MASTER'S THESIS

Supply Chain Simulation Models for Evaluating the Impact of Rescheduling Frequencies

by Guruprasad Pundoor
Advisor: Jeffrey W. Herrmann

MS 2002-9

DEDICATION

To my Parents

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to **Dr. Herrmann**, my advisor, whose guidance, enthusiastic support, and advise throughout this research project is invaluable. Every minute that I spent with him in meetings and discussions was productive.

I would also like to thank **Dr. Lin** (CIM Lab) for guiding me through the initial phases of the project and for helping me get through technical difficulties. I would like to acknowledge the contribution of **Dr. Zhao** (R. H. Smith School of Business) during Spring 2001, when I worked with Mr. Jens and Ms. Jana from the business school. I would also like to thank ***ISRHelp*** for providing me with all the technical help on time.

I am grateful to **Dr. Ball** and **Dr. Chen** for accepting to be on my thesis committee.

Thanks are also due to my roomies and other friends who made my stay here for the last two years very memorable. Last but not least, very special thanks to my parents who helped me in all the phases of my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

1.1. Systems Engineering

A system is a combination of elements or parts forming a complex or unitary whole (Blanchard, 1998). With complicated systems, it is not easy to consider each and every aspect without some systematic procedure. Systems engineering tries to adopt a goal centered and systematic approach to analyze and integrate all the aspects of a system.

The primary goal of systems engineering is to ensure that the system satisfies its requirements throughout the life cycle. The life-cycle of a system starts with requirements analysis. In this stage, the functions that the system is expected to perform are elicited. Once the system requirements have been laid out, system design and development are carried out. This evolves through conceptual design, preliminary systems design, and detailed design of the system (Blanchard, 1998). Testing and evaluation of models of the system are carried out at this stage. Upon completion of design and development of a system, the system is implemented.

Every system has components, attributes, and relationships (Blanchard, 1998). Components are the operating parts of a system consisting of input, process, and output. Attributes are the properties or discernible manifestations of the components of a system. Relationships are the links between components and attributes. Systems can be represented as network, layered, or hierarchical structures (Austin and Frankpitt, 2000).

A network is a set of modules that are connected by a set of interfaces for communication. In a hierarchical structure, the components of a system may themselves be systems, and every system may be part of a larger system hierarchy. A layered system is one where the hierarchy of system components is clustered into horizontal strata.

1.2. System Modeling and Simulation

A model represents a system and the essential relationships involved (Blanchard, 1998). Model building can be defined as the process of deriving a model for the real life system, given information regarding the real system. It is not always possible to experiment with a real life system. Models are useful to obtain information about a system being designed, when it is hard or impossible to experiment directly with a prototype (Herrmann, 2001). Decisions and improvements can be made based on the analysis of the model.

Development of system models can be broadly divided into two categories: Top down and bottom-up. In top down design, the highest level of the design is brought out first and the detailed design of parts of the system is deferred to a later stage. The problem is decomposed into modules as more and more details are obtained in the course of solving the problem. In bottom-up design, the problem is solved as independent modules and then put together. One of the major drawbacks of top down design is that it does not allow for reuse of modules. At the same time, having a good overall picture of the system is important and this cannot be captured effectively in bottom-up development. Hence a combination of these two approaches is usually used.

Figure 1.1 shows how a model helps make decisions in real life systems. The model of the system is built and experiments are carried out on the model. The output from the model is analyzed and mapped to the performance of the real world system. If the performance is as desired and satisfies the requirements of the problem at hand, then the solution is implemented in the real world system.

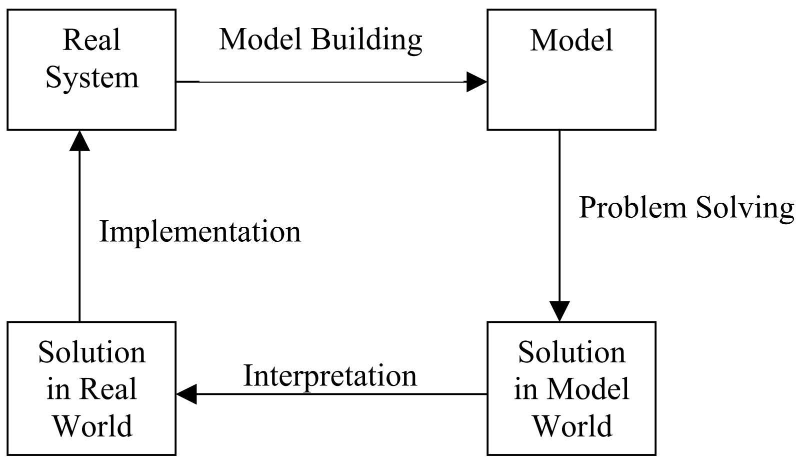

Figure 1.1. System Modeling (Pichler, 1992)

Simulation is an approach in which a model of the system is built so that one can experiment with the various scenarios that might occur during the life cycle of the system. A simulation model is behaviorally equivalent to the real life system. One way of simulation is to build computer simulation models where computer programs imitate the behavior of the system. Simulation is a form of mathematical modeling. Another approach using mathematical modeling is the analytical approach.

Building a proper simulation model for any system consists of a number of steps. The process starts with properly defining the problem and system at hand and ends with implementing the results in the real world system. The following are the steps in a typical simulation study (Law and Kelton, 1991):

1. Formulate the problem and plan study.
2. Collect data and define model.
3. Check validity of data.
4. Construct computer program.
5. Make pilot runs.
6. Check validity of the model.
7. Design experiments.
8. Run experiments.
9. Analyze output data.
10. Document, present, and implement results.

1.3. Supply Chain and Simulation

A supply chain is a dynamic, stochastic, and complex system that might involve hundreds of participants. It can be defined as a network of suppliers, manufacturers, distributors and retailers, who are collectively concerned with the conversion of raw materials into goods that can be delivered to the customer. Three kinds of flow are to be considered in any supply chain: material flow, information flow, and cash flow. Material flow refers to the flow of material from the supplier to the retailer that involves converting the raw material into finished product, and finally, delivery to the customer.

This includes the transportation of products from one participant to another and the movement of raw materials in the shop floor. Information flow refers to the data that are recorded or read every time a change in the system status occurs. For example, every time a customer places an order, information is generated that is recorded in the customer order table. Cash flow is the flow of money in the supply chain. Examples include assigning costs to job orders and applying direct labor and overhead rates to products.

For simulating a supply chain, it is necessary to consider all three kinds of flows. It is also important to model precisely the interaction between the various participants. In addition, both planning and execution activities are to be considered. Typical activities include inventory management, production management, and delivery of finished goods.

The optimal performance of any particular participant in a supply chain depends to a large extent on the performance of the other participants. The difference between the analysis of a manufacturing system and a supply chain lies in the level of detail at which the analysis has to be carried out. Optimizing the performance of the production system or delivery system of a participant is important, but for improving the overall performance of a supply chain, it is necessary to view the system as a whole. This makes the problem very complicated. Coordination between the participants of a supply chain is very important.

Supply chain simulation is very useful in the decision making process either for implementing a new supply chain or for making changes to an existing one. The decisions that are usually taken before planning on the implementation of any supply chain can be classified into two categories: structural and operational. Structural decisions affect the long-term performance of the supply chain. This could be regarding the location of a particular distributor or selection of the capacity of a particular manufacturer. Operational decisions correspond to the short-term decisions. Examples include reorder levels for a particular item in the inventory, and rescheduling frequency. Simulation can be used as a tool for carrying out the decision making process for both structural and operational decisions.

Each participant of the supply chain may have his own set of activities. Despite differences between these activities, a number of processes are common to the participants of the supply chain. These processes can be explained using a common set of terminologies. This enables the principle of reuse in bottom-up development of a model. If the commonality between the participants can be explored, a set of modules can be built that can be put together to represent the various activities of the participants. Then these participants can be put together with proper interfaces to obtain a model for the entire supply chain.

With the current tools, it is very difficult to build a simulation model for a supply chain due to the large number of activities that have to be modeled. Discrete event simulation packages are available that can be used for this purpose, but they do not provide custom made modules for supply chain simulation. Most of the packages provide modules such as processes, queues, and transporters. These basic modules have to be combined in a bottom-up manner to build a supply chain simulation model. This way, a lot of effort is required even to build a very simple supply chain. Thus the analyst is left spending a lot of time on model building rather than analyzing the performance for making decisions. Moreover, when reusable modules are not available for supply chain simulation, it becomes difficult for the analyst to change the structure of the supply chain in order to evaluate the alternatives. Availability of custom-made modules can reduce this effort to a great extent.

1.4. Objectives of the Research

One of the objectives of this work is to build reusable modules that can be used to represent supply chains. The primary focus is reusability, and hence emphasis is laid on the standardization of modules. Using these modules, supply chain simulation models can be built with great flexibility with very little effort. In the present work, Arena, a discrete event simulation software, is integrated with Microsoft Excel using Visual Basic for Automation (VBA). Standardized Visual Basic procedures have been written that can be reused to build supply chains.

A systems-level view of material planning and control operations has been adopted for building the modules. The supply chain modules address an array of decisions affecting the system. Decisions made in one part of the system may affect the course of decisions in another part of the system. The level of detail at which the modeling is to be carried out is an important issue. For example, a manufacturer can be modeled at a very low level of detail, representing each machine and flow line in the shop floor, or it can be modeled at a very high level with just a simple process block for the entire operation of manufacturing. The problem with modeling at very low levels of detail is that the model becomes too problem specific and the flexibility is lost. At a very high level, the model may not be able to capture all the aspects of the problem accurately. In the present work, the objective is to model the supply chain at a level of detail that is not too low to make it very specific, and at the same time including all the necessary information so that the model is accurate.

