chains, including vendor-managed inventory (VMI) and Collaborative Planning, Forecasting, and Replenishment (CPFR) (Lee, et. al., 1997; Ireland and Bruce, 2000; Simchi-Levi, 2000, Xu, Dong and Evers, 2001). Both VMI and CPFR emphasize collaboration, and both tend to focus on the first tier manufacturer and the retailers. For example, VMI is an arrangement in which the vendor, such as Proctor and Gamble, manages the inventory for a retailer, such as Wal-Mart. CPFR, an internet-based business model, relies on the exchange of information between strategic trading partners, primarily in the consumer goods industry (Schachtman, 200; Wilson, 2001). Furthermore, the standards for information exchange in a CPFR environment are currently being developed, with several pilot projects underway (Schachtman, 2000), although the technology does not extend beyond the first tier supplier (White, 2001). Both VMI and CPFR tend to ignore partners upstream in the supply chain, the n-tier supplier. Although some studies have focused only on the downstream trading partners (Dong and Xu, 2001; Aviv, 2001), others have focused on all partners in the supply chain, particularly when investigating the bullwhip effect (Chen, et. al, 2000; Lee, 1997a; Lee, 1997b).

The purpose of this study is to describe the effect of operational improvements on supply chain dynamics, examining the impact on inventory fluctuations and the bullwhip effect for each partner in the chain under three different scenarios. The first scenario depicts the traditional supply chain in which information flows from the downstream entity, such as the retailer, to the next upstream entity such as the warehouse. There is no sharing of retail information or customer demand with any upstream partners. The second scenario depicts VMI in which the manufacturer, or tier 1 supplier, manages the inventory for the warehouse. The first tier supplier receives the same customer demand information as the retailer. Finally, the third scenario depicts a variant of CPFR. All partners receive customer demand information and the vendor continues to manage warehouse inventory.[1]

Within each of these scenarios, the impact of various operational improvements is investigated. These improvements include the reduction of transit time and the reduction of production lead times for each supplier in the chain.

Methodology

Three simulation models that depict the three different scenarios were constructed using the system dynamics software, ithink®. Each model contains four sectors: the retailer, the warehouse, the manufacturer, and the supplier. The manufacturer is referred to as the tier 1 supplier and the supplier to the manufacturer is referred to as the tier 2 supplier. Figures 1a through 1c show how goods and information flow between each partner in the chain for each scenario.

In Figure 1a, shown on the next page, the information which flows between the sectors is not the same. The retailer receives customer demand information; however, the warehouse only receives retail order information, not customer demand information. Likewise, the manufacturer receives warehouse order information and the supplier receives manufacturer order information. The upstream partners do not directly receive customer demand information.

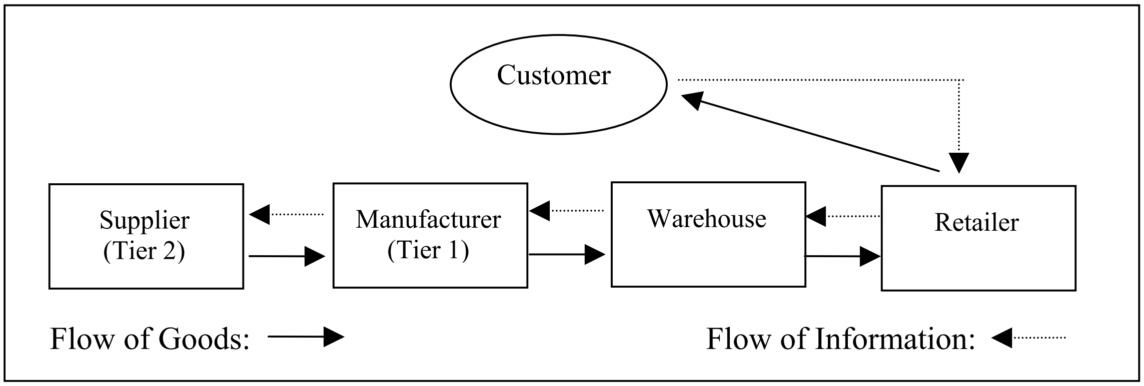

Figure 1a. Flow of Goods and Information, Scenario 1: The Traditional Supply Chain

In this traditional scenario the upstream partners do not directly receive customer demand information, unlike in the scenario depicted in Figure 1b.

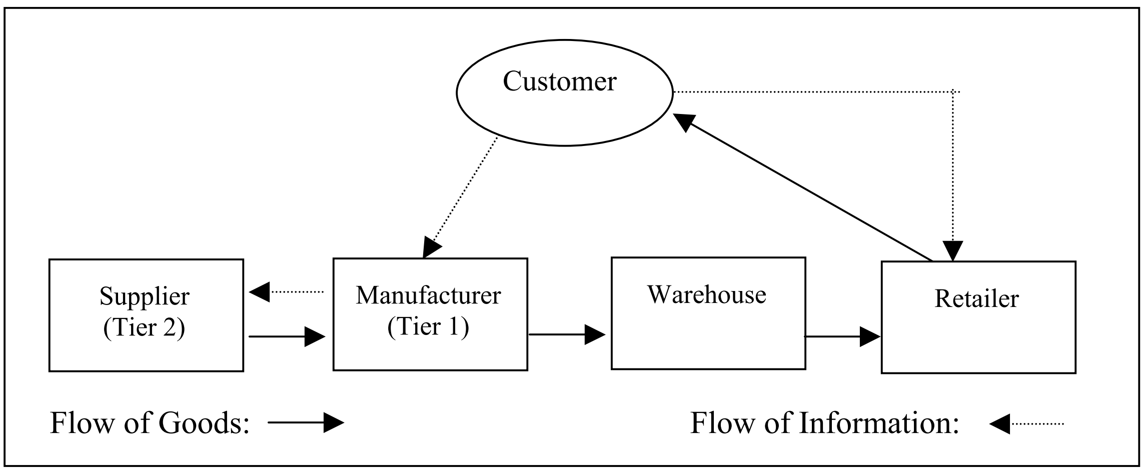

Figure 1b. Flow of Goods and Information, Scenario 2: Vendor Managed Inventory

In the vendor managed inventory scenario shown in Figure 1b, both the manufacturer and retailer receive customer demand information. The tier 2 supplier, however, receives manufacturer orders. In contrast, the CPFR scenario shown in Figure 1c on the next page depicts all partners receiving customer demand information at the same time.

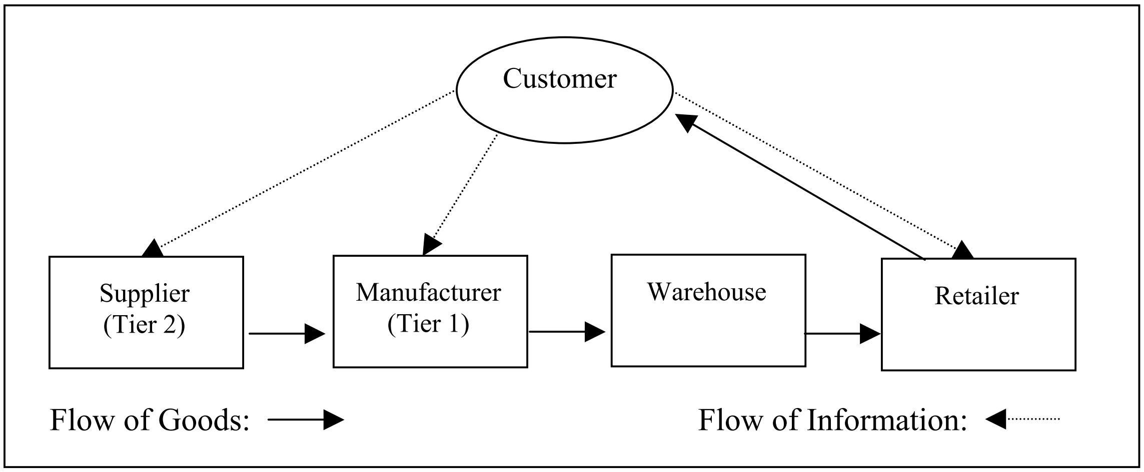

Figure 1c. Flow of Goods and Information, Scenario 3: Collaborative Planning Forecasting and Replenishment

For each scenario, daily demand is 10 units. The simulation period varies for each scenario in order to capture information after the warm up period. The traditional scenario is simulated for 400 days, VMI for 300 days, and CPFR for 208 days. Figure 2 shows the transit and production times used in each scenario. Although the model depicts them as days, the selection of another unit of time does not impact system behavior.

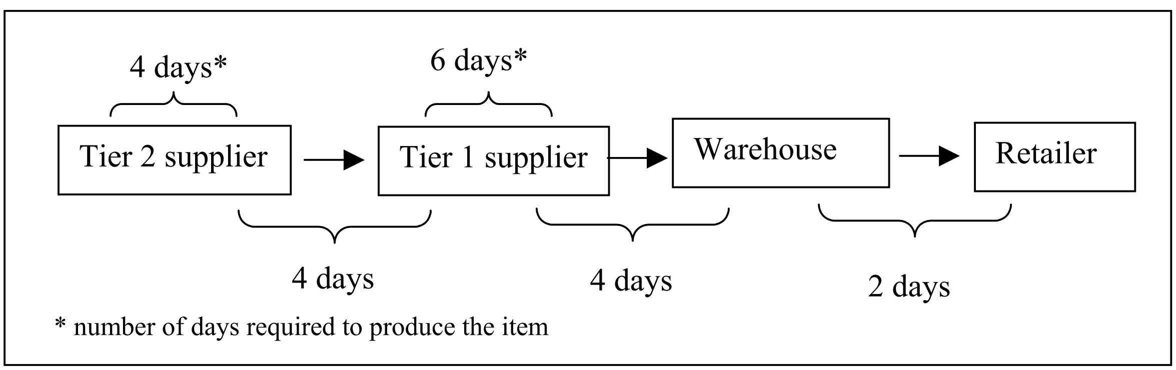

Figure 2. Transit Times and Production Times

Model Runs

For each scenario, six different runs were made. The first run is the base case and the remaining 5 each represent an operational improvement resulting in a reduction in lead time at various points in the supply chain. For each run, inventory fluctuations represented by average inventory level and standard deviation are computed. Table 1 summarizes the different "runs" for each scenario. A reduction in lead time or production time of 50% was arbitrarily chosen.

