

TECHNICAL RESEARCH REPORT

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Rescheduling Frequency and Supply Chain Performance

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Abstract

Scheduling decisions control the flow of material and information in a supply chain. In many cases, scheduling decisions are made periodically. This paper studies how changes to the rescheduling frequency affect the performance of the participants of the supply chain. In the supply chains studied, the scheduling decisions and order release activities occur together. Three types of decisions are considered: ordering raw materials, scheduling production orders, and scheduling deliveries. Experimental results from two supply chains show that order release frequency affects the system performance more significantly than the details of inventory and production control policies do. Coordinating scheduling decisions between participants affects the performance of not only the individual participants but also the entire supply chain.

1. Introduction

Supply chains involve uncertainty and variability in many activities. Variability along with limited resources makes it difficult to manage the system. The system performance depends to a great extent on the rescheduling policies for various planning activities. When rescheduling periods are too short, the result is a frequent change in plans, which may not be easy to implement. When the planning activities are scheduled over a very long time horizon, it becomes difficult to manage the system efficiently. This paper analyzes the direct and indirect effects of varying the rescheduling periods of various activities on the performance of a supply chain.

Although the importance of frequent communications has been noted, there are few studies that attempt to quantify this impact, which can help decision-makers make tradeoffs with other objectives.

A system may have continuous or periodic review. In continuous review, the status of the system is always known, and planning activities are carried out on an instantaneous basis, every time a change in the system status occurs. Continuous review systems are generally more expensive in terms of reviewing costs (Silver *et al.*, 1998). Moreover, these systems require frequent change of existing plans, which, in reality, is not common. In periodic review systems, the status of the system is checked periodically and planning activities are carried out accordingly. During any planning period, the change in the system from the previous period is analyzed and a new plan is made to accommodate the changes. Once these rescheduling plans are made, it is followed as closely as possible until the end of that planning period. In this kind of a system, there may or may not be synchronization among various planning activities.

This paper presents the results of investigating the impact of changing the frequency of three kinds of scheduling activities: sourcing raw materials from the suppliers, producing customer orders, and delivering customer orders. Discrete-event simulation models of two different supply chains were used to obtain the results.

The remainder of the paper is organized as follows. Section 2 reviews relevant literature. Section 3 explains the approach that was adopted for evaluating the supply chains. Section 4 describes the two supply chains that were studied. Section 5 presents the experimental results. Section 6 concludes the paper.

2. Literature Overview

Work has been done in the area of rescheduling, especially for production activities. Vieira *et al.* (2002) discuss the various rescheduling frameworks and performance measures that have been considered by researchers. They conclude that the scope of papers on rescheduling varies greatly. They emphasize that the rescheduling policies should be considered at manufacturing system design stage. This is rarely done since manufacturing system models do not usually address the issue of rescheduling.

Church and Uzsoy (1992) developed a hybrid event-driven rescheduling policy for single-machine and parallel-machine models with dynamic job arrivals. Vieira *et al.* (2000a) studied a single-machine system and developed analytical models to estimate system performance. The work considers two rescheduling policies: periodic and event driven based on queue size. Their results show that analytical models can accurately predict the performance of a single-machine system operating under those rescheduling strategies. Vieira *et al.* (2000b) extended that study by investigating parallel machine systems, which have more complex rescheduling strategies.

Intuitively, it seems natural that rescheduling more often yields better performance. A number of experimental studies support this hypothesis. Farn and Muhlemann (1979) used simulation to study a single-machine system with sequence-dependent setup times. They conclude that rescheduling more often leads to lower setup costs. Muhlemann *et al.* (1982) conclude that the rescheduling period affects system performance more when there is greater uncertainty and that managers need to explore the tradeoff between the cost of scheduling and the benefits of more frequent scheduling.

According to Wu *et al.* (1999), a robust, partial schedule leads to better system performance (less weighted tardiness) than dispatching rules. However, as processing time variability increases, dispatching rules lead to better performance. Leon *et al.* (1994) state that, as processing time variability increases, the improvement (in expected makespan and expected delay) due to robust schedules increases. Mehta and Uzsoy (1998) state that predictive schedules (with inserted idle time) increase predictability (reduce nervousness) but do not significantly degrade system performance (maximum lateness), compared to schedules generated by ignoring possible breakdowns.

Kim and Kim (1994) considered minor and major disturbances in their scheduling system. They conclude that there was an advantage to checking the system performance periodically and that

too-long monitoring periods resulted in worse performance of the systems. They also observed that too-frequent monitoring could negatively affect performance. Sabuncuoglu and Karabuk (1999) studied the frequency of rescheduling in the multi-resource environment of a flexible manufacturing system with random machine breakdowns and processing times. For the scenarios considered, they conclude it is not a good policy to never react to disturbances or to react to every disturbance.

One of the major objectives of Shafaei and Brunn (1999, 1999) was to examine whether a more frequent rescheduling policy would always improve system performance. They show that frequent rescheduling becomes more effective as the level of uncertainty increases. Herrmann and Delalio (2001) consider the effect of rescheduling period on decisions regarding batching and scheduling of sheet metal punch press operations.

The frequency of conducting activities also determines the speed with which the information is passed along the supply chain. Poirier (1999) points at the various advantages of having efficient enterprise resource planning. The advantages include a dramatic drop in the cycle times and reduction in inventory safety stocks.

Vollmann, Berry and Whybark (1988) talk about the appropriate frequency for processing the MRP time-phased records. They mention that the primary motivation for less frequent processing is the computational cost. Hopp and Spearman (2000) note that the cycle stock for the inventory increases as replenishment frequency decreases. They categorize planning activities into three categories: Long-range planning, intermediate-range planning and short-term control. Most of the production planning functions fall under intermediate-range planning. This includes master production scheduling and material requirements planning.

Most of the studies conducted so far consider the effects of rescheduling frequencies at the plant level. In contrast, this study considered the entire supply chain. Interactions between participants and supply chain wide effects of rescheduling frequencies are analyzed.

3. Methodology

Manufacturing systems are generally either make-to-order or make-to-stock. In a make-to-order system, the manufacturer makes and delivers products based on existing customer orders. In a make-to-stock system, the manufacturer creates products and stocks them in the finished goods inventory, where the customer takes them. In this paper, we consider both make-to-stock and make-to-order systems.

Inventory management has a very significant effect on the performance of the system. In the simulation models, the raw material inventory is managed using a (R, s, S) policy, where R is the interval at which inventory is checked, s is the reorder level, and S is the order up to quantity. The inventory management system checks the inventory at regular intervals and assesses the net inventory levels. If the net inventory level is below the reorder level, then an order is placed with the supplier so that the replenishment takes place up till order up to level is reached.

The production management system releases orders for production based on a first-come-first-served policy. It checks the orders for production release in the order they were received. If material is available to process an order, the order is released for production. Otherwise, the order is kept as pending for the next planning cycle, while the next order in the list is processed. All the orders that can be processed with the existing raw material inventory are released at once to the shop floor, where they must wait for a manufacturing resource.

During delivery of the finished goods, each order is shipped separately. When the delivery management system checks the finished goods inventory, all the orders that are waiting in the finished goods inventory are released for delivery. The available transporters deliver the orders. Delivery times are exponentially distributed.

This study evaluates supply chain performance using the cycle time and tardiness performance measures. The overall cycle time is the average time for the fulfillment of customer orders. This is the average time between the customer placing an order and the order being received at the customer's site. The Supply Chain Operations Reference (SCOR) Model (Supply Chain Council, 2000) divides this interval into four phases: order receipt to start build, start build to finished goods, finished goods to release for delivery and release for delivery to receipt at customer site. The duration of the *order receipt to start build* phase is the time until a received customer order is released for production. This depends upon both the production scheduling frequency and the raw material availability. The duration of the *start build to finished goods* phase is the time that the order spends in the shop floor during production. Production activities include production, testing, packaging, and staging the finished product into the finished goods inventory. The duration of the *finished goods to release for delivery* phase is the time that an order spends in the finished goods inventory. The duration of the *release for delivery to receipt at customer site* phase is the time that from when the order is scheduled for delivery until the delivery at the customer site. This involves transportation time plus any time spent waiting for a transportation resource to become available.