Another objective of the work is to analyze the effect of rescheduling frequency on the performance of the supply chain. Order release decisions control the flow of work in a supply chain system. In many supply chain systems, order release decisions are made periodically. The frequency of these decisions affects the performance of the system. Three such activities are considered: sourcing of raw materials from the supplier, releasing of orders for production, and releasing of orders for delivery.

In addition to the delay encountered in processing the information, a higher rescheduling period in planning activity has other effects. One significant effect is the lumping of orders. This happens when too many orders are released at a time. Lumping of orders puts extra pressure on the limited capacity of the system. It increases the variability. When orders are released in bulk, the shop floor might not have enough capacity to process all the orders at a time. This will result in the build up of queues and affect the performance of the system. This might lead to a chain effect and may result in a delay in downstream activities also.

Carrying out rescheduling activities has an associated cost. Keeping the rescheduling period too low might lead to very high costs. So a trade-off has to be reached between the rescheduling period and the performance. This trade-off is studied for two different supply chains. Also, production and inventory policies are varied to check if they have a more significant effect compared to the effects due to changing the frequency of rescheduling activities.

1.5. Outline of the Thesis

The reminder of the thesis is organized as follows: The next chapter gives a survey of the existing literature in the fields of supply chain simulation and rescheduling frequency. The chapter also gives an overview of literature dealing with analytical and simulation modeling of supply chains and manufacturing systems.

The chapter on simulation modeling of supply chains gives an overview of the various activities involved in the supply chain. Supply Chain Operations Reference model, proposed by the Supply Chain Council, has been followed for building the reusable modules. SCOR model divides the activities of a supply chain into various categories in an effort to make them standardized. This approach is explained in Chapter 3. The chapter also details the procedure and tools adopted for carrying out the simulation. The various features of the simulation model including the performance measures are explained in Chapter 3.

Chapter 4 deals with the analysis of the effect of rescheduling policy on the system performance. Two separate supply chains have been built and analyzed. One of the supply chains has two suppliers, one manufacturer, and two customers. The other supply chain has four suppliers, one manufacturer, two distributors, two retailers, and two customers. The results from both these supply chains are given in this chapter.

Chapter 5 presents the summary of the results and the conclusions. The limitations of this work and scope for further work are discussed in this chapter.

2. Literature Review

A large body of literature exists on the modeling of manufacturing systems and supply chains. Mathematical models have been developed that integrate two or more activities within a particular participant or between participants. This chapter gives an outline of the literature reviewed for the purposes of this work. In Section 2.1, a review of the literature on supply chain simulation is given. Section 2.2 discusses supply chain simulation frameworks that have been proposed in the past. Section 2.3 deals with research related to rescheduling frequency in the shop floor. This section also discusses works dealing with rescheduling periods under uncertainty in activities. Section 2.3.2 gives details of rescheduling research in supply chains and MRP systems. A summary of the review is given in Section 2.4.

2.1 Analytical Modeling of Supply Chain Systems

There is extensive literature available on the analysis of supply chains. Two of the most common ways of analyzing a supply chain are through simulation and analytical modeling. On the analytical front, efforts have been made to integrate two or more activities and solve them together. The major activities of a supply chain include sourcing of raw materials, manufacturing the product and distributing the finished product. Literature is available that considers combinations of these activities. One of the earliest attempts at solving a combined problem was by Folie and Tiffin (1976). In the paper, an optimization algorithm is developed for an actual multi–product production and distribution problem. The problem deals with determining the distribution of products among the factories of a company and the warehouse to which products are delivered. The objective is to minimize the overall production and distribution costs. Williams (1981) describes heuristic algorithms for joint production–distribution scheduling problem. Cohen and Lee (1988) developed an analytic procedure for evaluating the performance of production–distribution systems. One of the more recent contributions is by Dhaenens-Flipo and Finke (2001). This paper formulates the production–distribution problem in the form of a network flow problem. The problem is formulated for a given number of plants and production lines. It tries to solve multi-facility, multi-product and multi-period industrial problem considering the production and distribution costs.

In the analytical method, as the problem size increases, obtaining solutions becomes more difficult. Moreover, even for reasonable sized problems, it is not easy to consider all aspects of the problem in analytical solutions, especially the uncertainty. This is where simulation approach is preferable. It is easier to imitate the real life problem in a simulation model. Simulation approaches take into account the uncertainty of the system. Softwares are available that can be used to build simulation models with great ease. Swaminathan, Sadeh and Smith (1995) studied the influence of sharing supplier capacity information on the performance of a supply chain. They use simulation for comparing different information sharing scenarios after deriving the optimal inventory policy for the manufacturer under stochastic demand. Towill, Naim and Wikner (1992) conducted simulation study to analyze the effect of system redesign strategies on the performance of a supply chain. They simulate a supply chain with three echelons: factory, distributor, and retailer. The various strategies tested include the effect of integrating information flow throughout the supply chain and removing the distributor echelon.

2.2 Supply Chain Simulation Framework

General-purpose discrete event simulation software cannot be directly used for simulating supply chains. The simulation modules provided in the software should be combined or modified to represent the activities typical to supply chains. Bhaskaran (1998) performed an analysis of supply chain instability for an automobile industry. In this study, it is shown how supply chains can be analyzed for continuous improvement opportunities using simulation. For building the simulation model, an automobile supply chain simulation software originally developed to GM's specifications was used. This supply chain simulation software could be used to study the impact of many production control and material management policies on important measures such as inventory levels, forecast stability, and material shortages.

In supply chain modeling, effort is made to consider the effect of policies on the performance of the supply chain. The effects of policies are tested either analytically or through simulation. In the case of simulation for supply chains, effort involved in building the supply chain simulation model can be reduced to a great extent if the models can be built hierarchically from existing modules. Eliter *et al* (1998) worked on the concept of Agent Programs. An agent consists of a body of software code that supports a well-defined application programmer interface and a semantic wrapper that contains a wealth of information. As part of the work, the team developed agents for various functions of supply chain management systems. A simulation model of a supply chain application based on agents was built using commercial softwares such as Microsoft Access and ESRI's MapObject. Swaminathan *et al* (1998) describe a supply chain modeling framework that can be used for constructing supply chain simulation models. They have developed software components for representing various types of supply chain agents such as retailers, manufacturers and transporters. The authors divided the set of elements in their supply chain library into two categories: Structural Elements and Control Elements. Structural elements correspond to agents (eg. manufacturer agents, transportation agents) and control elements correspond to the control policies.

Jain *et al* (2001) observe that the level of detail included in the development of a simulation model should be appropriate to the objective of the study. They conclude that inclusion of more detail than necessary can easily lead to too large an effort for the objective at hand and the effort not being approved by the parent organization. As part of the work, the authors developed a high level supply chain simulation model using a general-purpose simulation model. Their justification for using general-purpose simulation software instead of a commercially available supply chain simulation tool was that general-purpose simulation software lets the user select the desired level of abstraction. IBM Supply Chain Simulator is one of the commercially available packages for simulating supply chains.

Supply-Chain Operations Reference (SCOR) model (2000) has been developed to describe the business activities associated with all the phases of satisfying a customer's demand. This model was developed by Supply Chain Council. One of the primary objectives of this model is to provide a standard framework for describing the activities associated with supply chains. SCOR model divides the business activities into four basic *process categories*: Source, Make, Deliver, and Return. These *process categories* are further divided into *process elements*. This provides a good standardized framework for defining the activities of a supply chain. Barnett and Miller (2000) describe how SCOR model provides the process structure necessary to understand supply chain systems. They explain how the SCOR model is implemented in e-SCOR, a commercially available supply chain simulation software based on the SCOR model.

2.3 Rescheduling Frequency

A rescheduling period refers to the interval at which the existing plans are reviewed to accommodate any changes in the system status. Determining the impact of a rescheduling policy on a dynamic manufacturing system requires careful study, modeling, and analysis of the specific manufacturing system.

Church and Uzsoy (1992) developed a hybrid event-driven rescheduling policy for single-machine and parallel-machine models with dynamic job arrivals. Their system reschedules the facility periodically, taking into account work that is already in the system. Regular events occurring between routine rescheduling are ignored until the next rescheduling moment. However, when an event is classified as an exception, immediate action is taken, with the entire facility being rescheduled and resulting schedule implemented until the next schedule generation point. To create a schedule, the system uses the Earliest Due Date rule to minimize maximum lateness. The paper also presents analytical models to bind the maximum completion time. The paper states that periodic rescheduling policies lead to near optimal performance (minimal maximum lateness) when order release is periodic. In addition, rescheduling at the arrival of a "rush" job (one with a tight due date) is useful, but more frequent rescheduling does not improve system performance significantly. Thus, if done carefully, good system performance can be maintained while reducing the rescheduling effort.

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. These papers show that rescheduling frequency can significantly affect the system performance (average flow time). A lower rescheduling frequency (which causes longer rescheduling periods) lowers the number of setups (and reduce time wasted on setups) but increases manufacturing cycle time and WIP. Event-driven and periodic strategies exhibit similar performance. Rescheduling when a machine fails or becomes available after a repair decreases manufacturing cycle time slightly but increases the frequency of rescheduling.

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. Arriving jobs are included in the schedule at the next rescheduling point, and the schedule is created using a heuristic. They conclude that rescheduling more often leads to lower setup costs. But it should also be noted that more frequent rescheduling leads to more planning expenses.

2.3.1 Rescheduling Frequency under Uncertainty in Processing Times

Muhlemann *et al.* (1982) studied the dynamic job shop scheduling problem and experimentally compared different scheduling heuristics across a range of scenarios, including rescheduling period length, the number of jobs in the backlog, and the amount of uncertainty in processing times and machine failures. They 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.

Bean *et al.* (1991) showed that the matchup algorithm (which requires more job reassignments) leads to better performance (less total tardiness) than a simple pushback strategy that simply delays tasks.