The name of each run refers to the type of operational improvement. For example, the base run contains no improvements, and the lead times are the same as those presented in Figure 2. The run, "WH to Retail" represents a reduction in transit lead time between the warehouse and the retailer. "T1 to WH" represents a reduction in transit time between the tier 1 supplier and the warehouse; "T1 Lead Time" represents a reduction in the production time for the tier 1 supplier; "T2 to T1" represents a reduction in transit lead time between the tier 2 and the tier 1 supplier; and finally "T2 Lead Time" represents a reduction in production time for the tier 2 supplier.

Name of Run	Time in transit from warehouse to retailer	Time in transit from tier 1 supplier to warehouse	Tier 1 supplier production time	Time in transit from tier 2 to tier 1 supplier	Tier 2 supplier production time
Base	2	4	6	4	4
WH to Retail	1	4	6	4	4
T1 to WH	2	2	6	4	4
T1 Lead Time	2	4	3	4	4
T2 to T1	2	4	6	2	4
T2 Lead Time	2	4	6	4	3*

* modified from the original value of 2 to compensate for structural sensitivity in the model

Table 1. Transit and Lead Times (in days) for Each Run for Each Scenario

The structure of the simulation model, including detailed discussion of each scenario, is discussed in greater detail in the next section

The Simulation Model

Model Structure, Assumptions, and Testing

It is challenging to construct a general model of a supply chain and validate its behavior without the guidance of empirical data. Therefore, it is important to use other techniques to verify the model structure, identify its weaknesses, and to ascertain when the structure of the model itself, rather than the supply chain relationships, accounts for the simulation results. First, assumptions need to be clearly stated and understood. Second, model testing should assist in identifying problems with the model structure and limits to realism. Finally, the structure within each sector of the model should be consistent, depicting how information is shared, how orders are placed and released, and how inventory is managed.

The assumptions of the simulation model are:

- Backorders are permitted. Lost orders occur only if the production system cannot physically produce them.
- Partial shipments are permitted, with no minimum order size.
- Orders are placed continuously.

In addition to these assumptions, it was also necessary to perform some simple tests to ensure that the simulation results were somewhat realistic with respect to inventory fluctuations. One technique is to note the extent of the bullwhip effect, which should diminish as more collaboration occurs. The bullwhip is greatest in the traditional scenario, and the least under CPFR, and somewhere in between in the VMI scenario. This is a result which we would expect to see, and is apparent in these three different scenarios as well. Therefore the presence of the bullwhip effect serves, to some extent, to validate the model structure.

Two other questions were addressed in order to test the model structure:

- How sensitive is the behavior of the model to the parameters chosen for production lead times and transit times?
- Will similar behavior occur for other relative values of these variables?

To assess the sensitivity of the model to relative values of transit time, a simple 2^3 factorial design was used to test the effect of a 2- or a 4-day transit time from the warehouse to the retailer, from the tier 1 supplier to the warehouse, and from the tier 2 supplier to the tier 1 supplier. With one exception, the pattern of inventory fluctuations did not change, although periodicity and amplitude varied somewhat. The one exception occurred when the transit time from the tier 2 supplier to the tier 1 supplier was reduced to 2 days. (This run is referred to as "T2 to T1" in Table 1.) A "reverse" bullwhip effect occurred, in which the tier 1 supplier's inventory fluctuations exceeded the tier 2 supplier's inventory fluctuations. This result appears to defy the theory, which indicates that under certain conditions, inventory variability will always be greater for the next upstream partner.[2]

The model structure itself produced these spurious results for this one particular run, so further tests of the model structure were conducted. First, the ratio of production lead times for the tier 2 and tier 1 supplier were tested. Recall that the tier 1 supplier's production lead time, 6 days, exceeds the tier 2 suppliers production lead time of 4 days, a 6:4 ratio. Perhaps this ratio, in conjunction with reduced transit time, produces the reverse bullwhip effect. Model testing indicated that whenever this ratio exceeds 7:4, the "reverse" bullwhip effect appears again, in which the tier 1's inventory fluctuations exceed those of the tier 2's fluctuations. The effect was exacerbated as the transit time between the 2 suppliers was reduced, and the effect was ameliorated as the transit time between the 2 suppliers was increased. Further investigation showed that this phenomenon was created by the selection of the value for the subassembly adjustment time. Inventory adjustment time represents that period of time over which a supply chain partner strives to close the inventory gap, which is the difference between the actual inventory and the target inventory level. In the tier 2 supplier sector, which is shown in Figure 3d, the number of subassemblies starting in the production process is equal to the subassembly inventory gap divided by the subassembly adjustment time. For a given gap, as the adjustment time increases, fewer subassemblies are started, which keeps the tier 2 subassembly inventory level low. Therefore, tier 2 subassembly inventory fluctuations also tend to be suppressed. The subassembly adjustment time for the tier 1 supplier has a similar effect, in that it determines how quickly the manufacturer wants to close their inventory gap. A longer adjustment time results in lower order quantities placed with the tier 2 supplier, which lowers the tier 2 supplier's subassembly inventory. Experimentation with the model revealed that lowering either adjustment time (subassembly adjustment time for the tier 1 or the tier 2 supplier) from 2 days to

1 day eliminated the reverse bullwhip effect. Therefore, the run “T2 to T1” was modified to include a 1 day reduction in the subassembly adjustment time. This change didn’t affect the inventory levels or inventory variability for the other supply chain partners.

Another problem in the model structure was also apparent in the last run, “T2 Lead Time”, which represents a reduction in the tier 2 supplier’s production lead time from 4 days to 2 days. This time, the tier 2 supplier’s inventory became totally flat, while other supply chain partners experienced inventory fluctuations mirroring the bullwhip effect. Experimentation with the simulation model revealed that this behavior is the result of the interaction of subassembly adjustment time and the amount of reduction in the tier 2 supplier’s production lead time. Therefore, for the run, “T2 Lead Time”, subassembly adjustment time is reduced to 1 day, and the production lead time is reduced from 4 to 3 days, a 25% reduction, instead of a 50% reduction of 2 days.

Table 2 summarizes the changes made to two parameters in the model in order to overcome the initial problems with the model structure.

Name of Run	Subassembly Adjustment Time	Tier 2 Supplier Production Lead Time
T2 to T1	1 day	----
T2 Lead Time	1 day	3 days

Table 2. Changes made in selected parameters to correct problems in the model structure

These changes are relatively minor, however they do point to weaknesses in the model structure and limitations to interpretation of the results. Because of the problems with these 2 runs, it is reasonable to question the results produced by the model regarding the tier 2 supplier. The model appears to be fairly robust, however, with respect to the other supply chain partners.

Other insights into model structure can be obtained by understanding the logic of the model, ensuring that it depicts the actual behavior of supply chain partners through its portrayal of information flow, order placement, and inventory management.

The next section describes this logic for each partner in the supply chain in the traditional scenario. The logic is very similar for both the VMI and CPFR, which are discussed in subsequent sections.

Model Structure: The Traditional Supply Chain Scenario

The traditional scenario has a structure that is similar to the Beer Game (Sterman, 1989), in which upstream partners receive information directly from their downstream supplier. Demand from the downstream customer triggers a shipment of goods from inventory, which is then replenished from the next upstream supplier. Perceived inventory gaps are filled at a rate that depends on the inventory adjustment time for that sector, resulting in the bullwhip effect.

Figures 3a through 3d show the structure of each sector.

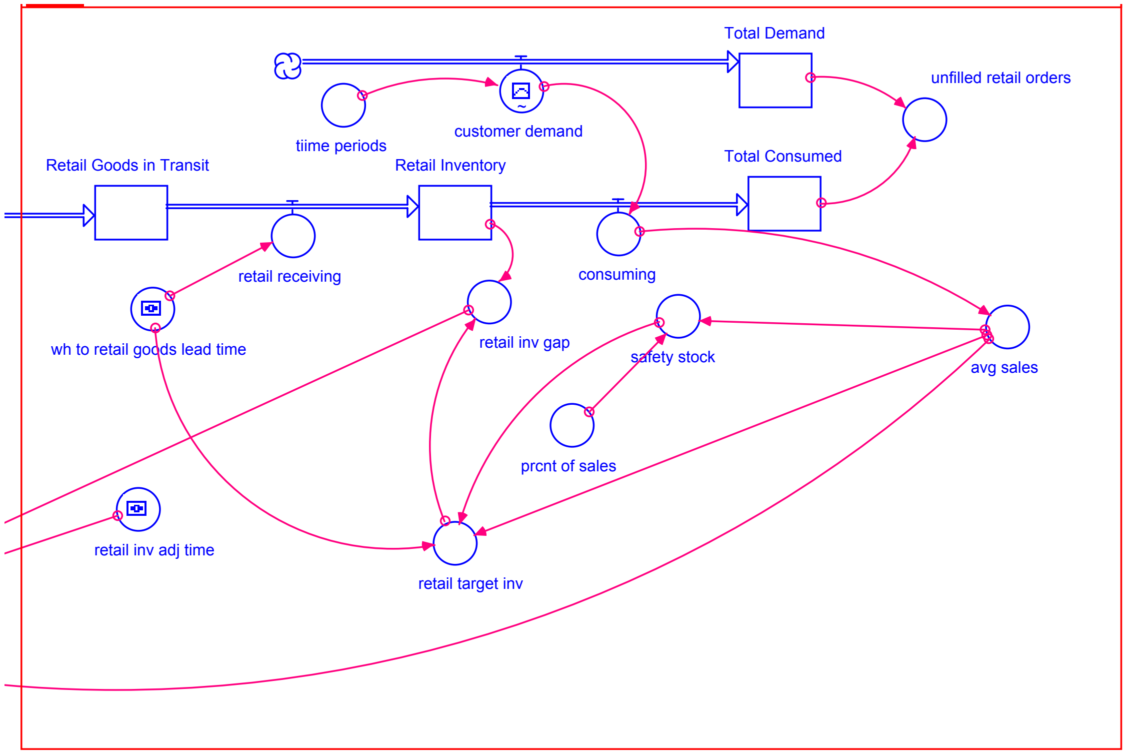

Figure 3a. The Retail Sector

The retail sector is shown in Figure 3a. As retail inventory falls orders are placed with the warehouse. Customer demand information triggers a shipment, which is replenished from the next upstream supplier. Unfilled retail orders, the difference between total demand and total consumption, is also computed.