In addition to the cycle time performance measure, the on-time delivery performance of the orders is also analyzed. After receiving an order, the manufacturer assigns a due date to the order based on the estimated lead time. If the order is delivered at the customer site after the due date, the order is considered tardy. The tardiness performance measure is the percent of orders that are tardy.

4. Description of Supply Chains and Design of Experiments

To gain some insight into the impact of rescheduling frequency, we considered two different supply chains, constructed discrete-event simulation models of each, and conducted a set of experiments. The sections below describe the two supply chains and the corresponding design of experiments.

4.1 Supply Chain One

4.1.1 Supply Chain Structure

The supply chain has five participants: two suppliers, one manufacturer, and two customers. The manufacturer produces two kinds of products: Product 1 and Product 2. Both products are made-to-order. Each customer places orders for both the products. Each unit of Product 1 consists of one unit of Component 1 and one unit of Component 2. Each unit of Product 2 consists of one unit of Component 1 and one unit of Component 3. Supplier 1 supplies Component 1 and Component 2, while Supplier 2 supplies Component 3. Figure 1 shows the schematic of the supply chain. The capacity of all the resources in the simulation model have been set so that the utilization is around 85%. The manufacturer uses a periodic review policy for reordering all components. The order-up-to quantity S equals the average demand for seven days.

4.1.2 Design of Experiments

This section explains the scenarios considered in the experimental study. The goal is to compare the impact of changing the rescheduling frequency to the impact of changing other production and inventory control parameters. The independent variables are the three rescheduling periods, the dispatching rule, and the reorder level.

The rescheduling periods range from 0.1 hours (very close to continuous review) to 120 hours. We consider eleven different rescheduling periods. They are: 0.1, 1, 2, 4, 8, 16, 24, 48, 72, 96, and 120 hours. While one rescheduling period varies, the other rescheduling periods remain equal to 4 hours. There is no synchronization between the planning activities for the participants.

The reorder levels have two values. In the first case, the reorder level equals to the order-up-to quantity, the average demand for seven days. In the second case, the reorder level equals the average demand for five days.

The production release heuristic has two settings: first-in-first-out (FIFO) and shortest processing time (SPT). FIFO processes the orders in the sequence they were received, subject to material availability. SPT processes orders that require shorter average processing time before the ones that require longer average processing time, subject to material availability.

Table 1 lists the scenarios considered. The values given represent the rescheduling periods for the sourcing, production, and delivery activities at the manufacturer. In all the scenarios, we collect cycle times at various stages, overall cycle time, and percent tardy orders as the performance measures. Out of the 55 scenarios listed in Table 1, the one with a rescheduling period of 4 hours for all the three activities gets repeated in the first three categories. This gives a total of 53 distinct scenarios.

We carry out ten replications for each scenario and calculate the average and standard deviation for the various performance measures and 90% confidence intervals. The replications are carried out in steady state. The simulation runs cover a period of ninety days after a warm-up period of thirty days.

Scenarios	Source	Make	Deliver	Production Heuristic	Reorder Level (Days of Inventory)
1 to 11	0.1 to 120	4	4	FIFO	7
12 to 22	4	0.1 to 120	4	FIFO	7
23 to 33	4	4	0.1 to 120	FIFO	7
34 to 44	0.1 to 120	4	4	FIFO	5
45 to 55	4	0.1 to 120	4	SPT	7

Table 1. Scenarios for Supply Chain One

4.2 Supply Chain Two

4.2.1 Supply Chain Structure

The second supply chain has ten participants: four suppliers, one manufacturer, one warehouse, two retailers, and two customers. The manufacturer produces three kinds of products: Product 1, Product 2, and Product 3. Each customer places orders for all the products with the retailer. Each unit of Product 1 consists of one unit of Component 1 and one unit of Component 2. Each unit of Product 2 consists of one unit of Component 1 and one unit of Component 3. Each unit of Product 3 consists of one unit of Component 1 and one unit of Component 4. Supplier 1 supplies Component 1, Supplier 2 supplies Component 2, Supplier 3 supplies Component 3, and Supplier 4 supplies Component 4. Figure 2 shows the schematic of the supply chain.

Product 1 represents a high demand product that the retailer stocks. When a customer places orders for this kind of product, the retailer supplies the product immediately provided it is in stock. The demand for Product 2 is intermediate, and the retailer does not stock this product. When a customer places an order with the retailer, the retailer in turn places an order with the warehouse. The warehouse stocks this product and delivers the product to the retailer, who in turn delivers it to the customer. The demand for Product 3 is very low. Neither the retailer nor the warehouse keeps any inventory for this product. When a customer places an order with the retailer for this kind of product, the retailer sends the order to the manufacturer, who makes the product and delivers it to the retailer through the warehouse. The retailer then delivers it to the customer. Customer 1 and Customer 2 both purchase all three products, but Customer 1 places nearly two-thirds of all the orders.

The reorder levels take into account the variability in the demand for the product, the variability in the supplier cycle time, and the delay due to periodic rather than continuous review (Silver *et al.*, 1998). The order-up-to quantity equals the reorder level. The following equation is used for calculating the reorder levels:

$$s = (a + b CT)D$$

$$= (3 + 2 CT)D$$

where

s = Reorder level

a = Sourcing rescheduling period

b = Factor to take into account the variability in lead time and demand (safety stock)

CT = Supplier's cycle time for the product in days

D = Average demand for the product per day

In this study, $a = 3$ days (72 hours) is the maximum rescheduling period, and $b = 2$.

Initially, the inventory levels for all the participants are set equal to the quantity sufficient to meet the demands for one week. We start at the suppliers, who are the most upstream participants in the supply chain. Based on the cycle time for the suppliers, the inventory levels for the manufacturer are set. These values are used for the next iteration. During each iteration, after setting the inventory level for an upstream participant, we carry out a new round of simulation to check the cycle time performance with the new inventory levels and based on those values, the inventory levels for the corresponding downstream participant(s) is (are) set. We repeat this process till all the inventory levels have been established. The cycle time values obtained during these simulation runs are used to set the lead times for products at various participants.

We set the lead times based on the pilot runs after the inventory values have been set. Pilot runs are carried out with all the rescheduling periods set at the medium value. The lead times are set based on the cycle times obtained from the pilot runs.

$$LT = k CT$$

LT = Lead time

k = Factor of safety to account for variability

CT = Cycle time for the pilot run

For example, Product 3 is a make-to-order product. So when a customer places orders with Retailer 1 for Product 3, the product has to go through the Manufacturer, Warehouse and Retailer 1 before it is delivered to the customer. Therefore, for this product at Retailer 1,

$$LT_{\text{Retailer1, Product3}} = k(CT_{\text{Manufacturer}} + CT_{\text{Warehouse}} + CT_{\text{Retailer1}})$$

In the simulation experiments, k has been set at 1.5.

4.2.2 Design of Experiments

The purpose of the experimental study is to determine the impact of rescheduling activities on the supply chain performance. The independent variables are the rescheduling frequencies for each participant and the synchronization between these activities.

If all participants are performing rescheduling at the same frequency, they are, in theory, making scheduling decisions simultaneously. But each participant uses information generated by the other participants' decisions. In practice, there is a delay between the decision-making and the transmittal of information to another participant. Some participants may choose to wait for

information before making their decisions, but the decision-makers must avoid the deadlock that can occur if two participants are waiting on each other.

To overcome this situation, some type of coordination or synchronization is needed. This study considered two kinds of synchronization: backward synchronization and forward synchronization. In backward synchronization, scheduling decisions are timed so that (among the decisions that should be made simultaneously) the most downstream decisions are made first, followed by the ones immediately upstream, and so forth. In this situation, participants are able to utilize information generated by the decisions that downstream participants make with little delay. In forward synchronization, the situation is reversed.