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. The simulation mechanism to select a dispatching rule is called at major disturbances (e.g. arrival of urgent jobs and major machine breakdowns) or periodically, according to a monitoring period. Several values for the monitoring periods were studied. 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. A moderate level of scheduling frequency is suggested to alleviate the negative effects of machine breakdowns.

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. According to the performance measure used, they conclude that, in loose due date conditions, the performance is not particularly sensitive to changes in rescheduling period. However, under tight due date conditions, the rescheduling interval had a much more significant effect on performance. They also show that frequent rescheduling becomes more effective as the level of uncertainty increases. With the sharp decline in the price of computer hardware and growing increases in the capabilities of production control systems, a more frequent rescheduling policy can be more easily and economically introduced. Although it could increase the computational effort, a shorter rescheduling period can improve system performance through better coordination. Herrmann and Delalio (2001) consider the effect of rescheduling period on decisions regarding batching and scheduling of sheet metal punch press operations. Their results indicate that, when material is inexpensive, decreasing the scheduling frequency can significantly reduce costs because fewer setups occur and more parts are produced from inexpensive unsheared sheets. However, when material is expensive, changing the scheduling frequency does not affect costs as much.

2.3.2 Rescheduling Period in Supply Chains

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. More frequent processing of the MRP records increases computer costs but results in fewer unpleasant surprises. The need for frequent processing must be assessed by each company in light of the computational costs, the rapidity of the decline in record accuracy, and the complexity of their products. They also mention about two kinds of record processing. The first is regeneration, where all the records are processed in one computer run. The second alternative is net change processing, where only those records that are affected by the new or changed information are reconstructed.

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.

2.4 Summary

Simulation is a useful tool for studying supply chains. Discrete event simulation packages available today are not very suitable for supply chain simulation. The amount of effort needed in building supply chain models can be greatly reduced by reusing components from supply chain component libraries. The need is for a modular approach to build the components of supply chain. The modules have to be made standardized to ensure their usage across different kinds of industries. Moreover, the modules have to be generalized. This constraint defines a level of detail for implementing the modules. If the modules are too detailed, they might become specific to a particular industry. For example, in Bhaskaran (1998), though a modular approach to building supply chain simulation models has been followed, the modules are specific to a particular type of industry. So care has to be taken to make the modules generic and at the same time, including as many features as possible.

Standardization and customization are two primary conflicting objectives. In the simulation frameworks studied, many of the packages try to provide modules for implementing supply chains. One of the primary drawbacks with those modules is that they are not standardized. Most of the packages use package specific terminologies for describing the activities of the supply chain. Another disadvantage is that even in packages that implement standard terminologies, the software acts like a black box between the model and the simulation implementation. The need is to provide a layer of standardized modules that can be easily modified by the user to implement company specific activities.

While a great deal of work has been done to determine the effect of rescheduling frequency on the shop-floor performance, not much research is available in the field of rescheduling periods for supply chains. One difficulty is that supply chains involve many different planning activities conducted by different participants. It is unclear how the rescheduling frequency of one participant will affect the performance of the entire system.

3. Simulation Modeling of Supply Chains

3.1 Introduction

A supply chain is a network of facilities that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers. A typical supply chain may consist of many participants, such as suppliers, manufacturers, distributors, retailers and the final customer. Each participant in the supply chain has his own set of objectives. Due to its inherent complexity, analytical modeling of supply chains becomes difficult. Moreover, a typical supply chain faces uncertainty in many of its activities, for example, in the supply of raw materials from the suppliers. Under such complex and uncertain situations, simulation becomes the best alternative for analysis.

Three kinds of flow have to be considered while modeling any supply chain: material flow, information flow, and cash flow. Material flow is the actual movement of the materials in the supply chain. This includes the transportation of products from one participant to another and the movement of materials within a participant. Information flow refers to the data that is recorded or read every time a change in the system status occurs. For example, every time a customer places an order with a participant, information is generated and recorded in the customer order table of the corresponding participant. Cash flow is the flow of money in the supply chain. Examples include assigning costs to job orders and applying direct labor and overhead rates to products.

Each participant of the supply chain may have his own set of activities. Despite differences between these activities, a number of processes are common to the participants of the supply chain and they can be explained using a common set of terminologies. This fact can be exploited to build standard modules that can be used for building supply chain simulation models. Instead of building models from scratch, these standardized modules can be assembled to obtain the desired supply chain network. The models can then be used to analyze different operational and strategic policies in the supply chain.

The modules have been built based on the Supply Chain Operations Reference model, Version 4.0, proposed by the Supply Chain Council. The SCOR model has been developed to describe the business activities associated with all phases of satisfying a customer's demand. SCOR is founded on four distinct management processes: *Plan, Source, Make,* and *Deliver*. Supply chains can be described using these process building blocks, which are also known as *Process Categories*. Each of these *Process Categories* is again decomposed into a lower level of detail, called the *Process Elements*. SCOR model also distinguishes between Planning, Execution and Enable level process categories. Planning processes balance aggregated demand across a consistent planning horizon. Planning processes generally occur at regular intervals. Execution processes are triggered by planned or actual demand that changes the state of products. These include scheduling and sequencing, transforming materials and services, and moving product. Enable processes prepare, maintain and manage information or relationships upon which planning and execution processes rely (SCOR Version 4.0, 2000).

The remainder of the chapter is organized as follows. The next section gives the technical details of the software used and the interactions between them. Section 3.2.1 explains the data that is necessary to initialize the model. Section 3.2.2 describes the execution of the supply chain simulation model. The cash flow section deals with the financial considerations in the model. The section on performance measures details the various performance measures that are collected during the simulation. Summary and conclusions are provided in the final section.

3.2. Model Implementation

The modules make use of Arena 4.0 and Microsoft Excel 2000. The Arena software interacts with Microsoft Excel using Arena VBA. Each participant of the supply chain has an Excel file associated with it. So whenever the VBA is called, depending on the participant to which the VBA block in Arena belongs, the corresponding Excel file is accessed and data is read or written using Excel VBA. Functions and procedures are written in Excel VBA to take care of planning activities such as allocation of raw materials for orders, and bill-of-materials explosion.

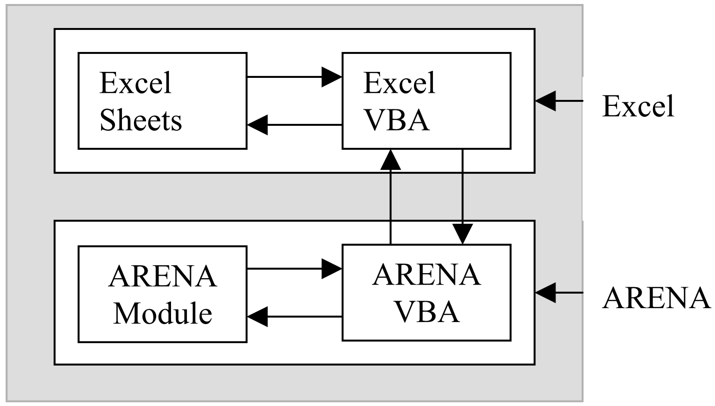

Figure 3.1. Arena Excel Interaction

For building supply chain models using these modules, the modules are put together and connected using their interfaces. So each participant in the supply chain has his own set of modules. In addition, Excel files corresponding to each participant should also be present. These Excel files and Arena modules are linked for each participant. Arena provides for hierarchical modeling. This means that a model can consist of submodels. The supply chain simulation model consists of submodels that correspond to the modules in the proposed template. The submodels are built at the process element level in the SCOR. The Excel files and macros perform planning activities. Execution is carried out in Arena. Enable processes are modeled as input to the simulation either in the form of Excel data or parameters in the Arena model.

Arena triggers various planning actions in Excel either at periodic intervals (e.g., checking inventory) or based on random events (e.g., customer placing an order). In order to prevent the Excel files from becoming too large in the course of a simulation run, clean up actions are triggered at periodic intervals. The customer orders and purchasing orders that have been fulfilled are archived once the performance measures relating to those orders are taken. The archived customer orders are put in a text file and this can be viewed at the end of the simulation if necessary.

3.2.1. Model Initialization

In addition to building the supply chain model using the modules, the user also has to provide the data corresponding to each module. Some of these data are entered in the Arena model while some others are entered in the Excel file corresponding to the participant. Data entered in the Excel file include the inventory policy, initial inventory level and, cost data for each activity. In the model, data such as the identification number for the participant, frequency of orders by the customer, warm-up period and the number of replications are entered.

While some of these data are dependent on the modules, some others depend on the product type. For example, processing times at various process elements depend on the job type. These are entered in the Excel files and entries are made corresponding to each possible product type. The price for each kind of product can also be specified. Each resource in the Arena model has a fixed capacity that has to be specified in the Excel sheet. Users can also specify the operating and overhead costs for the various resources, which will be used for obtaining the cash flow information in the supply chain. The model runs on a 24-hours per day schedule.

3.2.2. Model Execution

This section deals with the way the model is executed with the input data. Three kinds of participants are defined for the purpose of explanation: consumers, producers, and traders. Consumers are those participants who place orders for finished products, but do not supply any products to any other participants. They are the most downstream participants of the supply chain. Producers are the most upstream participants of the supply chain. Producers supply parts to other participants, but do not receive any. Traders are the intermediate participants in the supply chain. Traders both place orders from other participants and deliver orders to other participants. Traders include manufacturers, warehouses, and retailers.