Retail ordering policy is based on the difference between the target and actual inventory, the inventory gap. The target inventory is equal to the average sales plus safety stock, which is based on a percentage of average sales. The inventory adjustment time determines how quickly the inventory gap is closed.

The structure of the simulation model for the warehouse is similar to that of the retailer, shown in Figure 3b.

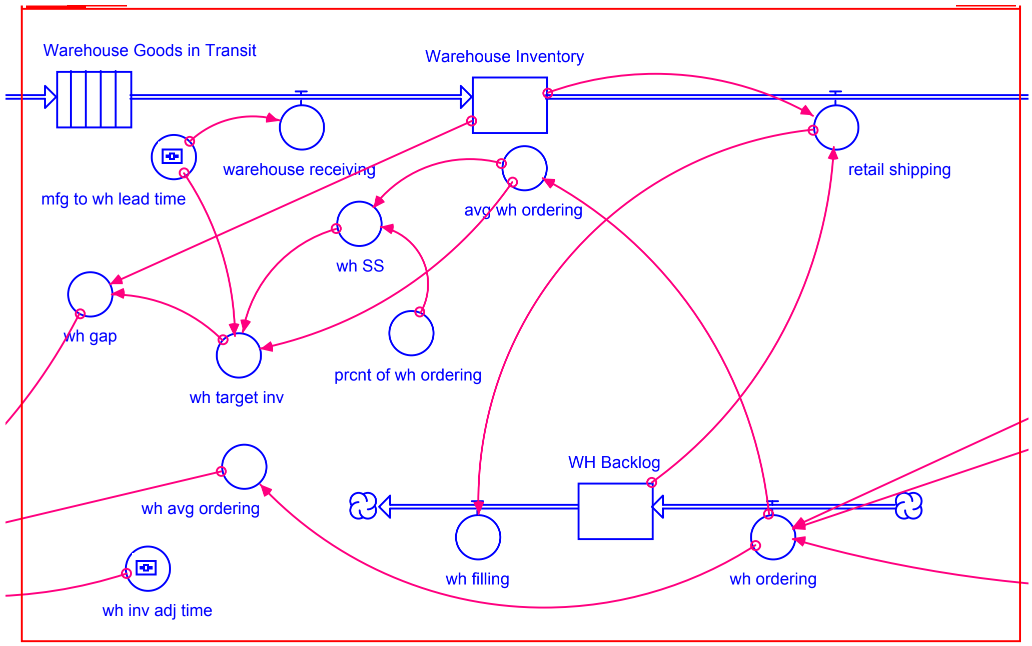

Figure 3b. The Warehouse

As the retailer places orders with the warehouse, shown as *wh ordering* in Figure 3b, the orders are placed into an order backlog. Goods are then shipped to the retailer, depending on whether or not the goods are in stock. If there is no order backlog, then no goods are shipped. If there is an order backlog but not enough goods to fill the order, then some of the goods are shipped. If all items are available, then all are shipped. As goods are shipped, the order backlog is reduced.

The remainder of the warehouse sector is structured the same as the retail sector. A target inventory is based on the average order size placed by the retailer and safety stock. Warehouse order policy is based on the average order size placed by the retailer, *wh avg ordering*, the inventory gap and the warehouse adjustment time. The orders placed by the warehouse appear in the manufacturing sector as *mfg ordering*, shown in Figure 3c.

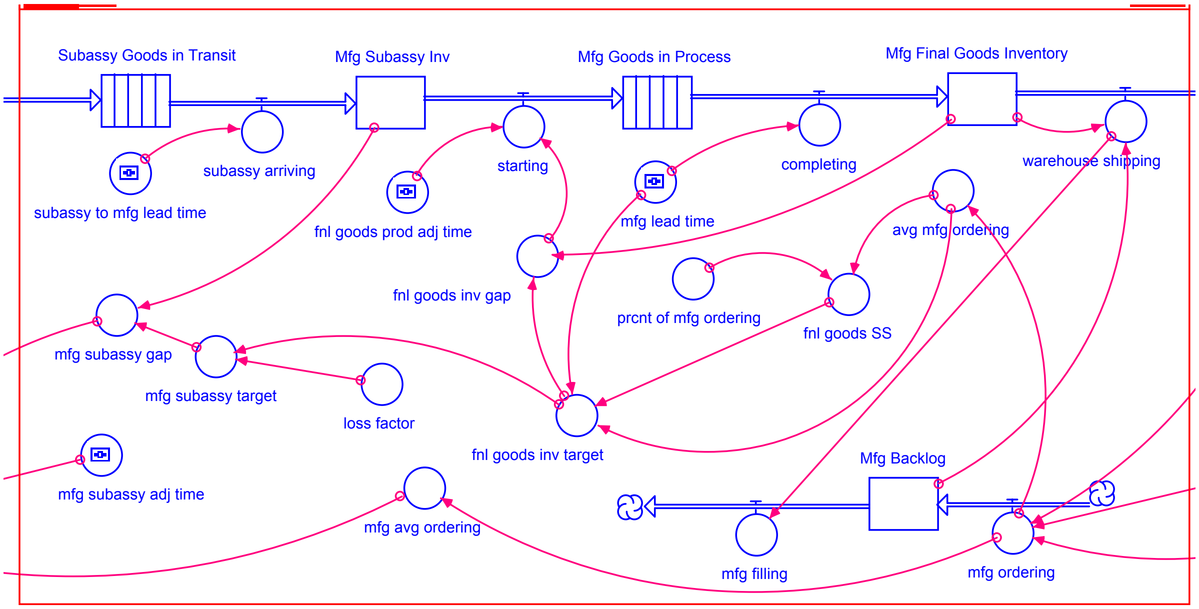

Figure 3c. The Tier 1 Supplier (Manufacturer)

The manufacturer, or tier 1 supplier sector, is structured slightly different from the warehouse and retailer due to the inclusion of subassemblies. Subassemblies flow into the tier 1 supplier's subassembly inventory, where they remain until they are processed and sent to final goods inventory.

Just as in the retail and warehouse sector, the orders placed by the manufacturer depend on the average order size of the warehouse orders, safety stock, and inventory gap. One difference occurs, however, because the manufacturer is not only basing their ordering decision on the final goods shipped, but also on the amount of subassemblies in stock.

Next, consider the second tier supplier sector, shown in Figure 3d.

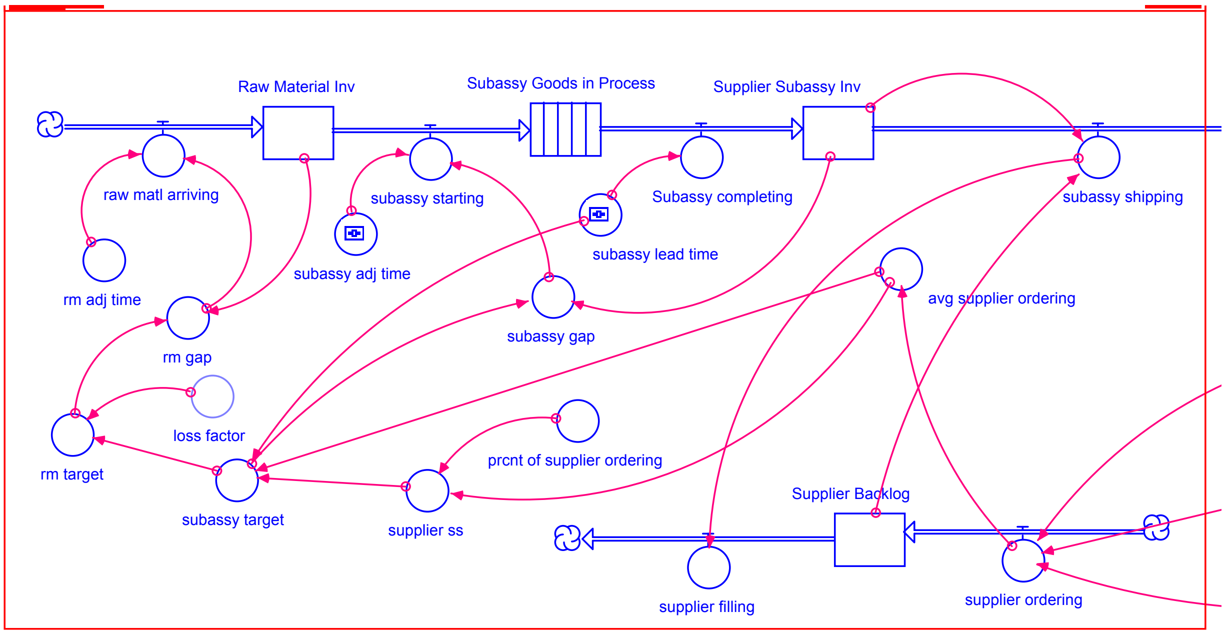

Figure 3d. The Tier 2 Supplier

The tier 2 supplier is the last upstream partner represented in this supply chain model, and the modeling of this sector is slightly different than the other three because orders are not placed with the next upstream supplier. Instead, this activity is depicted by the flow variable, *subassy starting*, the number of subassemblies that are processed when subassembly inventory levels fall below the target level. The number of subassemblies starting equals the subassembly gap divided by the adjustment time. For a given gap, a shorter adjustment time increases the rate at which subassemblies start, whereas a longer adjustment time decreases this rate. As subassemblies are processed, raw material inventory falls, triggering the arrival of new materials as though a raw material supplier was present.

The next section describes the changes in the model structure that were made in order to depict vendor-managed inventory.