The experiments considered three levels of rescheduling periods: 4 hours (low), 24 hours (medium), and 72 hours (high). Each participant has one rescheduling period. These values correspond to the intervals at which a participant makes decisions for sourcing, production, and delivery.

The experiments considered six different scenarios for analyzing the effects of synchronization. These scenarios correspond to low, medium, and high rescheduling periods for all the participants. One set of three scenarios uses backward synchronization, while another set of three scenarios uses forward synchronization.

For analyzing the effects of varying the rescheduling period of one participant, the manufacturer's rescheduling period varies while the other participants have medium rescheduling periods. This is done with both backward synchronization and forward synchronization. This requires a total of six different scenarios. (Two of these—all medium rescheduling periods with backward synchronization and forward synchronization—were included in the first set of experiments.)

The supply chain has two retailers: Retailer 1 and Retailer 2. Customers place more orders with Retailer 1 than with Retailer 2. Retailer 1 gets nearly 7 orders per day while Retailer 2 gets only 3 orders per day. The order sizes are also smaller for Retailer 2.

For understanding the impact of the retailers' rescheduling periods, the experiments considered scenarios in which the rescheduling period for the two retailers varied independently, while the other participants have medium rescheduling periods. This yields eighteen different combinations: nine with backward synchronization, and nine with forward synchronization. (Of these eighteen, two scenarios were included in the first set of experiments.) Tables 2, 3, and 4 summarize the scenarios considered.

The evaluation of each scenario is similar to that for Supply Chain One. For each scenario, ten replications are performed to get estimates on the mean and variance of the performance measures and 90% confidence intervals. The cycle times and percent tardy are the performance measures for the manufacturer, the warehouse, and the retailers. Since the customers interact with the retailers, the retailer performance measures describe the performance of the supply chain as seen by the customer.

Scenarios	Rescheduling Period	Synchronization
1	Low	Backward
2	Medium	Backward
3	High	Backward
4	Low	Forward
5	Medium	Forward
6	High	Forward

Table 2. Scenarios with different kinds of synchronization

Scenarios	Rescheduling Period				Synchronization
	Manufacturer (Source)	Manufacturer (Make)	Manufacturer (Deliver)	Suppliers, Warehouse, and Retailers	
7	Medium	Low	Medium	Medium	Backward
2	Medium	Medium	Medium	Medium	Backward
8	Medium	High	Medium	Medium	Backward
9	Medium	Low	Medium	Medium	Forward
5	Medium	Medium	Medium	Medium	Forward
10	Medium	High	Medium	Medium	Forward

Table 3. Scenarios with different rescheduling periods for the manufacturer

Scenarios	Rescheduling Period			Synchronization
	Suppliers, Manufacturer, and Warehouse	Retailer 1	Retailer 2	
11	Medium	Low	Low	Backward
12	Medium	Low	Medium	Backward
13	Medium	Low	High	Backward
14	Medium	Medium	Low	Backward
2	Medium	Medium	Medium	Backward
15	Medium	Medium	High	Backward
16	Medium	High	Low	Backward
17	Medium	High	Medium	Backward
18	Medium	High	High	Backward
19	Medium	Low	Low	Forward
20	Medium	Low	Medium	Forward
21	Medium	Low	High	Forward
22	Medium	Medium	Low	Forward
5	Medium	Medium	Medium	Forward
23	Medium	Medium	High	Forward
24	Medium	High	Low	Forward
25	Medium	High	Medium	Forward
26	Medium	High	High	Forward

Table 4. Scenarios with different rescheduling periods for the retailers

5. Simulation Results

This section describes the results of the simulation runs for the two supply chains. The results for Supply Chain One show the impact of varying the three rescheduling periods, the inventory policy, and the scheduling heuristic. The results for Supply Chain Two include the impact of forward and backward synchronization, varying the rescheduling period of a single activity, and varying the rescheduling periods of the retailers independent of each other.

5.1 Supply Chain One

5.1.1 Impact of Varying Sourcing Rescheduling Period

The sourcing rescheduling period affects the inventory performance and hence the availability of raw materials for production. Figure 3 gives the bar chart representation of the average values for the performance measures at the manufacturer. A stage by stage representation is given in Figure 4. For rescheduling periods in the range of 0.1 to 48 hours, there is no significant change in the overall cycle time. For values higher than this, the overall cycle time starts to rise steeply. This is due to the shortage of raw materials. Moreover, when sourcing is done at very large intervals, the order size tends to be larger. Suppliers take more time to supply larger orders, as the production time is dependent on the order size. Another effect that can be noticed is the

increase in the cycle time for the second stage at higher rescheduling periods. This stage corresponds to the time an order spends in the shop floor. At higher sourcing rescheduling periods, there is frequent shortage of raw materials. This leads to a number of orders pending for production. When a sourced order arrives at the manufacturer, all the orders that can be produced with this new supply are released on to the shop floor. This puts excessive pressure on the limited capacity of the shop floor, leading to increased congestion and longer manufacturing cycle times.

5.1.2 Effect of Varying Production Rescheduling Period

Varying the production rescheduling period affects the time between order receipt to release for production and the production duration. Figure 5 shows that there is no significant effect on the overall performance of the system until the rescheduling period reaches 24 hours. Figure 6 shows that the order receipt to start build cycle time varies in this range, but the overall effect due to this increase is not very significant. Under efficient inventory management, the increase in the time between order receipt to start build varies linearly as the production rescheduling period increases. Figure 5 illustrates this, as the order receipt to start build cycle time for each scenario is approximately half the production rescheduling period. On the other hand, the effect on production duration is more unpredictable. The number of orders released for production in a rescheduling cycle depends upon the production rescheduling period. As the rescheduling period increases, more orders are released at once to the shop floor, which increases congestion and manufacturing cycle time. Figure 5 shows that the start build to ready for shipment cycle time increases at very high values for production rescheduling periods. On the other hand, for production rescheduling periods in the range from 0.1 to 24 hours, this effect is not present. These increases in cycle time also increase the percentage of tardy orders.

5.1.3 Effect of Varying Delivery Rescheduling Period

Figure 7 shows the impact of varying the delivery rescheduling period. Figure 8 plots the two delivery activities that are affected by the rescheduling period. Delivery rescheduling period affects both the average time for release of orders for delivery and the actual time for delivery. These two are plotted for the eleven scenarios. The effect is very similar to the one discussed before for increase in production rescheduling period. Whereas the increase in the average time an order stays in the finished goods inventory is directly proportional to the delivery rescheduling period, the increase in delivery time is dependent on the number of transporters available. The percent of delayed orders rises at high values of delivery rescheduling periods.

5.1.4 Effect of Varying Inventory Policy

Figure 9 shows the impact of changing the reorder point on the performance of the manufacturing system. Reducing the reorder point has little impact on the performance for any of the rescheduling periods. The values for five-day reorder level model are slightly higher than the corresponding original model for the order release cycle time. But this difference is quite insignificant when compared to the overall cycle time. At lower rescheduling periods, the effect is not very significant since even with five-day reorder levels, the inventory is usually sufficient to cover the demand during the supplier's lead time. At higher rescheduling periods, the two

systems behave almost identically. This is because at high rescheduling periods, both the systems will place sourcing orders during each cycle and when an order is placed, the order quantity is decided by the order up to quantity. The order up to quantity is the same for both the models. Hence in the current comparison, there is no significant difference in the performance of the two systems. For lower sourcing rescheduling periods, the five-day reorder level system would result in less inventory and fewer number of sourcing orders and hence should be preferable.