Model execution is determined by the information flow within and between the various participants. Consumers, producers, and traders have certain activities that are carried out periodically. Every time a planning activity is carried out, the system status is checked and actions are taken depending on the status. Information flow can be of two types. One type of information flow records the status of the system that will be used for calculating the performance measures. The other type of information flow triggers events in the model. This includes planning activities that occur while checking the status of the system and events such as placing of an order by the customer. The simulation progresses due to the triggering of such events. Following are the activities in the model that trigger actions in Excel and Arena and determine the course of the simulation:

1. A consumer placing new orders with a trader or producer.
2. A trader checking his inventory and placing orders for raw materials with other traders or producers if necessary.
3. A trader or producer checking existing open orders for production and obtaining the production plan based on material availability.
4. A trader or producer checking open orders for delivery to construct a delivery plan.

In addition to this, each entity in the simulation model, while passing through the various stages of the supply chain, invokes the corresponding VBA code to record its status and performance.

In the following subsections, each of these activities is explained. There are small differences in the way the three kinds of participants, consumers, traders, and producers, are implemented in the supply chain. In the case of the producers, raw material sourcing is not performed. A fixed amount of raw materials is assumed to be available all the time.

The consumer acts as a place for receiving the products corresponding to the orders that he places. So the consumer does not perform production and delivery activities. Because participants such as distributors or retailers do not have any manufacturing processes, the corresponding models do not have produce and test modules.

3.2.2.1 Consumer placing an order

The consumer places orders with the traders and the producers. The product type and the distributions for the interval between orders and order quantities are set in the Arena model.

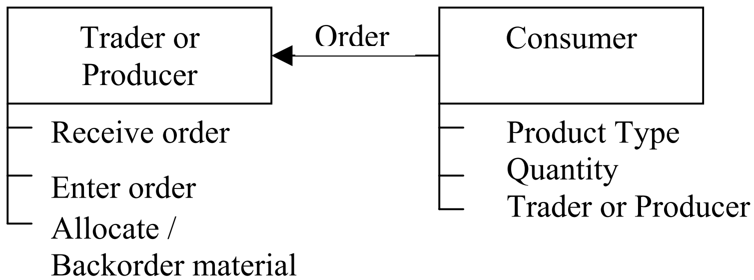

Figure 3.2. Consumer Placing an Order

When a trader (or producer) receives a new order, it is entered in the customer order table. Table 3.13 (Part I and Part II), shows a customer order table which has orders placed by two consumers in various stages of processing. The trader (or producer) tries to allocate material for this new order using his raw material inventory. If not enough raw material is available, the shortage is marked as back order. These values are used for placing new sourcing orders. The entries are made in the *Item Master* table (Table 3.4). The trader (or producer) sets an expected delivery date based on the lead time for the product. Lead time is dependent on the product type and has to be specified in the *Item Master* sheet at the beginning of the simulation. Order tardiness is calculated based on the expected delivery date.

3.2.2.2 Sourcing

Traders perform sourcing at periodic intervals. The trader orders raw materials from his supplier based on an inventory control policy. The model currently runs under periodic *(R, s, S)* policy, where *R* is the interval at which inventory is checked, *s* stands for the reorder level, and *S* is the order up to quantity. These values are defined for each type of product and are specified in the *Inventory Management* table (Table 3.8). The net inventory position is calculated based on the inventory on hand, on-order, allocated inventory, and backorders.

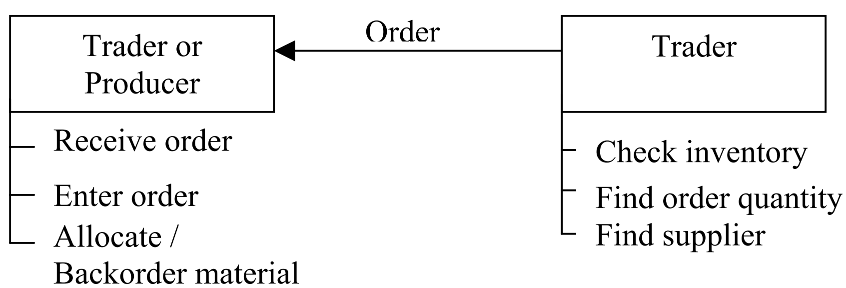

Figure 3.3. Sourcing of Raw Materials by the Trader

For each trader, the *Schedule Product Deliveries* submodel in Arena, which corresponds to module S2.1 in SCOR, triggers an event periodically that invokes the Excel procedure for checking the inventory levels. The net inventory position for each of the components in the raw material inventory is checked. If the net inventory position is less than the reorder level, an order is placed so that the net inventory position equals the order up to quantity. The formula for deriving the reorder quantity is given below.

$$I(t) = H(t) - A(t) - B(t) + O(t)$$

If $I(t) \leq s$ then,

$$Q = S - I(t)$$

Else,

$$Q = 0$$

Where,

I(t) = Net inventory level at time *t*

H(t) = On hand inventory at time *t*

A(t) = Quantity allocated at time *t*

B(t) = Back order at time *t*

O(t) = Quantity on order at time *t*

Q = Order quantity

S = Order up to quantity

s = Reorder level

The values for inventory on hand, on order, allocated inventory, and backorders for each component can be obtained from the *Item Master* table (Table 3.4). Excel VBA calculates the sourcing quantity based on these values. The trader's (or producer's) name for each component is obtained from the *Item Master* table. For each component, there can be only one trader or producer. The process of placing a sourcing order is similar to the consumer placing orders, which is explained in section 3.2.2.1.

Sourced products are received in three stages: *receive, verify* and *transfer*. In the *receive* stage, the sourced products seize a resource at the receive module. The processing time is dependent on the product type. The processing times are exponentially distributed. After receiving, the product goes through the verification stage. If there is a supplier certification program for a particular product, the processing time for this stage is set as zero. This value has to be set in the Excel file (Table 3.5) of the trader. The verification stage consists of a process block and causes some delay in the movement of the sourced product. Currently there is no provision for rejecting any order at the verification stage. All orders are assumed to be perfect. In the *Transfer* stage, a resource is seized for transfering the sourced products into the raw material inventory. Here also the average processing time is product dependent. The processing times are exponentially distributed. Each of the processes has an associated cost (Table 3.1) and this cost is added to the sourced product depending on the amount of time the product spends at each resource.

Once the sourced products reach the raw material inventory (after the transfer stage), an Arena VBA block calls the Excel VBA procedure for updating the inventory status in the *Item Master* table. It also updates the *Purchase Action Report* (Table 3.9), and the *Material Release* table (Table 3.10). *Material Release* table keeps track of the values of the raw material available in the inventory. This is used for calculating the direct material cost for the customer orders.

3.2.2.3. Checking of open orders for production

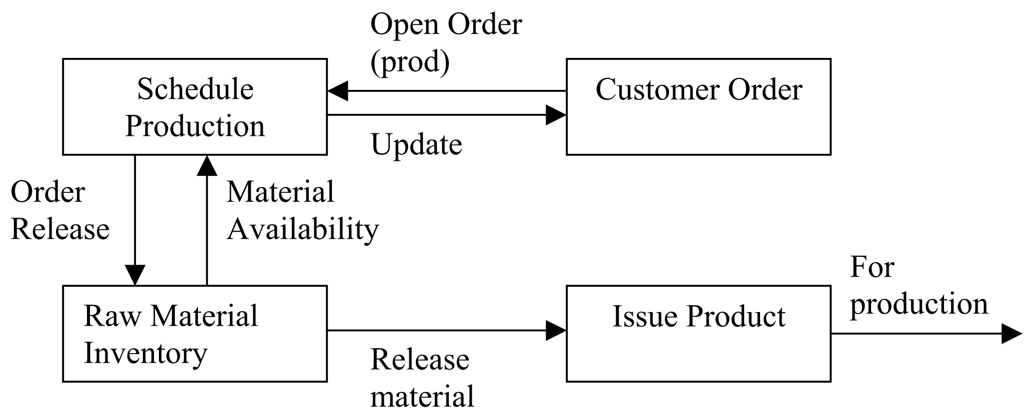

Figure 3.4. Checking Open Orders for Production

All unfinished customer orders have their status indicated by a tag in the *customer order* table (Table 3.13, Part II). The possible status for an existing order include *received, in-process, FGI, in-transit,* and *delivered*. The *Customer Order Tracking* table (Table 3.14) keeps track of the orders that are open for production. All the orders with status *Received* are open for production. That is, these orders have been received, but not yet scheduled for production. Periodically, these orders are checked for production release. The interval between each such check depends on the production rescheduling period. If material for processing the whole order is available, then it is released for production. All the open orders for which material is available are released at the same time for production. Presently there is no provision for carrying out capacity planning activities. If enough material is not available, the order is retained as *open* and is checked again during the next production order release cycle.

During each production order release cycle, Excel VBA checks the inventory status to check which orders can be released for production. For checking the material availability, both the order size and the bill of materials for the corresponding product have to be considered. This is carried out in Excel VBA. During each planning cycle, open orders are listed for processing based on some heuristic. Raw material requirement is calculated using the bill of materials. The bill of materials can be specified upto one level deep (Table 3.7). Whenever an order is released for production, equivalent raw material is removed from the inventory. Raw material inventory is managed on a FCFS basis. When an order is released for production, its status is changed from *Received* to *In-process.*

The orders that are released for production seize the *Issue Product* resource. This resource transports the raw materials from the raw material inventory to the shop floor. The processing time for this stage is dependent on the product and follows an exponential distribution. The mean value for the distribution is taken as the product of processing time per part (Table 3.5) and the quantity requested in the order.

After the raw material has been issued to the shop floor, it goes through the *Produce and Test* stage. (This stage is skipped for participants such as warehouse and retailers who do not carry out any production activities.) The average processing time for this stage is taken as the product of processing time per part and the order quantity. The processing time per part is product dependent and is exponentially distributed. The test stage is a rework loop where a portion of the orders is sent for rework. This value can be set as a parameter in the Arena model.