Model Structure: Vendor-Managed Inventory Scenario

Figure 4a shows how the manufacturing sector (tier 1 supplier) was modified, and Figure 4b shows the changes made to the warehouse sector.

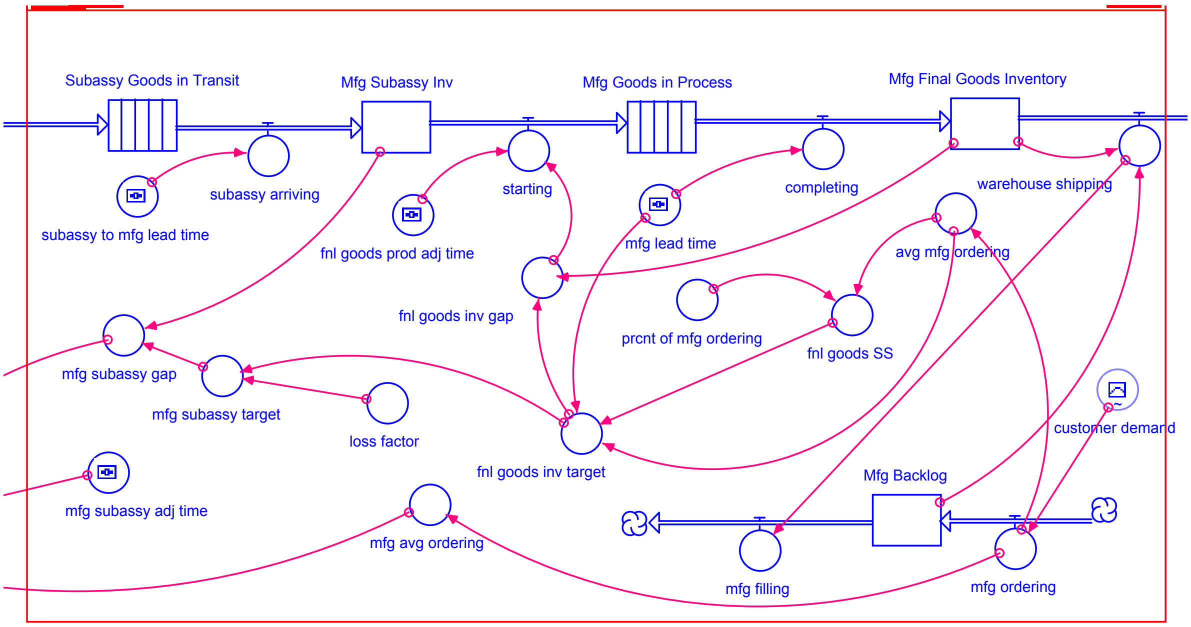

Figure 4a. Modifications Made to the Tier 1 Supplier for VMI.

The mechanism driving order placement is the only modification made for the tier 1 supplier sector. Instead of the warehouse placing orders with the tier 1 supplier, the tier 1 supplier obtains customer orders directly, bypassing the warehouse. In turn, the tier 1 supplier determines the quantity and timing of orders placed with the warehouse, and the warehouse functions primarily as a transport delay in the system. The modifications made to the warehouse sector are depicted in Figure 4b.

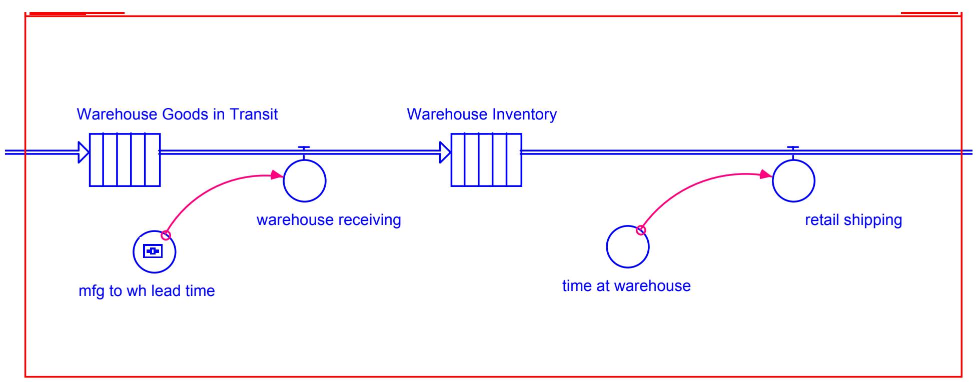

Figure 4b. The Warehouse Sector in the VMI Environment.

Note that the warehouse no longer places orders with the tier 1 supplier. Warehouse inventory has been changed from a stock to a conveyor, where inventory passes through for 1 time unit (1 day, in this case).

The retail sector and the tier 2 supplier sector remain unchanged from the traditional scenario. Additional modifications were made in order to construct the scenario for CPFR.

Model Structure: CPFR Scenario

Figure 5 shows the change made to the model depicting the tier 2 supplier for CPFR. The tier 2 supplier fills orders based on demand information obtained directly from the customer instead of the downstream supplier. The tier 1 supplier and the warehouse are structured the same as in VMI, and the retail sector remains unchanged.

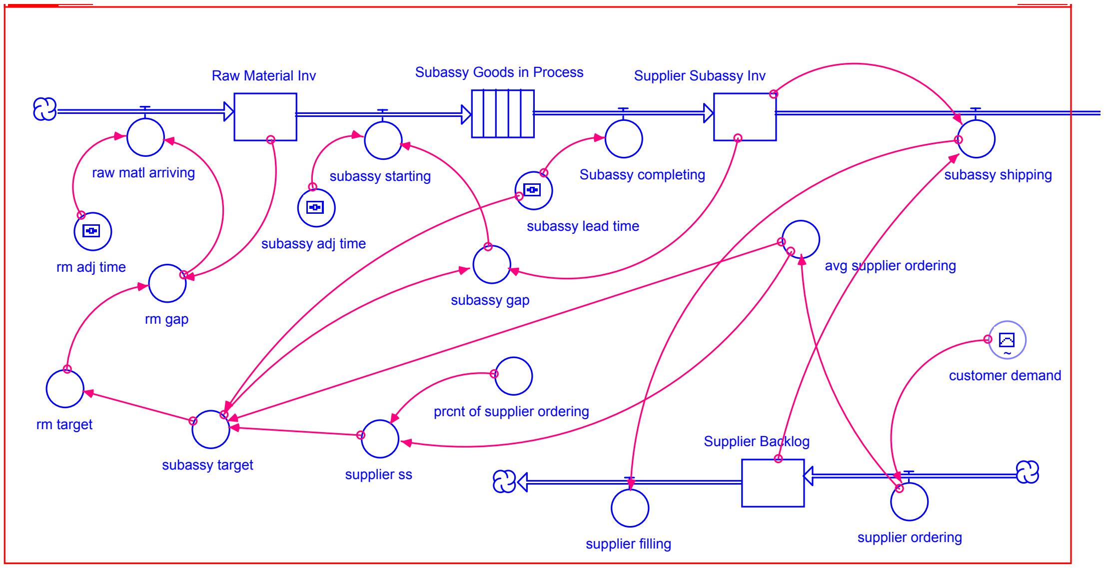

Figure 5. The Tier 2 Supplier in a CPFR Environment.

Six different runs were made for each scenario, and the results compared, discussed in the next section.

Model Results

Traditional Scenario

Table 3a and 3b summarize the results for each run for the traditional model. The tables show average and standard deviation of inventory levels for each partner. In all cases, no retail orders were unfilled. In order to avoid estimation errors, the transient period of 150 days was excluded from the calculations for average and standard deviation, which are based on day 151 through 400.

Run (lead time reduction)	Retail Inventory	Warehouse Inventory	Tier 1 Final Goods Inventory	Tier 2 Subassembly Inventory
Base	28	98	262	429
WH to Retail	**12**	**60**	151	412
T1 to WH	27	**62**	113	**178**
T1 Lead Time	30	71	**13**	244
T2 to T1	28	98	261	390
T2 Lead Time	28	99	233	394

Table 3a. Traditional Scenario: Daily Average Inventory Levels for Lead Time Reductions in the Supply Chain

The numbers in bold in Table 3a indicate the lowest average inventories for each partner. By far the greatest gains are realized by the tier 1 supplier when they reduce their own lead times. This behavior clearly demonstrates Little's Law, which states that as cycle time (or lead time in this case) is reduced, work in process inventory is reduced as long as throughput stays constant (Hopp and Spearman, 2001). It is also apparent that operational improvements in the supply chain make some partners better off without adversely affecting others, achieving a Pareto optimum. It is in every partner's best interest to reduce lead times and production times, with the most benefit occurring to the supply chain partner closest to the improvement. For example, when the transit time from the warehouse to the retailer is reduced, the retailer average inventory level drops by 57%, the warehouse by 39%, the tier 1 final goods inventory by 42%, and the tier 2 subassembly inventory by 4%. Note that the greatest improvements for the retailer and the warehouse occur when transit time from the warehouse to the retailer is reduced. The warehouse and the tier 2 supplier also benefit from reduced transit between the tier 1 supplier and the warehouse. The tier 1 supplier experiences reduced average inventory levels when the immediate downstream transit time is reduced. The impact on the tier 2 supplier of reduced transit time to the tier 1 supplier is not clear from this model. Nevertheless, the model suggests that reduced transit time from the tier 2 to the tier 1 supplier should reduce inventory fluctuations for the tier 2 supplier. There is a slight reduction from 429 to 390, but 390 may not be an accurate result. Additionally, Little's Law indicates that average inventory will fall when the tier 2 supplier reduces their production lead time. The value of 394 units may be too high. In spite of these problems with the tier 2 supplier for these 2 runs, the inventory levels of other supply chain partners are NOT sensitive to the parameters that were adjusted for these 2 runs, and the results for these other partners can be accepted with a higher level of confidence.

These reductions in average inventory level are a direct result of faster transmission of information. Considering only the first 4 runs, a clear pattern emerges. As delays are removed from the system, average inventory levels fall, particularly for those partners who are downstream of the information delay. As delays throughout the supply chain are reduced, so are the impacts of information delays. In essence, what has occurred is the ability of a partner to respond more quickly to order information. Each lead time reduction reduces the total information flow time. It should also be pointed out, however, that these reductions are on the magnitude of 50%, not an easy level to achieve.