5.1.5 Effect of Varying Scheduling Heuristic

Figure 10 shows that for lower rescheduling periods, there is no significant difference between the performances of the two scheduling heuristics. At high rescheduling periods, the SPT heuristic performs better than the FIFO heuristic. At very high production rescheduling periods, the system releases a large number of orders for production simultaneously. SPT processes orders that need lower processing time first; thus leading to a decrease in the total waiting time. This results in a better overall cycle time performance. The orders become tardy due to the increased congestion. Expediting the orders with lower processing times leads to a decrease in the average waiting time. This leads to a drop in the percentage of orders that get tardy.

5.2 Supply Chain Two

5.2.1 Impact of Synchronization

Figures 11, 12, and 13 show the difference in supply chain performance due to two kinds of synchronization. The figures show the variation of average cycle time with respect to rescheduling period for three different participants of the supply chain. In all three cases, the average cycle time corresponding to forward synchronization is greater than the average cycle time for backward synchronization, for all the rescheduling periods. We also see that the gap in cycle times increases as the rescheduling period is increased.

The general increase in cycle times at higher rescheduling periods is due to two reasons: the additional delay in processing information and the larger order size. At higher values of rescheduling periods, sourcing, production, and delivery planning are carried out less frequently and this leads to an increase in the time delay for processing the information. Also, at higher rescheduling periods, inventory replenishment orders are placed at larger intervals in time, reducing the number of orders. Since the overall demand at any participant does not change, fewer numbers of orders leads to an increase in the average order size. As the production time is directly proportional to the order size, a larger order on an average takes more time in the shop floor. This results in an increase in the average cycle time.

For Supplier 1, the difference in the average cycle time is nearly equal to the rescheduling period. For the manufacturer, this difference is more than the rescheduling period for the medium and high values. This extra difference is due to the shortage of raw materials. In the case of backward synchronization, even at higher rescheduling periods, all the orders that are processed in any planning period for a participant are made available before that participant carries out his planning activities. This enables the participant to place sourcing orders in time. On the other hand, in forward synchronization, sourcing requirements for a particular participant are conveyed

to that participant only after the participant has carried out planning activities for the period. This puts excessive pressure on the on-hand inventory at the manufacturer. The probability of the manufacturer running out of raw materials is higher for forward synchronization than for backward synchronization. This leads to an increase in the average cycle time. Hence the difference in the average cycle times for the manufacturer is a combination of the delay in processing information and the shortage of raw materials. As the supplier does not experience shortage of raw materials, this additional difference is not seen in Figure 11.

For Retailer 1, the effect due to synchronization is a combination of the effects at the other participants. As the two customers place orders with the retailer at random intervals, there is no difference between the ways the orders get processed by the retailer under the two scenarios. But since Product 2 and Product 3 are make-to-order, demands for these products are passed on as sourcing orders to the warehouse or the manufacturer. As the average cycle time at the manufacturer and the retailer increases at a more rapid rate in forward synchronization than in backward synchronization, the difference between the average cycle times starts to grow. Moreover, for Product 1, which is make-to-stock, the probability of a stock-out is higher at higher values of rescheduling periods. Since order replenishment takes more time under forward synchronization than under backward synchronization, stock-out related increase in cycle time also starts to contribute to the difference at higher rescheduling periods.

The performance for the other suppliers is very similar to that of the Supplier 1. The values corresponding to the warehouse follow the same pattern as the manufacturer. The two retailers have similar performance. Hence we consider only three participants for our discussion of the results.

5.2.2. Effect of Varying Manufacturer's Production Rescheduling Period

Figure 14 shows the impact of varying the rescheduling periods of production activity at the manufacturer while maintaining all the other rescheduling periods at a value of 24 hours (under backward synchronization). There is no significant difference in the performance of any of the participants except the manufacturer when the production rescheduling period at the manufacturer is varied in the range of 4 to 72 hours. There is no change in performance of the suppliers, as production rescheduling at the manufacturer does not lead to any changes in the sourcing. The sourcing pattern at the manufacturer remains the same in all the three cases.

At the manufacturer, the average cycle time does not rise in the range from 4 to 24 hours. In fact, there is a slight drop in the average cycle times, but this drop is not significant as observed from the 90% confidence interval values. From 24 to 72 hours, there is nearly a one-day increase in the average cycle time. This difference is significant. The difference can be explained as follows: In the 24 hours case, since the warehouse and the retailers place their orders before the manufacturer carries out his production planning, there is no delay in the processing of the orders. This is because the results correspond to backward synchronization. When the production rescheduling periods is increased to 3 days, one third of the orders are processed immediately, one third of the orders encounter a delay of 1 day, while the remaining one third takes 2 days to get processed. Thus the average delay encountered is one day. This is reflected in the increase in the cycle time.

Compared with the performance of Supply Chain 1, it can be noticed that the effect of varying the production rescheduling period is much less significant for this supply chain. This is primarily due to the effect of rescheduling periods of other activities. In the case of Supply Chain 1, the rescheduling periods for all the other activities were maintained at 4 hours. For Supply Chain 2, the rescheduling periods were maintained at 24 hours. In addition, there is synchronization between activities. So decreasing the production rescheduling period below 24 hours does not improve the performance. Moreover, from 24 to 72 hours, the change is not as significant as that for Supply Chain 1 since the rescheduling periods for other activities are higher in Supply Chain 2.

At the retailer and the warehouse, there is no significant change in the average cycle times. At the warehouse, two out of the three products are sold on a make-to-stock basis. So except in the case of backorder, the warehouse cycle time for these two products do not depend on the cycle time of the manufacturer. In all the three cases of rescheduling periods, the inventory policy effectively guards the warehouse against backorders. Product 3 is make-to-order. But the orders for Product 3 are placed directly with the manufacturer. Hence for the warehouse, cycle time for Product 3 depends only on the time that the product spends at the warehouse. This time is not dependent on the manufacturer's production rescheduling period.

At the retailer, Product 1 is make-to-stock and the warehouse supplies Product 2. The inventory policies at the retailers and the warehouse ensure that the manufacturer's production rescheduling period does not affect the cycle times of these two products. For Product 3, the cycle time increases with increase in the manufacturer's production rescheduling periods, as the product has to be supplied from the manufacturer based on make-to-order policy. The retailer has to place an order with the manufacturer and then the manufacturer has to start manufacturing the product. But the increase in the manufacturing cycle time is very small when compared with the overall cycle time for Product 3. Hence we notice that there is no significant change in the cycle time at the retailer. Results for Retailer 2 are very similar to that of Retailer 1 and hence are not shown.

5.2.3. Effect of Varying the Rescheduling Periods of Retailers Independent of Each Other

Figures 15, 16, and 17 show the impact of varying the retailers' rescheduling periods. The results correspond to backward synchronization. Figure 15 shows the cumulative effect on the average cycle times at the Supplier 1 (S1), the Manufacturer (M), and the Warehouse (W). Average cycle times corresponding to four stages is shown for each participant. Stage 1 indicates the order receipt to start build stage. Stage 2 is the start build to finished goods stage. Stage 3 is the finished goods to release for delivery stage. Stage 4 is the release for delivery to customer receipt stage.

Figure 15 shows that the sum of the average cycle times remains approximately the same for all the scenarios in which both retailers have a rescheduling period less than 72 hours. In the remaining three scenarios, Retailer 1 has a rescheduling period of 72 hours, and the sum of the cycle times is higher. The sum of average cycle times is the highest when both the retailers have a rescheduling period of 72 hours. The performance of the manufacturer and the warehouse are

directly dependent on the order size at the retailers. Since Retailer 1 receives the majority of the customer orders, a high rescheduling period at this participant has a significant effect on the performance of the supply chain, irrespective of the rescheduling period of Retailer 2. When both the retailers place orders once every 72 hours, the warehouse also places orders with the manufacturer at that frequency, though the warehouse carries out sourcing planning every 24 hours. So the average order size at the warehouse tends to be much higher and this leads to an increase in the average production time at the manufacturer. This has a significant effect on the sum of the average cycle times. As can be seen in Figure 15, the increase in the cumulative cycle times is largely due to the increase in the production cycle times at the manufacturer. The cycle times do not rise significantly when the rescheduling period of Retailer 2 is increased from 24 to 72 hours, provided the rescheduling period for Retailer 1 is not high. This is because the demand at the second retailer is considerably lower than that at the first retailer. So even if this retailer carries out rescheduling activities at longer intervals, the sourcing order size does not grow proportionately. Therefore, the change in rescheduling period at this retailer does not have a noticeable impact on the performance of other participants. In scenarios where the rescheduling period for Retailer 1 is 72 hours, but that for Retailer 2 is lower, the warehouse gets to place orders with the manufacturer during every sourcing planning cycle. This is so because Retailer 2 places orders at a frequency more than or equal to that of the warehouse. This leads to a smaller average order size at the manufacturer, and hence the average cycle time at the manufacturer does not increase much.