Once the production is carried out, the order goes through the *Package* stage where the average processing time depends on the product type. After packaging, the order is sent for *Staging*. Here also, the average processing time is dependent on the product type. At the end of staging, the order is ready for delivery and is put in the finished goods inventory. At this time, the status of the order is changed form *In-process* to *FGI*. The order waits in the finished goods inventory until a delivery plan releases it for delivery. Each of the processes mentioned above has costs associated with it and the costs are added to the order using job order costing method.

3.2.2.4 Checking open orders for delivery

The finished goods inventory status is checked periodically. The *Customer Order Tracking* table (Table 3.14) keeps track of the orders that are available for delivery in the finished goods inventory. These orders are sent for delivery during delivery order release. For example, in Table 3.13, order number 220 is in the finished goods inventory. This order will be released for delivery during the next delivery order release cycle. The delivery process requires seizing of a resource. The processing time here corresponds to the transportation time from the producer (or trader) to the customer. Each order is delivered separately. The return time of the transporter after the delivery of the order is not modeled. The cost for transportation gets added to the cost of the order. Once the order is delivered, its status is changed to *Delivered.* The price for the order is obtained from the item master table (Table 3.4). This value, along with the accumulated cost, is used for calculating the profit. After the performance measures corresponding to the order have been taken, it is removed from the Excel file and archived in a text file.

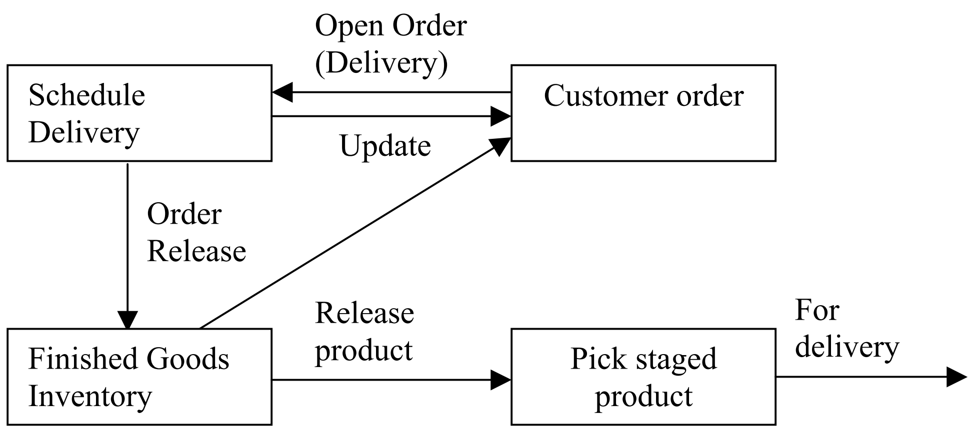

Figure 3.5. Checking Open Orders for Delivery

3.3. Cash Flow

In addition to time based performance measures, the simulation model also gives financial performance measures. Cash flow is obtained by associating costs to each order. Cost accumulation methods (the manner in which costs are collected and identified with specific customers, jobs, batches, orders, departments and processes) vary from firm to firm. In the modules developed, job order costing method is followed. In job order costing, costs are accumulated by jobs, orders, contracts or lots. In the simulation model, each order is considered as a job and costs are assigned to it. Direct material, direct labor, and overhead rates are considered for assigning costs to each order. All the process costs, including manufacturing costs, are applied to orders using predetermined rates along with an overhead rate associated with each activity. Direct material cost is obtained at the point of order release using first-in-first-out policy for the raw material inventory. The cost assigned to an order at a particular resource depends on the amount of time the resource was utilized by the order. Costs at various stages are added to arrive at the final cost for the order.

3.4. Performance Measures

Periodically, Arena VBA triggers Excel procedures that calculate the performance measures based on the entries in the corresponding Excel sheets. At the end of each replication, these performance measures are put together and the overall performance measures for the entire replication are calculated. The performance measures include cycle time, percent tardiness, inventory, cost performance, and resource utilization. Order based performance measures are calculated based on the orders that have been delivered during any given period. For purposes of cycle time calculations, the whole process from placing of an order to the delivery of the finished product at the customer site is divided into four stages. The cycle time refers to the average time at each of the stages, the average being taken over the customer orders. The overall cycle time is calculated as the average time between the placing of an order by the customer and the delivery of that order by the producer (or trader) at the customer site. Each product has an associated lead time. Whenever an order is placed, its estimated delivery date is given based on the lead time for that product. If the order is delayed beyond its estimated delivery date, then the order is considered tardy. Percentage of orders that were delivered after the due date is calculated as the percentage tardy performance measure. For calculating the resource utilization, variables are used to keep track of the amount of time the resource was busy in any given period. Cost performance measures are calculated based on job order costing. Costs are associated with each order and these values are used to obtain performance measures such as cost of goods sold.

***Delivery performance**:* Delivery performance includes the average cycle times at each stage, the overall cycle time, and the percentage of orders that were tardy. For calculating the cycle times, four stages are considered: order receipt to start build, start build to finished goods inventory, finished goods inventory to release for delivery, and release for delivery to delivery at customer site. The sum of the average cycle times at these four stages gives the overall cycle time. Sample delivery performance is shown in Table 3.17.

***Inventory Performance**:* Inventory performance is used to find out the inventory levels in terms of dollars. The inventory level is taken as a two-point average based on the inventory at the beginning and end of the period. The value of the inventory is given in terms of dollars of raw material, work in process, and finished goods inventory. Sample inventory performance is shown in Table 3.18.

***Cost of Goods Sold**:* Cost of goods sold is calculated based on the production costs, purchases, work in process, and finished goods inventory. For a manufacturing firm, cost of goods sold is the manufacturing expenses, along with other expenses for goods sold during the period, including raw material, direct labor, and overhead. For a retail firm, the manufacturing process is not present. Cost of goods sold can be used to find the gross profit during the period. The gross profit is defined as the difference between the sales and the cost of goods sold. The total sales can be obtained from the total price for the orders delivered during the period (Table 3.19).

Cost of Goods Manufactured*:* Cost of goods manufactured is the cost of orders that were put in the finished goods inventory during the period. This includes the cost of orders that were released for production in an earlier period but completed during the current period. This value is dependent on the manufacturing expenses for the period, including the overhead, and the work in process inventory at the beginning and end of the period. Table 3.19 shows the COGM performance for a sample simulation run.

Inventory Days of Supply*:* This is calculated based on the cost of goods manufactured and the average inventory level. This ratio measures the number of days it takes to sell the entire stock of inventory. Sample inventory days of supply performance measures are shown in Table 3.20.

Process Element Utilization*:* Process element utilization for each of the resources is calculated at the end of the period. This value is dependent on the time for which the corresponding resources were busy during the period. Sample process element utilization values are shown in Table 3.21.

Inventory holding expenses*:* Each product has an inventory holding cost associated with it. Inventory holding expenses are calculated based on the average inventory level. Table 3.22 gives some sample results.

3.5. Summary and Conclusions

As companies concentrate on improving the performance of the entire supply chain instead of looking at it as a set of independent organizations, coordination among various organizations becomes important. Simulation is a very efficient way of analyzing what – if scenarios in such an environment. With the advent of more and more powerful computers, it has become easier to simulate complex systems. But the amount of time needed to develop the simulation model can be quite high. There is a need for constructing libraries that can be used to build supply chain models. Such a library saves the user's time and effort in developing the model, thus helping the user to spend more time on analyzing the system.

Arena offers great features in terms of simulating discrete event systems. But the modules available in Arena are at a very basic level for use in supply chain simulation. This limitation can be overcome by developing modules hierarchically from the basic modules that would imitate the supply chain processes. In addition to this, using Arena VBA, the simulation model can be interfaced with other applications such as Microsoft Excel. By combining the simulation capabilities of Arena and the spreadsheet capabilities of Microsoft Excel, a very efficient and flexible library can be constructed for developing supply chain simulation models. In this direction, a sample set of modules has been built. In order to make the modules standardized, they have been built based on the Supply Chain Operations Reference model.

Name	Process Element	Capacity	Operation Costs $/hr	Overhead %
Receive	S2.2	1	100	24%
Verify	S2.3	1	111	12%
Transfer	S2.4	1	90	44%
Release Materials	M2.2	2	120	54%
Produce and test	M2.3	40	100	50%
Package	M2.4	1	80	77%
Stage Product	M2.5	1	60	76%
Deliver	D2.8	4	30	88%

Table 3.1. Capacity and cost table for the process elements

Period Interval (days)	1
Order costs ($ / Order)	100

Table 3.2. Period interval and order costs

Raw Material	WIP	FGI
30%	40%	50%

Table 3.3. Percent holding costs for the inventory

Raw Material or Product	Sup-plier	Supplier Name	Lead Time Days	Quantity on-hand	On - order	Allo cate d	Back order	Selling Price	Initial Inventory
1	1001	Sup1	4	12600	1030	250			12600
2	1001	Sup1	4	8400	360	100			8400
3	1002	Sup2	4	4200	3170	150			4200
4			5					210	
5			5					200	

Table 3.4. Item Master

Raw Material / Product	Description	Receive	Verify	Transfer	Release	Produce	Pack	Stage
1	C1	15	15	15				
2	C2	15	15	15				
3	C3	15	15	15				
4	P1				1	30	15	15
5	P2				1	30	15	15

Table 3.5. Processing Times (in minutes)

Customer Number	Name	Transportation time (hrs)
1004	Dis 1	4
1005	Dis 2	4
1003	Man 1	10

Table 3.6. Customer table

Product	Component	Quantity
4	1	1
4	2	1
5	1	1
5	3	1

Table 3.7. Bill of Materials

Raw Material	Supplier	Reorder level	Order upto
1	1001	12600	12600
2	1001	8400	8400
3	1002	4200	4200