This pattern of improvement is repeated for the standard deviation of daily inventory level, shown by the bold numbers in Table 3b. The retailer's variation is lowest when the transit time between the warehouse and the retailer is reduced. Likewise, the variation in warehouse inventory is lowest when the transit time from the tier 1 supplier to the warehouse is reduced. Variability for the tier 1 supplier is lower when they reduce their production lead time. Nevertheless, in comparison to the base case the tier 2 supplier experiences higher fluctuations in inventory levels when the transit time from the warehouse to the retailer is reduced and when the tier 1 production lead time is reduced (shown in italics). There are actually some rather odd results for the tier 2 supplier. It doesn't make sense that the variability would fall when transit time is reduced from the tier 1 supplier to the warehouse, yet increase when transit from the warehouse to the retail and tier 1 lead time are both reduced. This result may be pointing to structural issues with the simulation model, or a need for more in-depth analysis of impacts on the tier 2 supplier.

Run (lead time reduction)	Retail Inventory	Warehouse Inventory	Tier 1 Final Goods Inventory	Tier 2 Subassembly Inventory
Base	18	56	143	126
WH to Retail	**7**	42	102	*198*
T1 to WH	17	**33**	69	**80**
T1 Lead Time	20	44	**16**	140
T2 to T1	18	55	144	*186*
T2 Lead Time	18	59	105	127

Table 3b. Traditional Scenario: Standard Deviation of Daily Inventory Levels for Lead Time Reductions in the Supply Chain

Table 3c shows the coefficient of variation of inventory for each partner for each run. The bold values correspond to the runs in which each partner experience both the lowest average inventory level and the lowest standard deviation of inventory. Notice the clear patterns for the retail and warehouse, in which the scenarios resulting in the lowest average and standard deviations for inventory levels also produced the lowest coefficient of variations. This same pattern does not hold for the tier 1 supplier, even though the bullwhip effect has been greatly reduced when they reduce their production lead time in the run, "T1 Lead Time". Neither does the coefficient of variation exhibit a clear pattern for the tier 2 supplier.

The conclusion is clear for the retailer and warehouse – reduced transit times reduce average inventory levels and fluctuations substantially. Additionally, a reduction in the tier 1 supplier's production time reduces their average inventory level and fluctuations for final goods inventory precipitously, although the coefficient of variation more than doubles.

Run (lead time reduction)	Retail Inventory	Warehouse Inventory	Tier 1 Final Goods Inventory	Tier 2 Subassembly Inventory
Base	0.65	0.57	0.54	0.30
WH to Retail	**0.54**	0.70	0.68	0.48
T1 to WH	0.63	**0.53**	0.61	**0.45**
T1 Lead Time	0.67	0.62	**1.24**	0.57
T2 to T1	0.65	0.56	0.55	0.48
T2 Lead Time	0.65	0.59	0.47	0.32

Table 3c. Coefficient of variation of inventory levels for the traditional scenario

Figures 6a – 6f depict in graphical form the numerical information shown in Tables 3a,3b, and 3c. At the tope of each graph, the label, *Mfg Final Goods Inv*, refers to the tier 1 supplier's final goods inventory and the label, *Supplier Subassy Inv*, refers to the tier 2 supplier's subassembly inventory.

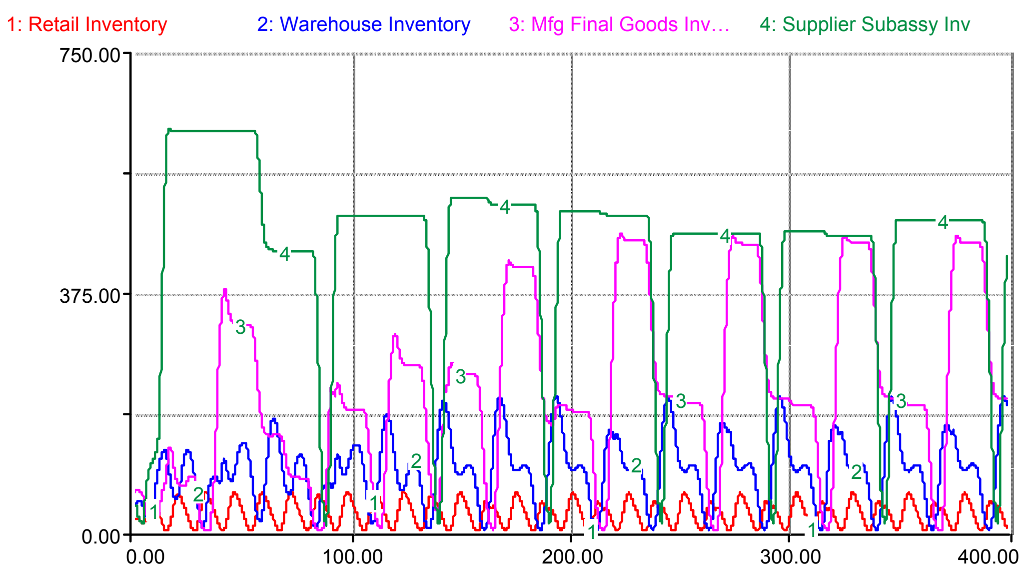

Figure 6a. Run 1: Base Run

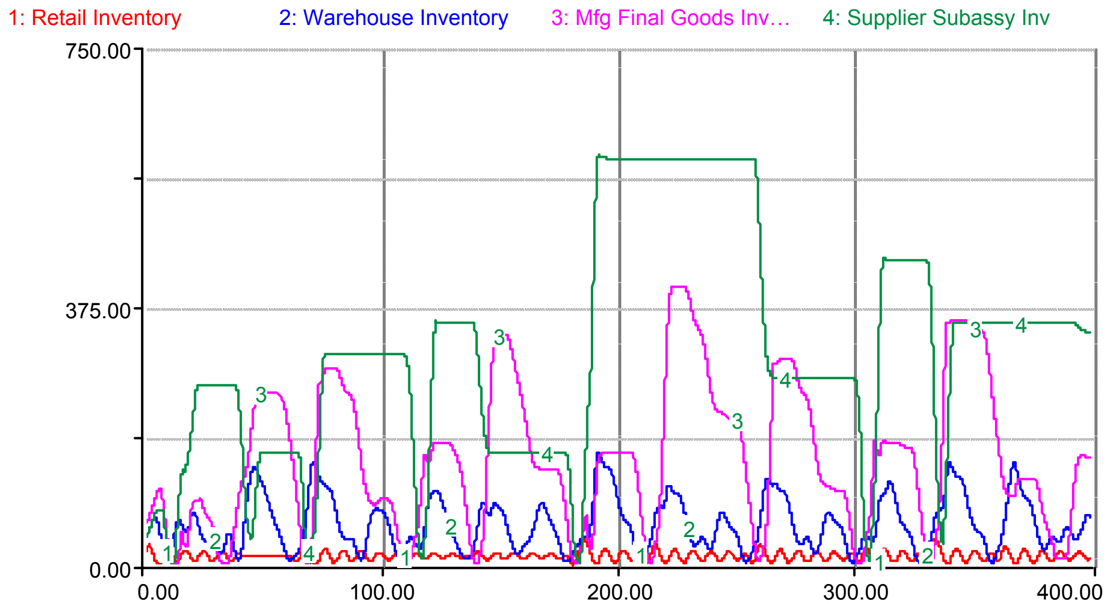

Figure 6b. Run 2: Warehouse to Retail Transit Reduction by 50%

Notice in Figure 6b the large jump in supplier subassembly inventory around day 200. If the run time of the simulation model is extended, this jump occurs again around day 470 and reaches nearly 750 units. Therefore when transit time from the warehouse to the retailer is reduced, the tier 2 supplier experiences somewhat lower average inventory levels, and lower fluctuation for the most part, but occasional large fluctuations occur. The extent to which the tier 2 supplier benefits is negligible. The tier 2 supplier receives much greater benefits in terms of inventory levels and fluctuations when the transit time from the tier 1 supplier to the warehouse is reduced, which is shown in Figure 6c.

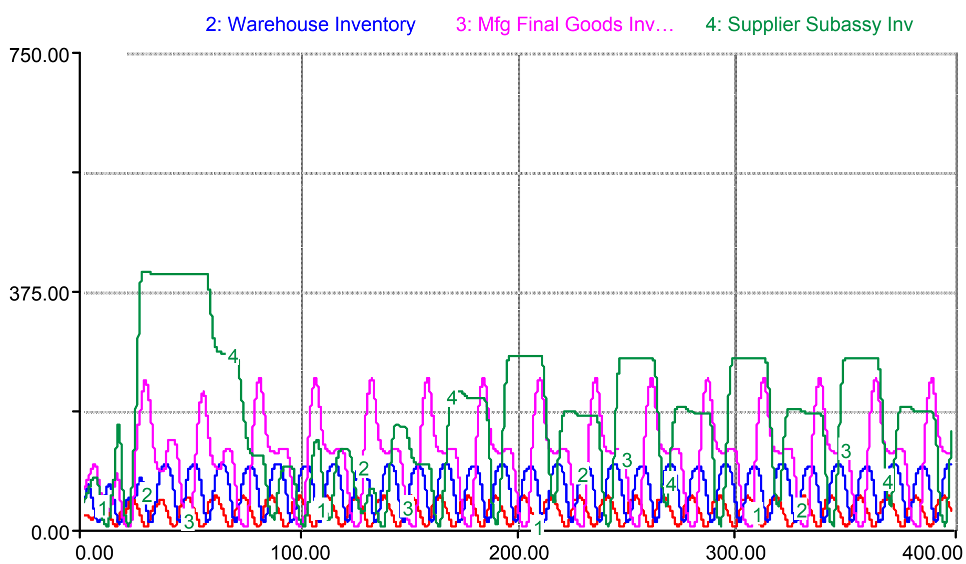

Figure 6c. Run 3: Tier 1 Supplier to Warehouse Transit Reduction by 50%

Compared to Figure 6b, both suppliers are much better off. This is due partly because the transit time is twice the reduction, 2 days, than in the previous run, which is 1 day. Both represent a 50% reduction in transit time.