Figures 16 and 17 show the average cycle times at the retailers. The average cycle times at a particular retailer are dependent directly on the rescheduling period at that retailer. As the rescheduling period is made larger, the average cycle times increase. There is no significant dependence of one retailer on the rescheduling period of the other. The only place where there is a noticeable change is the case where both the retailers have a high rescheduling period of 72 hours. Here, the cycle times for both the retailers are higher than the other scenarios with a high rescheduling period for just one retailer. This difference is significant under 90% confidence interval. The difference is due to the increased average cycle times at the manufacturer. When both the retailers carry out rescheduling activities at an interval of 72 hours, the order size from the warehouse tends to be larger. So the manufacturer takes more time to satisfy the orders. The retailers depend directly on the manufacturer's cycle time for Product 3. Though the product is stocked at places other than the manufacturer for Product 1 and Product 2, a large increase in the cycle time at the manufacturer leads to more frequent stock outs at the warehouse and the retailers. These together lead to a significant increase in the cycle time at the retailer.

6. Summary and Conclusions

This paper describes the performance of two different supply chains under varying conditions of rescheduling periods. The first supply chain has five participants, including two suppliers, one manufacturer, and two customers. The second supply chain has ten participants, including four suppliers, one manufacturer, one warehouse, two retailers, and two customers. In both supply chains, customers place orders for various products at random intervals, and the products are delivered to the customer either on a make-to-stock or on a make-to-order basis.

We observe from the results that the functioning of a supply chain is very complicated. The complexity increases as the number of participants in the supply chain increases. The frequency of planning activities is an important factor that needs to be considered while analyzing any supply chain. Simulation models are a useful way to quantify this impact.

In Supply Chain 1, rescheduling periods play a much more important role than inventory and production policies. A high rescheduling period at a particular activity may have adverse effect on the performance at downstream activities too. The improvements obtained by reducing the rescheduling periods are not significant beyond a certain point. Note also that reducing rescheduling periods increases the effort spent creating plans.

In Supply Chain 2, the synchronization of activities across participants of the supply chain has significant impact on the performance. Backward synchronization improves the performance of the system significantly. Backward synchronization can be implemented with the help of a supply chain management system in which all the participants share information with their upstream participants so that the participants can coordinate in a way that would benefit the performance of the entire supply chain. This type of coordination is feasible only if the participants have significant incentives to share information. The establishment of such incentives is a difficult challenge in supply chain leadership.

In Supply Chain 2, like in Supply Chain 1, longer rescheduling periods increased the cycle time of each participant. The study of Supply Chain 2 also showed how rescheduling frequency at downstream participants can affect the performance of upstream participants. We saw that a high rescheduling period at retailers led to an increase in the cycle times at the manufacturer due to larger order sizes. This shows that for a supply chain to achieve optimal performance, all the participants should coordinate.

Both supply chains indicate the significance of information flow within a participant and across participants in supply chains. While having enough capacity and manpower are important for good performance, planning activities should also be properly managed.

7. Acknowledgements

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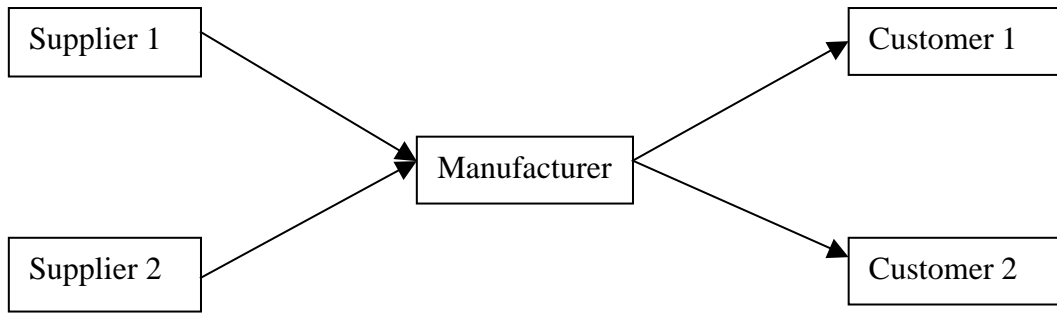