Table 3.8. Inventory Management

Period	Order Number	Comp-onent	Supplier	Quantity	Order Date	Request Due Date	Delivery Date	Status
13	337	3	1002	140	1/13/00	1/17/00		Ordered
13	342	3	1002	140	1/13/00	1/17/00	1/15/00	Delivered
14	345	1	1001	260	1/14/00	1/18/00	1/15/00	Delivered

Table 3.9. Purchase Action Report

Product	Cost per item ($)	Available	Worth ($)
1	60.00	4320	259,200.00
2	60.00	1840	110,400.00
3	30.00	2480	74,400.00
2	60.24	220	13,252.80

Table 3.10. Material Release

Product	Cost per item ($)	Available	Worth ($)
1	60.00	12240	734,400.00
2	60.00	5280	316,800.00
3	30.00	6960	208,800.00

Table 3.11. Initial Raw Material Inventory

Product	Qty
4	2
5	3

Table 3.12. Finished Goods Inventory

Order Number	Customer	Product	Order date	Quantity	Expected delivery date	Price ($)
123	1004	5	1/5/00	150	01/09/00	30000.00
185	1005	4	1/7/00	120	01/11/00	25200.00
220	1005	5	1/9/00	140	01/13/00	28000.00
227	1005	5	1/9/00	140	01/13/00	28000.00
238	1005	4	1/9/00	120	01/13/00	25200.00

Table 3.13 - I. Customer Order

Order Num-ber	Start build	Ready for shipment	Releas e for delive ry	Delivery Date	Deli very Peri od	Status	Cost ($)	Tar-dy
123	1/5/00	1/6/00	1/7/00	1/9/00	9	Delivered	21500.00	0
185	1/7/00	1/8/00	1/9/00			In - Transit	18447.90	0
220	1/9/00	1/9/00				FGI	18844.40	0
227	1/9/00					In-process	29107.90	0
238						Received	14400.00	0

Table 3.13 - II. Customer Order

Open Order Number (Production)	Open Order Number (Delivery)	Order Number	Row Number
1	0	245	49
2	0	259	50

Table 3.14. Customer Order Tracking

Order number	Prod-uct	Quanti-ty	Available for Release?	Customer	Customer Name	Row Number	Production Capability
124	4	100	1	1004	Dis 1	3	200
125	4	150	0	1005	Dis 2	5	120

Table 3.15. Order Release

Open Order Number	Order number	Customer	Product	Quantity	Row Number	Customer Name
1	121	1004	5	150	6	Dis 1
2	122	1005	5	140	7	Dis 2

Table 3.16. Delivery Plan

Period	Number of Orders Delivered	Order Receipt to Start build (Days)	Start build to ready for shipment (Days)	Ready for Shipment to Release for Shipment (Days)	Release for Shipment to Delivery at Customer (Days)	Average Cycle Time (Days)	% Tardy
6	12	0.0944	2.9266	0.00252	0.1662	3.1898	16.67%
7	10	0.0978	1.3862	0.00176	0.1709	1.6567	10.00%
8	15	0.0932	2.6086	0.00224	0.2255	2.9296	33.33%

Table 3.17. Delivery Performance

Period	Raw Material ($)	WIP ($)	FGI ($)	Total ($)
6	1,082,753.08	356,700.00	0.00	1,439,453.08
7	863,790.08	554,469.80	0.00	1,418,259.88
8	1,024,992.20	569,743.99	0.00	1,594,736.19
9	1,030,281.90	448,577.08	0.00	1,478,858.98

Table 3.18. Inventory Worth

Period	Total Manufacturing Costs ($)	COGM ($)	Transpo rtation costs ($)	COGS ($)	Price ($)	Gross Profit ($)
6	419,320.97	221,551.17	2,584.09	224,135.26	313,400.00	89,264.74
7	227,693.05	212,418.86	2,313.64	214,732.50	263,400.00	48,667.50
8	160,049.44	281,216.35	3,679.52	284,895.87	393,600.00	108,704.13
9	224,119.67	218,055.60	5,095.93	223,151.53	285,600.00	62,448.47

Table 3.19. COGS, COGM and Profit

Period	Inventory Days of Supply
6	6.45
7	7.09
8	5.46
9	6.63

Table 3.20. Inventory Days of Supply

Period	Receive (S2.2)	Verify (S2.3)	Transfer (S2.4)	Release Materials (M2.2)	Produce and Test (M2.3)	Package (M2.4)	Stage Product (M2.5)	Deliver (D2.10)
6	12.90%	13.12%	11.40%	88.50%	67.61%	10.25%	11.15%	28.09%
7	14.89%	7.59%	21.85%	79.46%	88.77%	13.24%	10.92%	43.88%
8	3.12%	12.11%	6.08%	15.59%	83.69%	17.55%	12.07%	81.84%
9	6.97%	6.75%	6.49%	53.48%	67.92%	13.61%	12.34%	77.74%

Table 3.21. Process Element utilization

Period	Raw Material ($)	WIP ($)	FGI ($)	Total ($)
6	799.95	499.27	0.00	1,299.22
7	776.21	616.01	0.00	1,392.22
8	844.63	557.98	0.00	1,402.61
9	816.80	494.91	0.00	1,311.71

Table 3.22. Inventory Holding Costs

4. Rescheduling Frequency

4.1 Introduction

Manufacturing systems involve uncertainties in many of its activities. It is important to keep track of the system status on a regular basis in order to obtain desired performance. Variability along with limited resources makes it difficult to manage a system. Variability is found in many of the activities involving manufacturing systems. 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, although this might lead to a better control over the system. When the planning activities are scheduled over a very long time horizon, it becomes difficult to manage the system efficiently. This chapter analyzes the direct and indirect effects of varying the rescheduling periods of various activities on the performance of a manufacturing system.

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, theses systems require frequent change of existing plans, which, in reality is not common. In a periodic review system, 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 plans are made, it is followed till the end of that planning period. In this kind of a system, there may or may not be synchronization among various planning activities.

We analyze the effects of changes in rescheduling periods of three kinds of planning activities in this chapter. The activities considered are: order release for sourcing of raw materials from the suppliers, release of customer orders for production, and release of customer orders for delivery. Two simulation models have been constructed that take into account the various activities involved in the production and distribution of goods and the planning activities associated with it. Each model corresponds to a unique supply chain. This chapter analyzes the performance of each supply chain under various combinations of rescheduling policies.

4.2. Methodology

The simulation models have been constructed to incorporate various aspects of a typical supply chain. This section explains those aspects in detail.

4.2.1 Make-to-Stock vs. Make-to-Order

Manufacturing industries can be broadly divided into make-to-order and make-to- stock categories. In a make-to-order industry, the company manufactures products based on existing customer orders. In a make-to-stock industry, the company manufactures products and stocks them in the finished goods inventory, to be picked up by the customer. The simulation models constructed consider both make-to-stock and make-to-order organizations. The same industry may be make-to-stock for a category of products, and make-to-order for another category. Since make-to-order companies produce according to the existing customer orders, given existing production schedules, capacity availability, and the customer's desired due date, a new order can be scheduled. Thus the production process is dependent on the existing orders and not on the demand forecast. On the other hand, for make-to-stock companies, the inventory levels for various products is determined by the expected demand for the product, and hence the performance is dependent to a great extent on efficient forecasting of demand.

4.2.2 Rescheduling Activities

We consider three main activities in the simulation models that are done on a periodic basis. Those are: placing orders with the supplier for raw materials, releasing customer orders for production, and releasing customer orders for delivery. In the case of placing orders with the supplier for raw materials, the inventory management system checks the inventory levels of the raw materials at periodic intervals and depending on the quantity on hand, allocated quantity, backorders, and on-order quantity, the system places new orders with the suppliers. For releasing orders for production, the production management system checks open orders for production periodically. Open orders for production are the orders that have been received but not yet released for production. If raw materials are available for a particular order, the order is released for production. The third activity under consideration is releasing finished orders for delivery. Here, the delivery management system checks the finished goods inventory at periodic intervals and if there are any orders that are waiting for delivery, those are released immediately.

The objective of this work is to determine the effects of changing the rescheduling periods on the performance of the supply chain. In addition to the delay encountered in processing the information, a higher rescheduling period in planning activity has other effects. One of the main effects is due to the lumping orders. Lumping orders put extra pressure on the limited capacity of the system. It increases the variability. When orders are released in bulk, the shop floor might not have enough capacity to process all the orders at a time. This results in the build up of queues and affects the performance of the system. This might lead to a chain effect resulting in a delay in downstream activities. All these together result in an increase in average cycle time and lead to delay in the completion of customer orders.

4.2.3 Inventory Management

Inventory management has a very significant effect on the performance of the system. In the simulation models, the raw material inventory is managed based on 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.

4.2.4 Production and Delivery Order Release

Production management system releases orders for production based on a first-come-first-serve 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. Depending on the capacity of the shop floor, there might be a queue build up in front of the machines.

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. Depending on the number of available transporters, there might be a queue build up.

4.2.5 Performance Measures

Manufacturing systems can be analyzed through various kinds of outputs. In this study, we compare the performance using the cycle times and tardiness performance under each scenario. We define the overall cycle time as 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. Supply Chain Operations Reference Model divides this activity into four lower level activities. These four sub activities are: 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 first division, that is, *order receipt to start build*, refers to the average time for a received customer order to be released into the shop floor for production. This is dependent on both the production order release frequency and the raw material availability. The *start build to* *finished goods* cycle time measures the average time that the order spends in the shop floor during production. Production activity includes production, testing, packaging, and staging the finished product into the finished goods inventory. The average time that an order spends in the finished goods inventory is measured in the *finished goods to release for delivery* cycle time. The last division, that is, *release for delivery to receipt at customer site* is the average time that an order takes from the point of approval for delivery to actual 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. Whenever the manufacturer receives an order, he sets a due date for 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 percent of tardy orders for each scenario is kept track of.