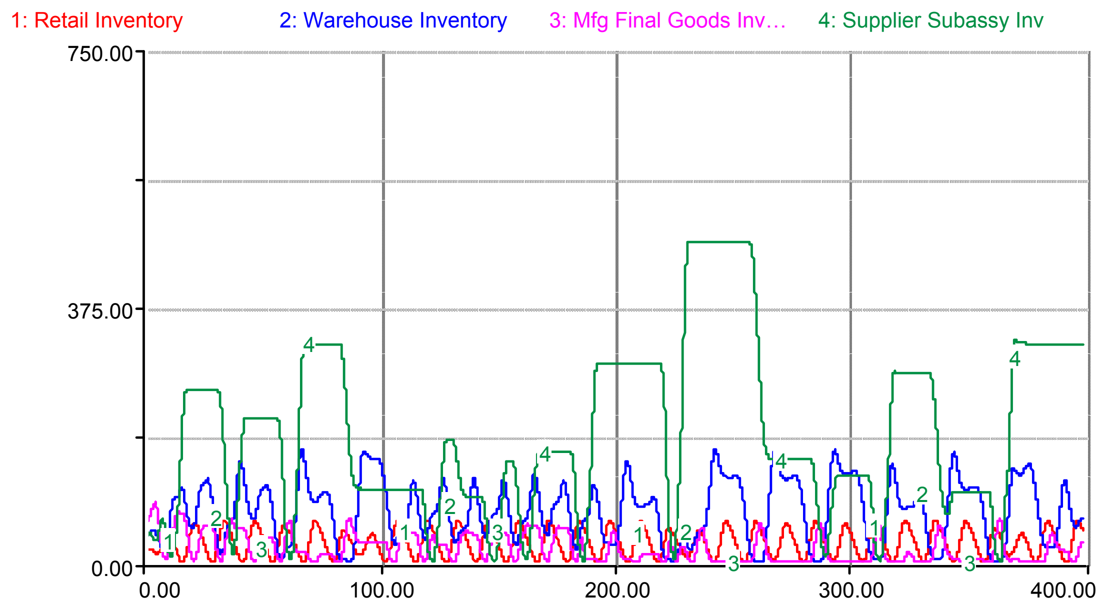

Figure 6d. Run 4: Tier 1 Supplier Production Time Reduction by 50%

Figures 6e and 6f show the results of the last 2 runs in which some structural problems were observed. Notice the consistent inventory behavior for the retailer, warehouse, and tier 1 supplier.

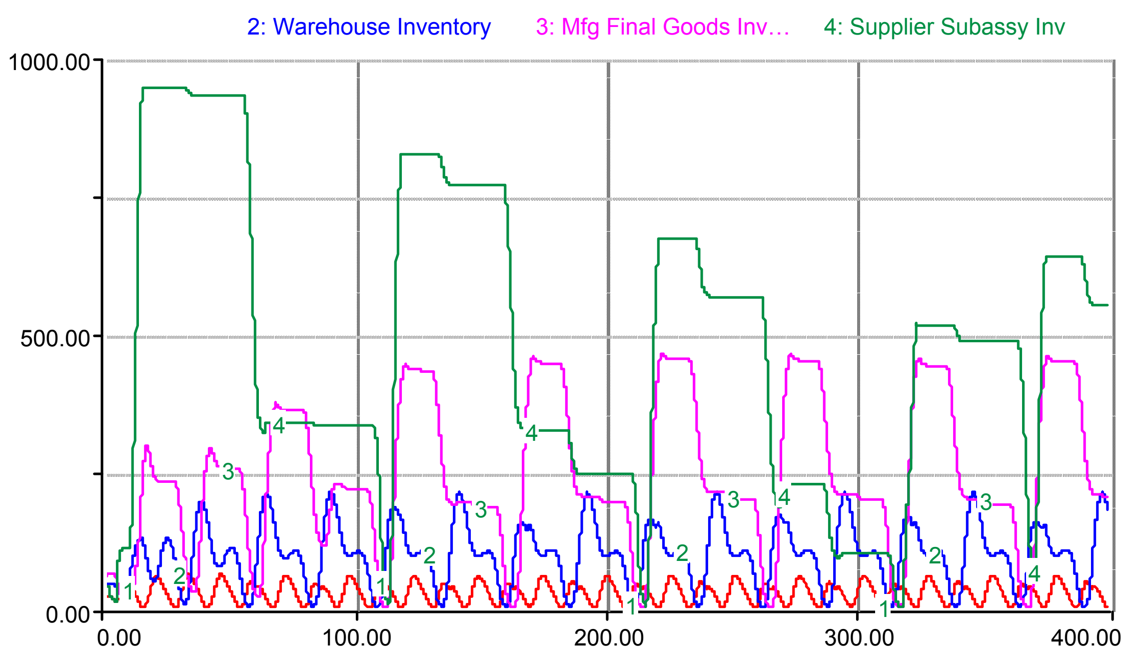

Figure 6e. Run 5: Tier 2 to Tier 1 Supplier Transit Reduction by 50%, where subassembly adjustment time equals 1 day

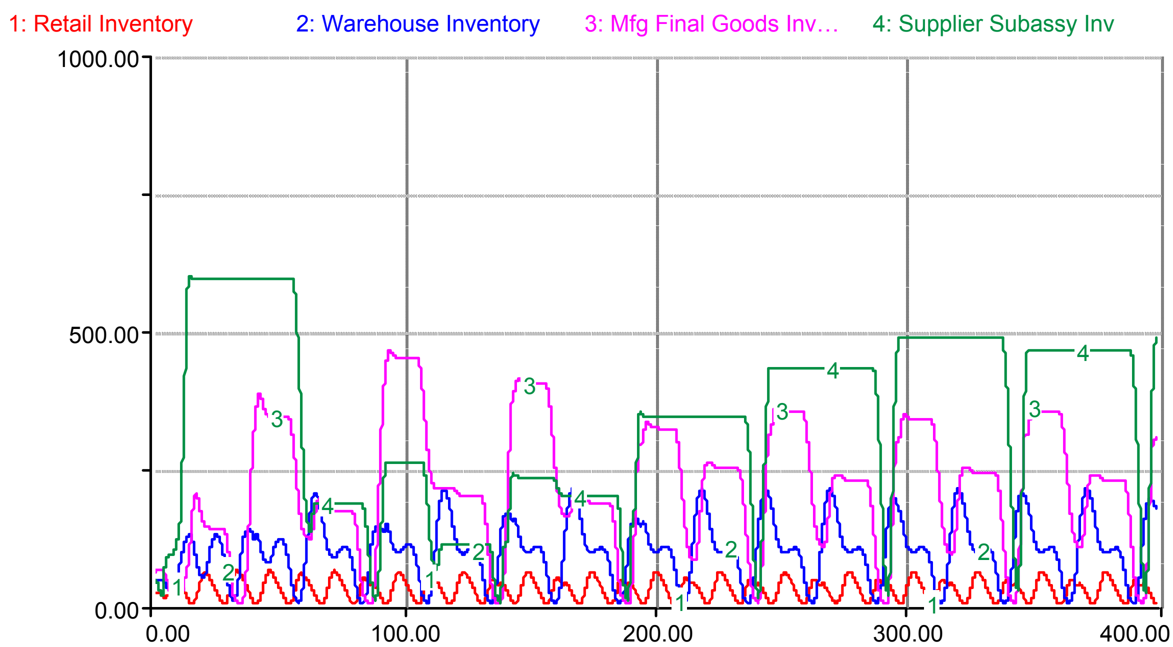

Figure 6f. Run 6: Tier 2 Supplier Lead Time Reduction by 25%; Subassembly Adjustment Time Reduction from 2 to 1 day

In conclusion, under the traditional scenario, reduction in transit and production times for the downstream partners – the retailer, warehouse, and tier 1 supplier, result in benefits to all of these partners as a result of the fast flow of information that is triggered by the faster receipt of goods. The benefit to the tier 2 supplier cannot be determined. Although their average inventory levels may fall as various lead times are reduced, it may be accompanied by an increase in the standard deviation of inventory. The reasons for this are not clear from this study, and warrant further research.

The next section discusses the simulation results for the VMI scenario.

Vendor Managed Inventory

With VMI, every partner experiences lower average inventory levels and variability than under the traditional supply chain scenario. In the worst case VMI scenario, the tier 1 supplier's average inventory levels are reduced by half compared to the best case scenario with the traditional chain. The results are summarized in Table 4a and 4b. The numbers in bold in Tables 4a and 4b indicate the lowest average inventories for each partner. Calculations for the average and standard deviation of inventory levels exclude the transient period of 80 days, and are based on day 81 through 300.

Run (lead time reduction)	Retail Inventory	Warehouse Inventory	Tier 1 Final Goods Inventory	Tier 2 Subassembly Inventory
Base	47	10	54	138
WH to Retail	47	10	54	138
T1 to WH	57	10	54	138
T1 Lead Time	40	10	**12**	**74**
T2 to T1	**37**	10	50	138
T2 Lead Time	**37**	10	52	147

Table 4a. VMI Scenario: Daily Average Inventory Levels for Lead Time Reductions in the Supply Chain

The results presented in Table 4a support the results of previous research, which found that the manufacturer (or tier 1 supplier) is the main beneficiary of coordination in terms of safety stock and waste reduction although there's little effect on the retailer (Xu, Dong, and Evers, 2001). This simulation model is not, however, focusing solely on safety stock levels but it seems to be supported by the research of Xu, et. al (2001).

Average inventory levels fall substantially, and the standard deviation drops precipitously in comparison to the traditional scenario. The tier 2 supplier stands to gain a great deal in terms of reduced inventory levels simply by supplying a manufacturer who engages in vendor managed inventory. If they have the luxury, suppliers should pick their customers carefully!