Figure 1. Supply Chain Network

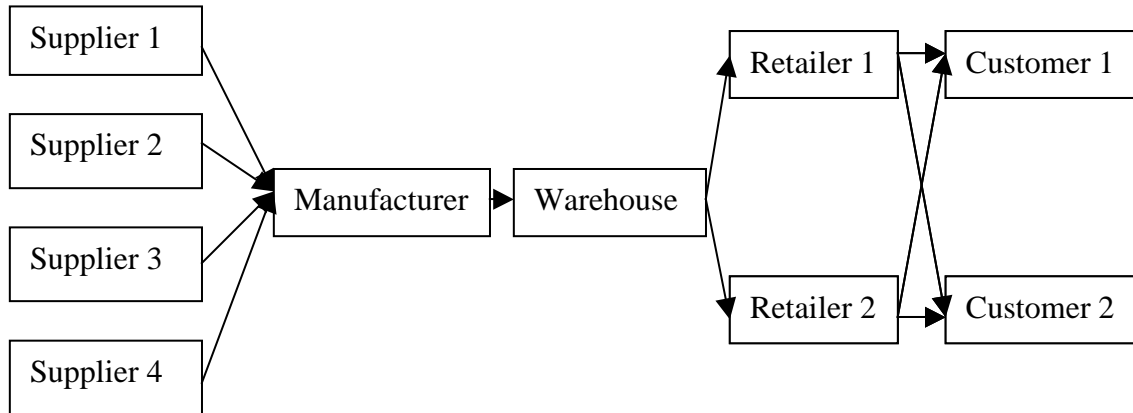


Figure 2. Supply Chain Network

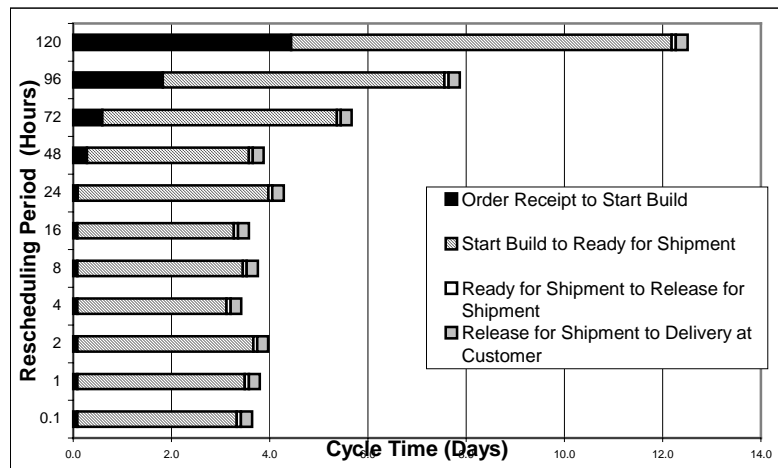


Figure 3. Cycle time and sourcing rescheduling period

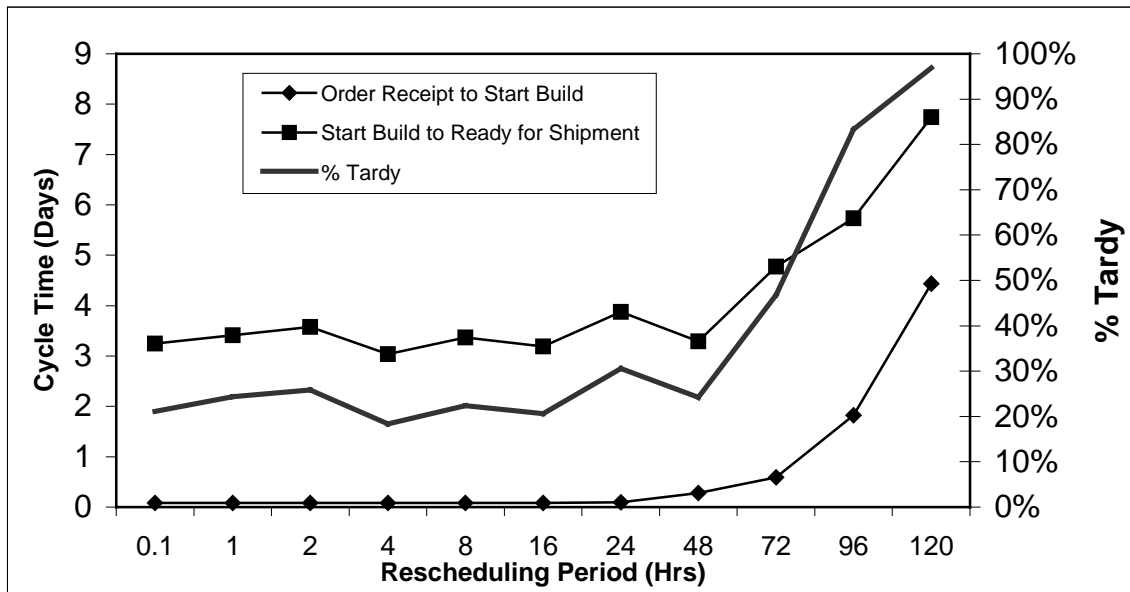


Figure 4. Effect of sourcing rescheduling period on raw material availability, production variability and due date performance

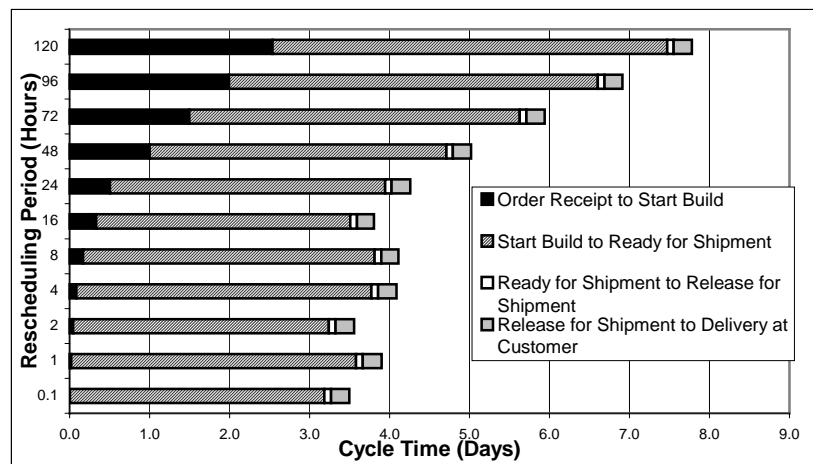


Figure 5. Cycle time and production rescheduling period

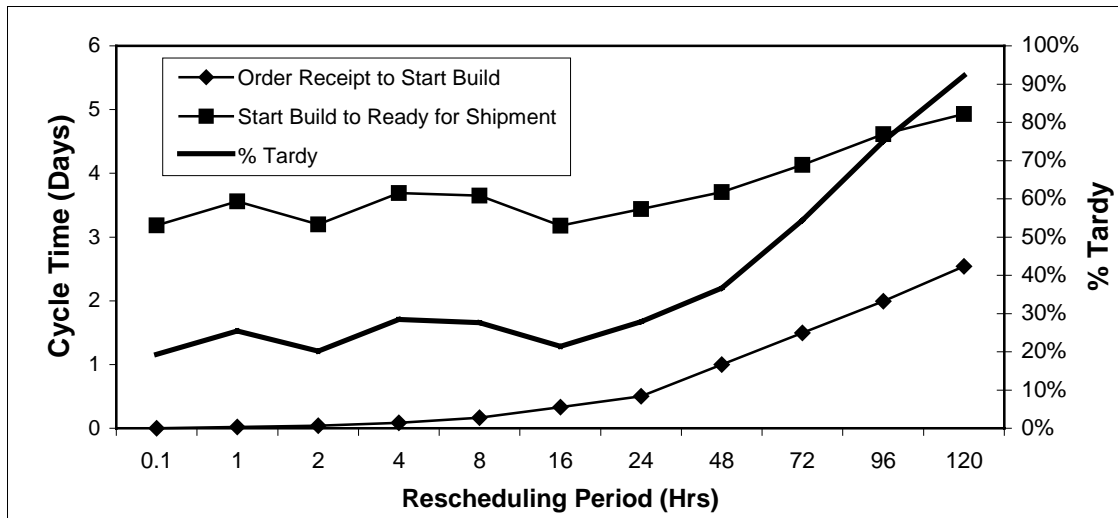


Figure 6. Effect of production rescheduling period on order release delay, production variability and due date performance

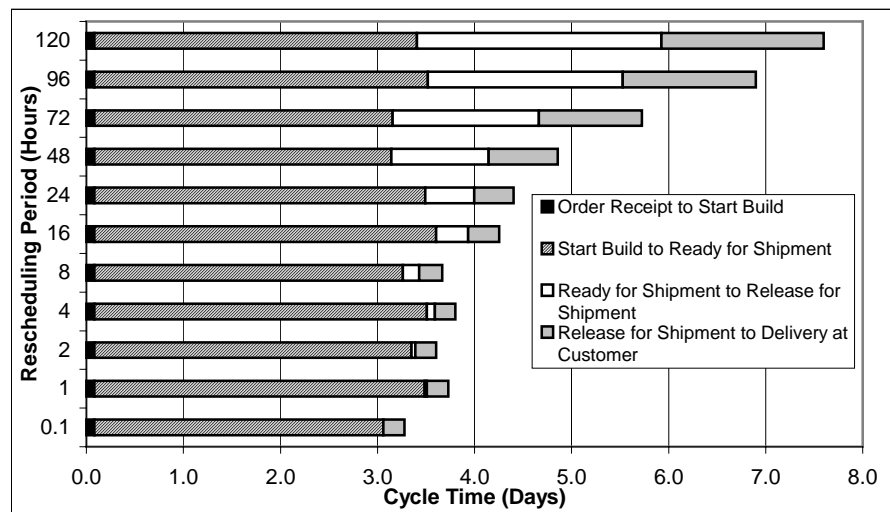


Figure 7. Cycle time and delivery rescheduling period

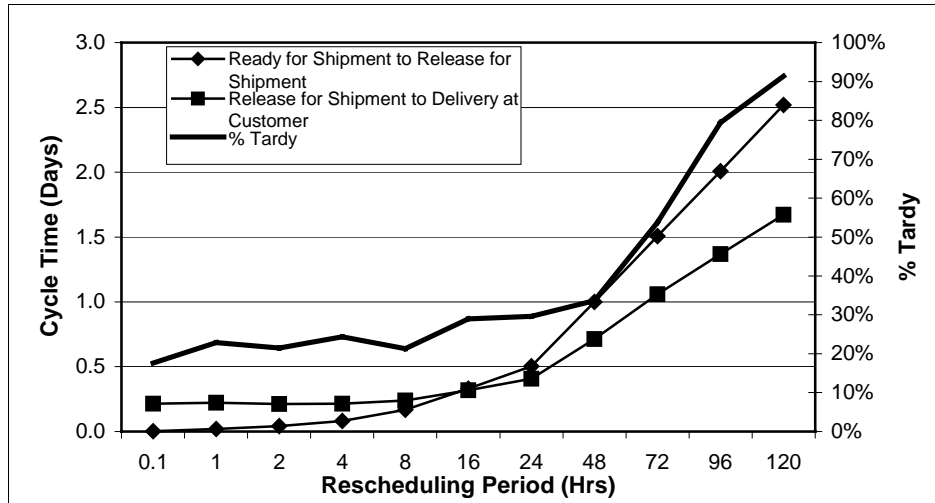


Figure 8. Effect of delivery rescheduling period on delivery release delay, delivery variability and due date performance