4.3 Description of Supply Chains and Design of Experiments

For analyzing the effects of rescheduling frequencies, we consider two different supply chains. The sections below explain the two supply chains and the design of experiments.

4.3.1 Description of Supply Chain One

4.3.1.1 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. 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 4.1 shows a schematic of the supply chain. Figure 4.2 represents the bill of material for the two products that the Manufacturer 1 produces.

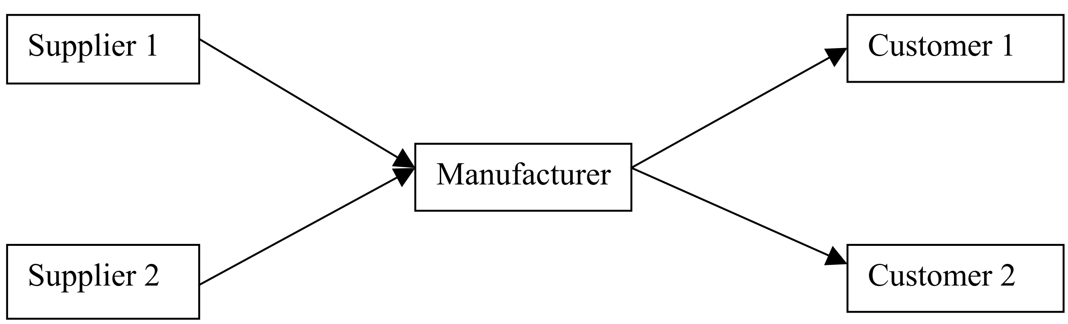

Figure 4.1. Supply Chain Network

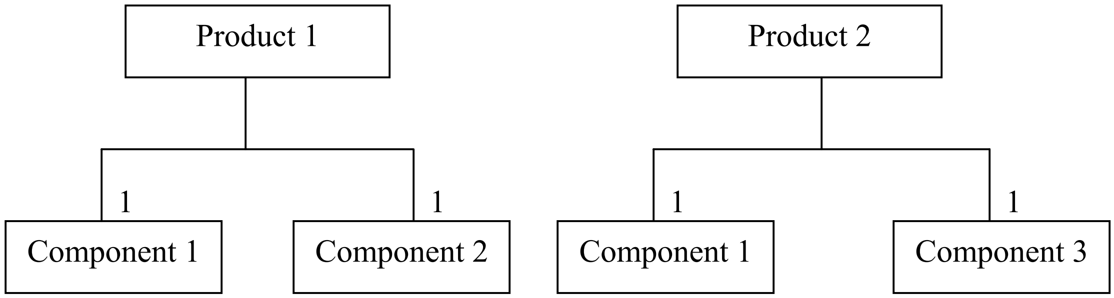

Figure 4.2. Bill of Materials for Manufacturer 1

The demands and order intervals from the customer follow a distribution with mean and squared coefficient of variance as shown in Table 4.1.

Customer	Product	Demand		Interarrival Time	
		Mean (Parts / Order)	Distribution	Mean (Hrs)	SCV
Customer 1	Product 1	200	Constant	6	1
Customer 1	Product 2	75	Constant	6	1
Customer 2	Product 1	100	Poisson	6	1
Customer 2	Product 2	75	Poisson	6	1

Table 4.1. Demand Table

4.3.1.2 Inventory Management

Inventory management is carried out based on a (R, s, S) policy. We set the order up to quantity based on the average demand. We consider two kinds of scenarios for setting the reorder level: In the first scenario, the reorder level is set equal to the order up to quantity, which is set as the quantity that would last the demand for seven days. In the second scenario, the reorder level is set equal to the quantity that would last the demand for five days. Whereas the first scenario would necessitate more frequent ordering, and result in a higher average inventory level, the second scenario runs a greater risk of raw material shortage. Table 4.2 shows the reorder levels and order up to quantities for the manufacturer. In the table, s_1 corresponds to reorder level for the first scenario while s_2 corresponds to the reorder level for the second scenario.

Component	Reorder Level (s_1)	Reorder Level (s_2)	Order Up to (S)
Component 1	12600	9000	12600
Component 2	8400	6000	8400
Component 3	4200	3000	4200

Table 4.2. Reorder Levels and Order Up to Quantities

4.3.1.3 Processing Times

The processing times at the suppliers are given in Table 4.3. The processing times given correspond to the average values. All the processing times are exponentially distributed. For Release and Produce activities, the processing times given are per part. For all the other processing times, the values correspond to time per order. Processing times at the manufacturer are given in Table 4.4. Mean delivery times between the participants of the supply chain are given in Table 4.5. Delivery times are exponentially distributed.

Participant	Raw Material	Release	Produce	Pack	Stage
Supplier 1	Component 1	1	4	15	15
Supplier 1	Component 2	1	4	15	15
Supplier 2	Component 3	1	4	15	15

Table 4.3. Processing Times at Suppliers (Mins)

Raw Material / Product	Receive	Verify	Transfer	Release	Produce	Pack	Stage
Component 1	15	15	15				
Component 2	15	15	15				
Component 3	15	15	15				
Product 1				1	30	15	15
Product 2				1	30	15	15

Table 4.4. Processing Times at the Manufacturer (Mins)

From	To	Time (hours)
Supplier 1	Manufacturer	2
Supplier 2	Manufacturer	10
Manufacturer	Customer 1	4
Manufacturer	Customer 2	4

Table 4.5. Mean Delivery Times (hours)

4.3.1.4 Server Capacities and Lead Times

For the Release Material stage and Produce stage, the total processing time, and hence the required server capacity, depends on the number of parts that are to be processed. For all the other stages, this value depends on the number of orders and not on the total number of parts. The capacities have been calculated by keeping the expected utilization at around 85%. In the case of the Deliver module, the server capacity represents the number of delivery vehicles. Table 4.6 gives the server capacities at various participants.

Participant	Stage	Capacity (Number of servers)
Supplier 1	Release	3
Supplier 1	Produce	10
Supplier 1	Package	1
Supplier 1	Stage	1
Supplier 1	Deliver	2
Supplier 2	Release	1
Supplier 2	Produce	5
Supplier 2	Package	1
Supplier 2	Stage	1
Supplier 2	Deliver	4
Manufacturer	Receive	1
Manufacturer	Verify	1
Manufacturer	Transfer	1
Manufacturer	Release	2
Manufacturer	Produce	40
Manufacturer	Package	1
Manufacturer	Stage	1
Manufacturer	Deliver	4

Table 4.6. Server Capacities

We set the lead times based on the pilot runs. Lead times are defined for each product. They are used to set the due dates for the customer orders. Values for lead times for the two products at the manufacturer are given in Table 4.7.

Product	Lead Time (Days)
Product 1	5
Product 2	5

Table 4.7. Lead Times for Participants and Products

4.3.1.5 Design of Experiments

This section explains the settings for the simulation runs. We carry out a total of ten replications for each scenario and based on these replications, we calculate the average and standard deviation for the various performance measures. From these results, we arrive at the values for 90% confidence interval.

The objective of the experiments is to analyze the effects of rescheduling periods of activities on the performance of the system. The rescheduling periods vary in the range of 0.1 hours (very close to continuous review) to 120 hours. While varying the rescheduling period of a particular activity, we maintain rescheduling period for all the other activities at 4 hours. There is no synchronization between the planning activities for the participants. This work also analyzes the effects of inventory policies by running the simulation with two different reorder levels. Another objective is to determine if production policy has a greater impact than the rescheduling period itself. We analyze this by changing the production release heuristic from first-in-first-out (FIFO) to shortest-processing-time (SPT). First-in-first-out processes the orders in the sequence they were received, subject to material availability. Shortest-processing-time processes orders that require shorter average processing time before the ones that require longer average processing time, subject to material availability. We vary the production rescheduling period between 0.1 to 120 hours under SPT, and compare the results with those under FIFO.

This work considers eleven different rescheduling periods. They are: 0.1, 1, 2, 4, 8, 16, 24, 48, 72, 96, and 120 hours. The replications are carried out in steady state. The simulation runs are for a period of sixty days, with a warm-up period of twenty days. Thus each simulation run is totally for a period of eighty days with statistics collected after the warm up period. In the case of higher rescheduling period for sourcing (48 - 120 hrs), the results showed that the system had not reached steady state in twenty days time. So we had to increase the warm up period to thirty days and the simulation length to ninety days after the warm up period. Table 4.8 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 4.8, 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.

Scenarios	Source	Make	Deliver	Production Heuristic	Reorder Level (Days of Inventory)
1 to11	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 4.8. Scenarios for Supply Chain One

4.3.2 Description of Supply Chain Two

4.3.2.1 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 4.3 shows a schematic of the supply chain. Figure 4.4 represents the bill of material for the three products that the Manufacturer 1 produces.

Product 1 represents a high demand product, and hence is stocked by the retailer. When a customer places orders for this kind of product, the retailer supplies the product immediately provided it is in stock. For product 2, the demand is intermediate. So, 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 kind of product and it delivers the product to the retailer, who in turn delivers it to the end customer. For products of type 3, the demand is very low. So 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, this is passed directly to the manufacturer and the manufacturer delivers the product to the retailer through the warehouse. The retailer then delivers it to the customer.