Run (lead time reduction)	Retail Inventory	Warehouse Inventory	Tier 1 Final Goods Inventory	Tier 2 Subassembly Inventory
Base	5	3	39	68
WH to Retail	5	3	39	68
T1 to WH	5	3	39	68
T1 Lead Time	**1**	**0**	**1**	**37**
T2 to T1	5	3	35	67
T2 Lead Time	5	3	38	61

Table 4b. VMI Scenario: Standard Deviation of Daily Inventory Levels for Lead Time Reduction in the Supply Chain

The bullwhip effect looks very similar for the base runs and the runs in which transit time is reduced. This similarity is also evident from the data in Tables 4a and 4b.

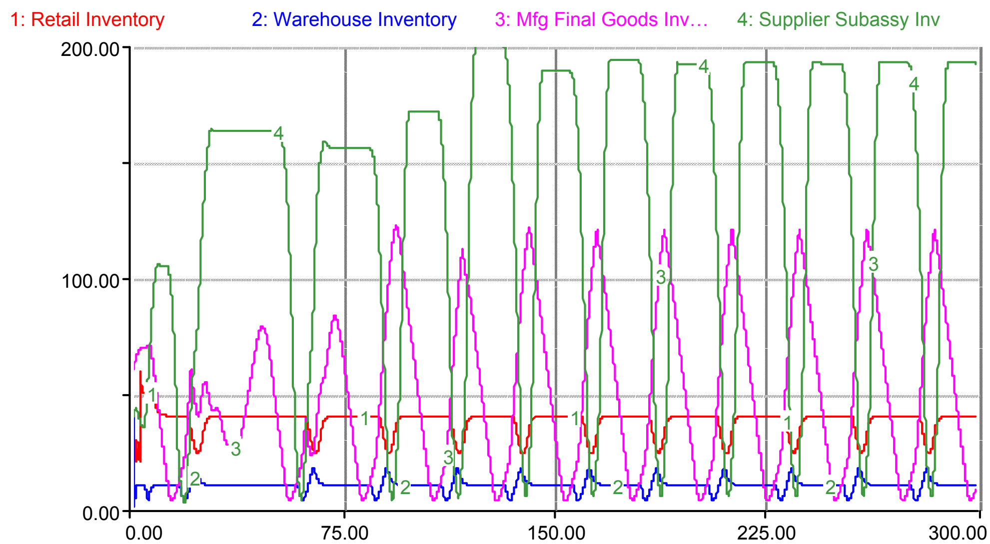

Figure 7a. VMI: Base Run.

Unlike in the traditional scenario, when transit time is reduced between the tier 2 and the tier 1 supplier ("T2 to T1"), the fluctuations vary only slightly from those shown in Figure 7a, and the "reverse" bullwhip effect has disappeared. Further, the effect demonstrates little sensitivity to subassembly adjustment time. Although reducing the subassembly adjustment time from 2 days to 1 day increases the bullwhip effect for the tier 2 supplier, there is no impact on the other supply chain partners. For this particular run, the structure of the VMI model appears to be much less sensitive than the traditional scenario to the selection of model parameters.

Another dissimilarity between the traditional scenario and VMI is demonstrated when the tier 1 supplier reduces their production lead time, shown in Figure 7b.

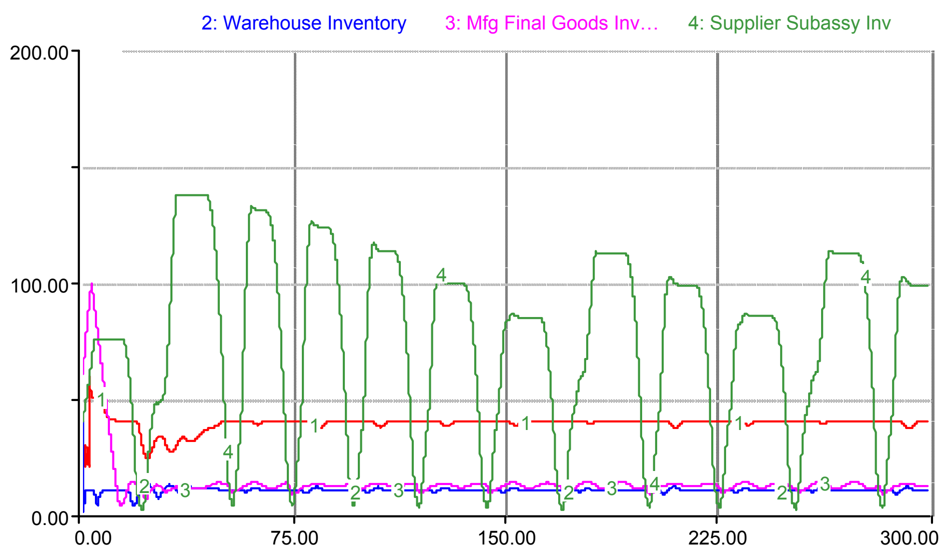

Figure 7b. VMI: Reduction in Tier 1 Supplier Production Time

The bullwhip effect disappears for each partner except for the tier 2 supplier, although their inventory fluctuations decline. The inventory fluctuations are almost negligible for the warehouse, the tier 1 supplier , and the retailer (although the average inventory level is slightly higher for the retailer).

Next, the impact of a reduction of the tier 2 supplier's production lead time is investigated. Just as in the traditional scenario, when the tier 2 supplier production lead time is reduced, the model can provide quite different results depending on the value selected for the subassembly adjustment time. When the adjustment time is set at 1 and the production time is reduced to 3 days instead of 2, as in the traditional scenario, inventory fluctuates as shown in Figure 7c.

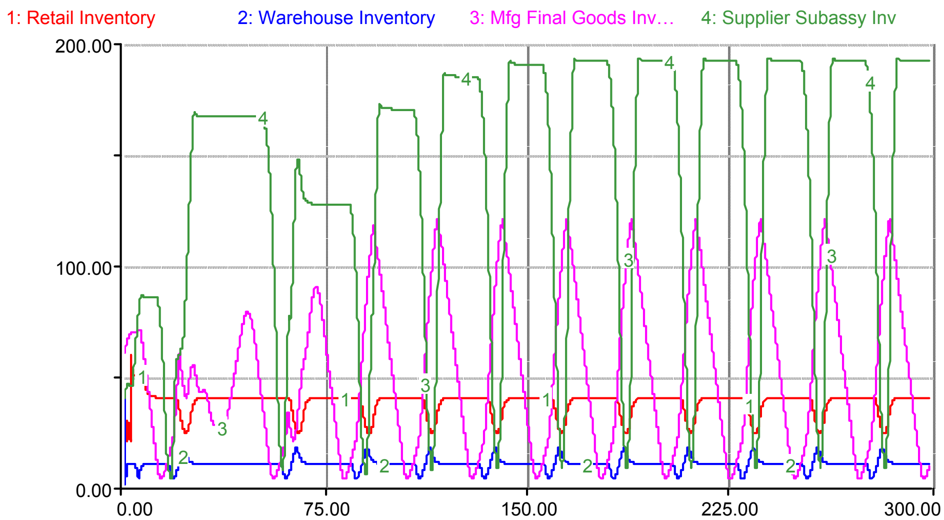

Figure 7c. VMI: Reduction in Tier 2 Supplier Reduction time by 25%, with Subassembly Adjustment Time Reduced to 1 Day

In all cases, the retailer, warehouse, and manufacturer experience more more stability in terms of inventory. Compared to the base case, the tier 2 supplier also experiences far less variability, although compared to the other supply chain partners, they remain the worse off in terms of inventory variability.

One would expect the tier 2 supplier to be even better off in a CPFR environment, which is presented in the next section.

Collaborative Planning, Forecasting and Replenishment

In terms of inventory levels, the big winner is the tier 2 supplier when CPFR is introduced, as shown in Tables 5a and 5b. As in the previous scenarios, the transient period of the first 28 days is excluded, and calculations are based on day 29 through 208.

Run (lead time reduction)	Retail Inventory	Warehouse Inventory	Tier 1 Final Goods Inventory	Tier 2 Subassembly Inventory
Base	37	10	50	22
WH to Retail	47	10	50	22
T1 to WH	57	10	50	22
T1 Lead Time	40	10	**12**	22
T2 to T1	37	10	57	22
T2 Lead Time	37	10	50	**12**

Table 5a. CPFR Scenario: Daily Average Inventory Levels for Lead Time Reductions in the Supply Chain

Run (lead time reduction)	Retail Inventory	Warehouse Inventory	Tier 1 Final Goods Inventory	Tier 2 Subassembly Inventory
Base	5	3	34	11
WH to Retail	5	3	34	11
T1 to WH	5	3	34	11
T1 Lead Time	**1**	**0**	**1**	11
T2 to T1	5	2	39	11
T2 Lead Time	5	3	35	**1**

Table 5b. CPFR Scenario: Standard Deviation of Inventory Levels for Lead Time Reductions in the Supply Chain

The numbers in bold in Tables 5a and 5b indicate where operational improvements make the greatest impact. Not surprisingly, inventory fluctuations are lowest for the tier 1 and tier 2 suppliers when they reduce their production time. The bullwhip effect does not entirely disappear in the CPFR scenario, a finding confirmed by earlier research (Chen, 2000). Figure 8 shows the inventory fluctuations for the base run, which is not markedly different for the other runs. The last run, however, is sensitive to the combination of lead time reduction and subassembly adjustment time; therefore the last run, “T2 Lead Time” was run with the same parameters as in the previous scenarios – with a lead time reduction of 1 day, and a subassembly adjustment time of 1 day.

The higher fluctuations of the tier 1 final goods inventory compared to the tier 2 supplier’s inventory is due the higher production lead time of the tier 1 supplier. It can be easily shown that the fluctuations in inventory are directly related to the production lead times for each supplier, which makes sense because both are receiving demand information directly from the customer.