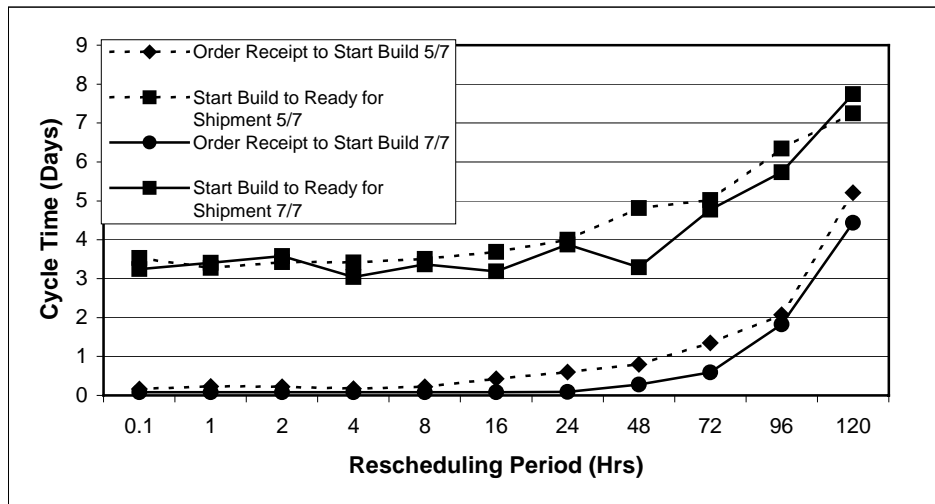


Figure 9. Comparing the performance under two different inventory policies

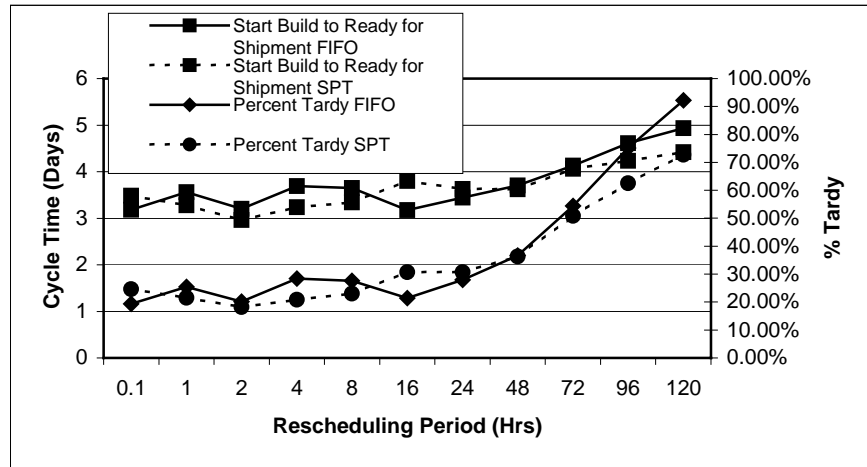


Figure 10 Performance of the manufacturing system under two different production policies

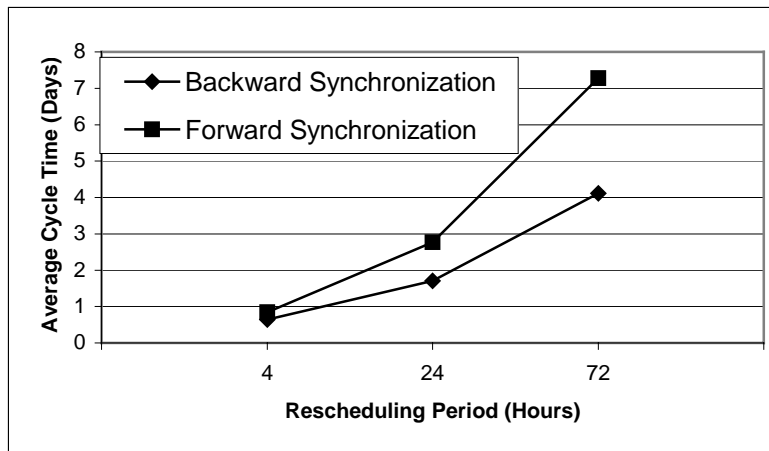


Figure 11. Effect of Synchronization: Supplier 1

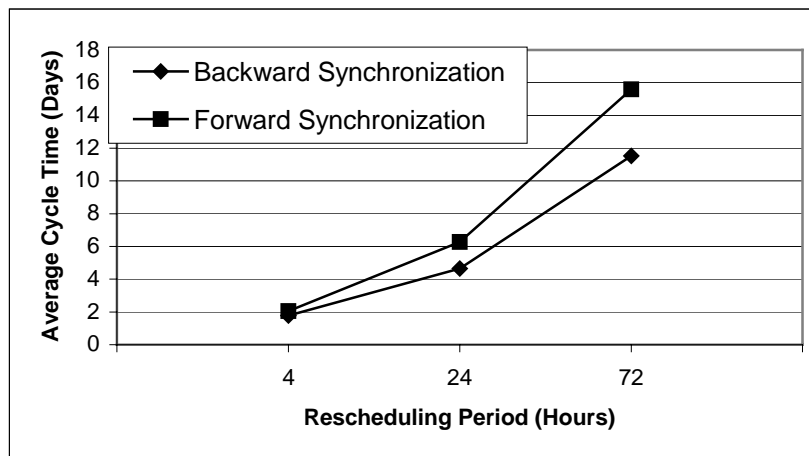


Figure 12. Effect of Synchronization: Manufacturer

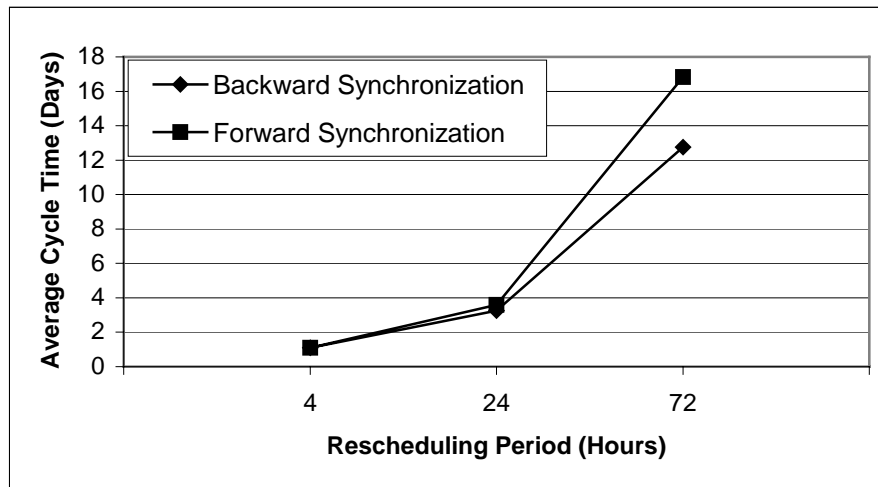


Figure 13. Effect of Synchronization: Retailer 1

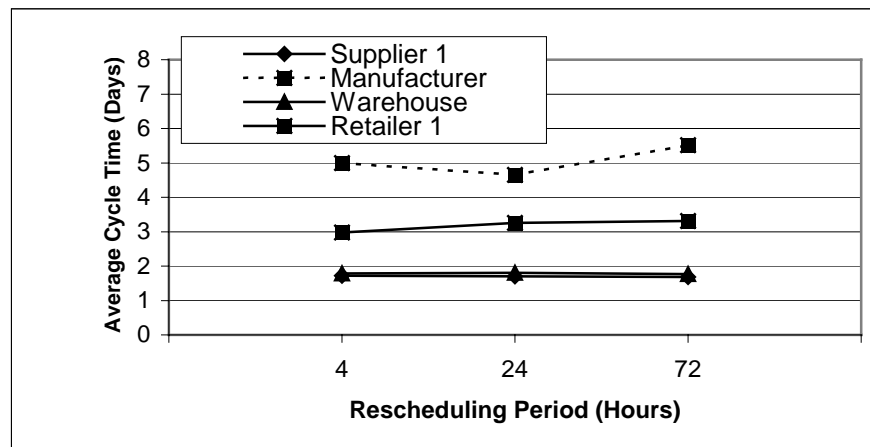


Figure 14. Effect of Varying Manufacturer's Production Rescheduling Period

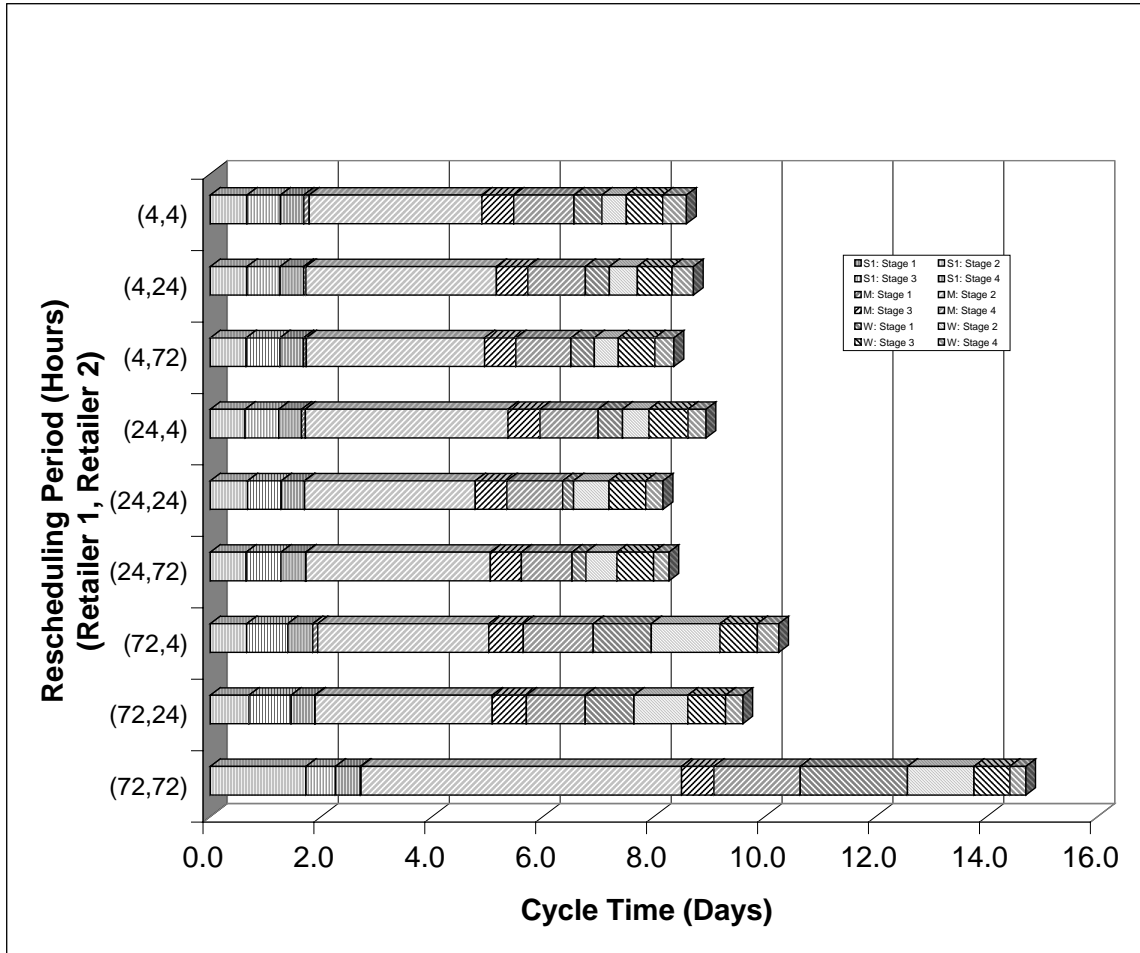


Figure 15. Effect of Varying the Rescheduling Periods at the Retailers

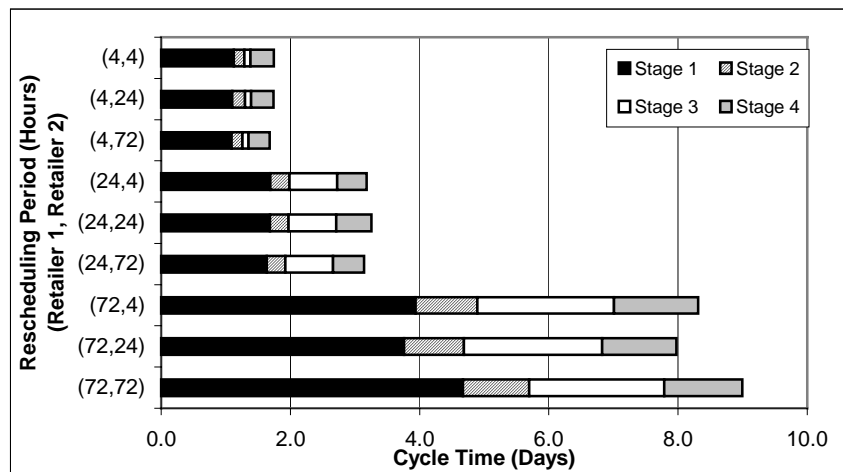


Figure 16 Effect of Varying the Rescheduling Periods at the Retailers on Retailer1

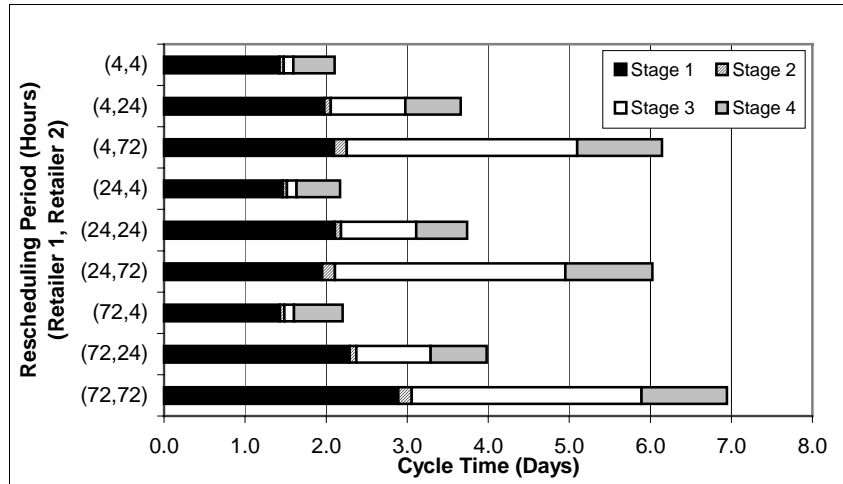


Figure 17 Effect of Varying the Rescheduling Periods at the Retailers on Retailer2