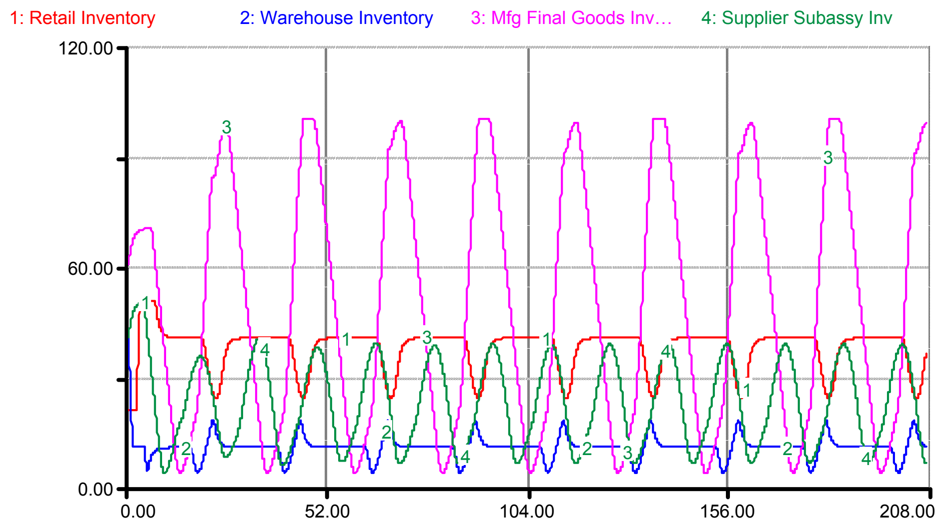

Figure 8. CPFR Base Run

The warehouse exhibits the least amount of fluctuation, followed by the retailer. The tier 2 supplier still experiences inventory fluctuations, but far less than in any other scenario. Of all the scenarios investigated, the tier 2 supplier reaps the greatest benefits in the CPFR. Interestingly, the state of the technology cannot yet accommodate the tier 2 suppliers.

The results of all of these scenarios are summarized in the next section, and conclusions are discussed.

Summary and Conclusions

Each scenario has some interesting results, and the traditional scenario contains four significant findings.

- The retailer receives the greatest benefits when transit time from the warehouse to the retailer is reduced; and the warehouse receives the greatest benefits when the transit time from the tier 1 supplier to the warehouse is reduced. The tier 1 supplier receives the greatest benefits when their production lead time is reduced. The results are inconclusive regarding the benefits received by the tier 2 supplier.
- Operational improvements that significantly reduce fluctuations for one partner do not necessarily improve fluctuations for other partners to the same extent, if at all. An example of this situation occurs when the tier 1 supplier reduces their production lead time. The retailer receives no benefit, and the coefficient of variation for the retailer rises slightly in this case, although it is not significant.
- The reduction in transit time from the tier 2 to the tier 1 supplier does not have much impact on inventory fluctuations anywhere in the system, and due to problems with the model structure, provide no clear conclusion regarding the result of reducing this transit time. Similarly, when the production lead time for the tier 2 supplier is reduced, the model demonstrates a great deal of sensitivity with respect to inventory behavior for the tier 2 supplier.

- There appear to be sensitivity problems with the model structure for the most upstream partner. Extending the supply chain to a raw material supplier may alleviate this effect because the structure for the last partner differs from the others. Care needs to be taken in the selection of parameters for changes that occur at the most upstream portion of the model.

Four significant results were found from the VMI scenario.

- In all the runs, inventory levels for the warehouse and retailer exhibit very little fluctuation, while the tier 1 and tier 2 supplier continue to experience the bullwhip effect.
- Both the tier 1 and tier 2 suppliers experience the least fluctuations in inventory when they reduce their production lead times. This improvement has minimal impact on the retailer and warehouse.
- The model exhibits the sensitivity to reduced transit time between the tier 1 and tier 2 supplier that was experienced in the traditional scenario.
- The model is sensitive to both the tier 2 production lead time and the subassembly adjustment time when the tier 2's production lead time is reduced. The tier 2 supplier's inventory fluctuations exhibit varying behavior depending on the values of these two parameters. Therefore, the results are inconclusive regarding the tier 2 inventory fluctuations when the tier 2 production lead time is reduced.

Five significant results were found in the CPFR scenario.

- The retail and warehouse inventory fluctuations are nearly identical to those in the VMI scenario.
- The tier 1 supplier's inventory fluctuations do not vary substantially from those in VMI.
- The tier 1 and tier 2 supplier experience the least fluctuations in inventory when they reduce their production lead times.
- The tier 2 supplier is the big winner, experiencing the greatest inventory reductions of any partner compared to VMI.
- The model still exhibits some sensitivity to the parameters, subassembly adjustment time, for the last run in which the tier 2 supplier's production time is decreased.

The results of the simulation runs for CPFR raise a couple of interesting questions. Why bother with CPFR if the impact on inventory fluctuations, compared to a well-functioning VMI system, is minimal? Secondly, even though the tier 2 supplier stands to realize the greatest gains from CPFR, will the technology for data exchange be capable of including partners beyond the first tier?

Although these simulation models are fairly simplistic with respect to the complicated operations of a supply chain, the intent is to capture the behavior of the supply chain in order to anticipate where operational improvements will have the greatest impact for different stages of supply chain integration. One consistent result is the finding that the tier 1 supplier experiences the least fluctuations in inventory when they reduce their production lead times, regardless of the supply chain structure. Further, in the absence of empirical data, a generalized supply chain model can be developed and existing theory used to validate its behavior.

This study has shown that operational improvements in one area of a supply chain may adversely affect other supply chain partners, depending on how information is shared. This research underscores the need for a better understanding of supply chain dynamics in order to assess these impacts, and has established that simulation modeling is one tool that is well suited to this type of analysis. In this respect, this study can be sued for education purposes, and convey the following messages to an audience.

1. The integrated nature of a supply chain creates interdependencies that may not be evident or intuitive.
2. Experimentation with simulation modeling assists in discovering these interdependencies, which can be helpful for building more realistic models by identifying essential information which needs to be gathered.
3. Simulation modeling can be a very useful tool for assessing tradeoffs, such as where it's best to pursue a transit time reduction, and the associated costs and benefits of pursuing a specific policy change.

This study has also demonstrated that regardless of the level of information sharing, the supplier and the manufacturer experience the greatest reduction in inventory fluctuations when they improve their internal operational efficiency. Why then, collaborate? Neither the warehouse or the tier 1 supplier experience lower fluctuations in CPFR compared to VMI; only the tier 2 supplier experiences lower inventory fluctuations in CPFR and the technology doesn't extend beyond the tier 1 supplier. It is obvious that all parties, except for the retailer, are best off either under the VMI or CPFR scenario. Further, the retailer has little to gain with respect to inventory levels in either VMI or CPFR, and has little incentive to participate, unless the net benefits of doing so are distributed throughout the supply chain. (Although the retailer no longer has to manage their inventory in CPFR or VMI, an important benefit.) How these benefits and costs should be redistributed are questions for future research which has also been raised by Lee (1997b).

Other areas also need to be addressed in future research, discussed in the next section.

Suggestions for Future Research

Several aspects of operational improvements need to be explored, including transit time between suppliers, relative production lead times, and the interaction of multiple improvements. This study showed little impact on the supply chain partners as transit times were reduced between upstream suppliers. This is a puzzling and unexpected result that should be investigated further. Second, in comparing the tier 1 and tier 2 inventory fluctuations in the VMI model, the supplier with the greatest production lead time experiences the greatest inventory fluctuation. This result should also be explored. Finally, this study did not consider how multiple improvements would effect supply chain dynamics, so that interaction effects could be analyzed, another potential topic for future research.

Besides investigating operational improvements, this research should be extended to include inventory costs and assess the impact of transportation disruptions. An attempt was made to include inventory costs in the traditional scenario, but the results did not coincide with the results from each run. That is, the runs with the lowest inventory fluctuations were not necessarily the same runs with the lowest total inventory costs. Therefore, inventory cost computations need to be carefully constructed to reflect ordering policy. These results will not be presented here, but warrant further research.

In addition to incorporating costs, the introduction of transportation disruptions is a timely and important extension. It is essential to understand how lead times are perceived by partners in a supply chain. For example, in the models constructed in this study, the partners were aware of lead time reductions that affected their operations, and they made the appropriate adjustments. Target inventory levels are computed as the product of lead time and average ordering plus safety stock. Therefore, as lead time was reduced, the target inventory level was lowered.

Consider the scenario in which a transportation disruption occurs, and a partner is not aware of the increased lead time. How should they respond, and what type of events would trigger a disruption? Certainly the terrorist attacks of September 11, 2001 created disruptions throughout the whole world, which has responded by heightened security measures. Increased security measures can lengthen transit time, and raises many questions with respect to the location of suppliers, third party logistics, and contingency plans.

In conclusion, this study has illustrated the existence of an imbalance in the distribution of costs and benefits in the supply chain as operational improvements are implemented and further, that the magnitude of the costs and benefits depends on the stage of supply chain integration. How to redistribute the costs and benefits remains to be resolved. Additionally, this study has shown that system dynamics simulation is a useful tool for simulating supply chain dynamics in order to assess system wide impacts of operational decisions. Finally, extensions to this study will contribute to a greater understanding of supply chain behavior that will hopefully help with the integration, analysis, and management of supply chain operations.

Notes

1. The actual information exchange process is more complicated than what is depicted in the CPFR model, as demand, inventory, and order information is fed both upstream and downstream.
2. According to Chen (2000), the lower bound on the increase in inventory variability from the retailer to the manufacturer is give by $\frac{\text{Var}(q)}{\text{Var}(D)} \geq 1 + \left[\frac{2L}{\text{p}} + \frac{2L^2}{\text{p}^2}\right]\left(1 - \rho^{\text{p}}\right)$ where q = order quantity; D = customer demand; L = lead time-1; p = number of periods over which demand is forecast, using a simple moving average; and ρ= correlation of customer demand between subsequent time periods. Applying this theory to this particular situation indicates that the variability of the tier 1supplier's inventory will always exceed the variability of the tier 2 supplier's inventory. Under no circumstances should the increase in variability be less than one, which would produce a "reverse" bullwhip effect.
3. A simple method was used to calculate total inventory costs, which are the sum of carrying and ordering costs. Carrying costs are slightly higher downstream as value is added to the products.

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