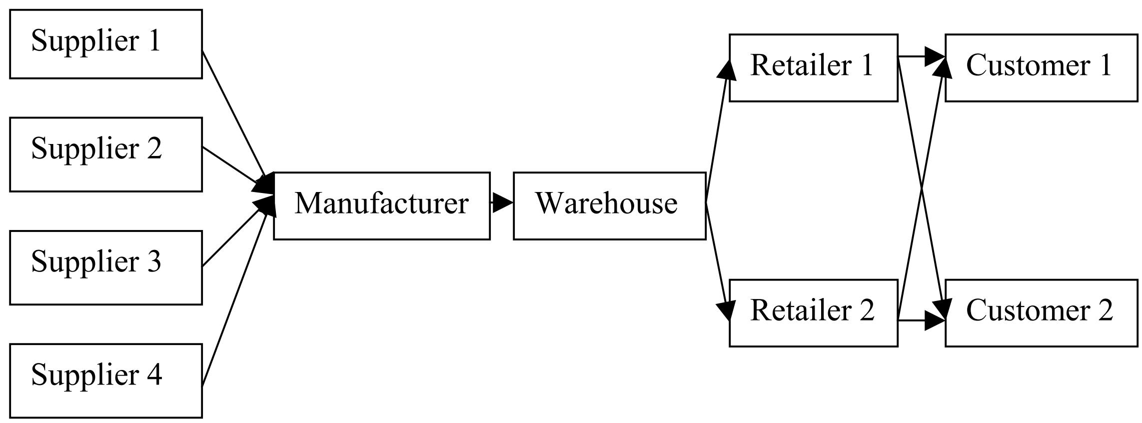

Figure 4.3. Supply Chain Network

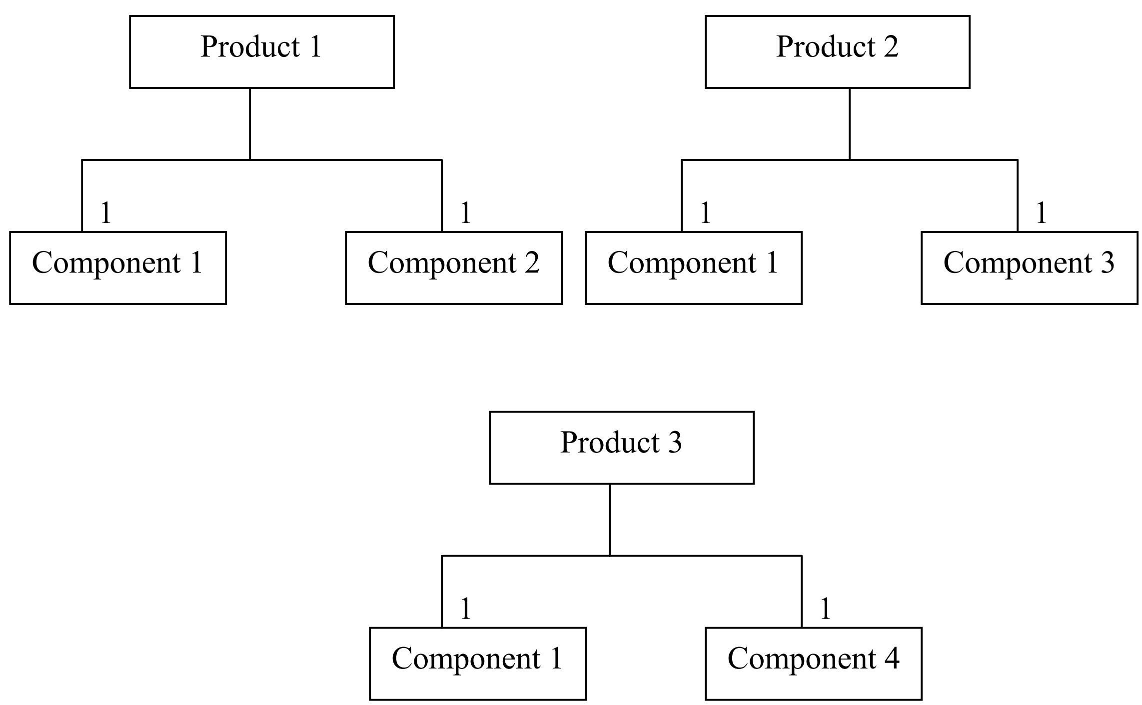

Figure 4.4. Bill of Materials for Manufacturer 1

The demands and order intervals from the customer follow a distribution with mean and squared coefficient of variance as shown in Table 4.9.

Customer	Retailer	Product	Demand		Inter-arrival Time	
			Mean (Parts / Order)	Distribution	Mean (Hrs)	SCV
Customer 1	Retailer 1	Product 1	100	Constant	8	0
Customer 1	Retailer 1	Product 2	50	Constant	24	0
Customer 1	Retailer 1	Product 3	25	Constant	48	0
Customer 1	Retailer 2	Product 1	50	Poisson	24	1
Customer 1	Retailer 2	Product 2	20	Poisson	48	1
Customer 1	Retailer 2	Product 3	10	Poisson	96	1
Customer 2	Retailer 1	Product 1	300	Poisson	24	0.5
Customer 2	Retailer 1	Product 2	50	Poisson	24	0.5
Customer 2	Retailer 1	Product 3	40	Poisson	72	0.5
Customer 2	Retailer 2	Product 1	50	Poisson	48	2
Customer 2	Retailer 2	Product 2	20	Poisson	48	2
Customer 2	Retailer 2	Product 3	10	Poisson	96	2

Table 4.9. Demand Table

4.3.2.2 Inventory Management

Inventory management is carried out based on a (R, s, S) policy. Table 4.10 shows the reorder levels and order up to quantities of the participants of the supply chain. This work follows an iterative approach for setting the reorder level. We set the reorder levels taking into account the variability in the demand for the product, the variability in the lead time of the supplier, and delay due to periodic rather than continuous review (Silver *et al*, 1998). We set the order up to quantity equal to the reorder level. The following equation is used for calculating the reorder levels:

$$s = (a + b\ CT)D$$
$$= (3 + 2\ CT)D$$

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 the equation, a = 3 days (72 hours) is the maximum rescheduling period in the set of simulation runs. We multiply the cycle time by a factor of two (b=2) in order to take in to account the variability in demand and the supplier's lead time.

The values for the inventory levels are fixed iteratively. 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 (section 4.3.2.5). The final values for inventory reorder level are given in Table 4.10.

Participant	Product	Reorder Level (s)	Order Up To (S)
Retailer 1	Product 1	4800	4932
Retailer 1	Product 2	0	0
Retailer 1	Product 3	0	0
Retailer 2	Product 1	600	617
Retailer 2	Product 2	0	0
Retailer 2	Product 3	0	0
Warehouse	Product 1	10125	9680
Warehouse	Product 2	1800	1721
Warehouse	Product 3	0	0
Manufacturer	Component 1	7433	6904
Manufacturer	Component 2	6075	5900
Manufacturer	Component 3	960	946
Manufacturer	Component 4	247	241

Table 4.10. Reorder Levels and Order Up To Quantities

4.3.2.3 Processing Times

The processing times at the suppliers are given in Table 4.11. The processing times given correspond to the average values. Processing times are exponentially distributed. For Release and Produce activities, the processing times given are per part. For all the other processing times, the values are per order. Processing times at the manufacturer are given in Table 4.12. Table 4.13 gives the processing times at the warehouse and the retailers. Mean delivery times between the participants of the supply chain are given in Table 4.14. Delivery times are exponentially distributed.

Raw Material	Release	Produce	Pack	Stage
Component 1	0.1	1	15	15
Component 2	0.1	1	15	15
Component 3	0.1	1	15	15
Component 4	0.1	1	15	15

Table 4.11. Processing Times at Suppliers (Mins)

Raw Material / Product	Receive	Verify	Transfer	Release	Produce	Pack	Stage
Component 1	15	15	15				
Component 2	15	15	15				
Component 3	15	15	15				
Component 4	15	15	15				
Product 1				1	15	15	15
Product 2				1	15	15	15
Product 3				1	15	15	15

Table 4.12. Processing Times at Manufacturer (Mins)

Product	Receive	Verify	Transfer	Release	Pack	Stage
Product 1	15	15	15	1	15	15
Product 2	15	15	15	1	15	15
Product 3	15	15	15	1	15	15

Table 4.13. Processing Times at Warehouse and Retailers (Mins)

From	To	Time (hours)
Supplier 1	Manufacturer	10
Supplier 2	Manufacturer	8
Supplier 3	Manufacturer	9
Supplier 4	Manufacturer	10
Manufacturer	Warehouse	6
Warehouse	Retailer 1	6
Warehouse	Retailer 2	7
Retailer 1	Customer 1	4
Retailer 1	Customer 2	6
Retailer 2	Customer 1	8
Retailer 2	Customer 2	9

Table 4.14. Mean Delivery Times (hours)

4.3.2.4 Server Capacities

The total processing time, and hence the required server capacity, depends on the number of parts for the Release Material stage and Produce stage. For all the other stages, this value depends on the number of orders and not on the order size. Since the number of orders at the warehouse, the manufacturer, and the suppliers depend on the inventory policies of their customers, one cannot estimate it with great accuracy. We have calculated the capacities wherever it is possible to calculate it with the available information. The expected utilization is set at around 85%. For all the other resources, we adjust the capacities during the pilot runs by analyzing the corresponding resource utilization and cycle time values. Table 4.15, 4.16, and 4.17 give the resource capacities at various participants.

Participant	Stage	Capacity (Number of servers)
Supplier 1	Release	1
Supplier 1	Produce	2
Supplier 1	Package	1
Supplier 1	Stage	1
Supplier 1	Deliver	5
Supplier 2	Release	1
Supplier 2	Produce	2
Supplier 2	Package	1
Supplier 2	Stage	1
Supplier 2	Deliver	5
Supplier 3	Release	1
Supplier 3	Produce	1
Supplier 3	Package	1
Supplier 3	Stage	1
Supplier 3	Deliver	2
Supplier 4	Release	1
Supplier 4	Produce	1
Supplier 4	Package	1
Supplier 4	Stage	1
Supplier 4	Deliver	2

Table 4.15. Server Capacities at Suppliers

Participant	Stage	Capacity (Number of servers)
Manufacturer	Receive	1
Manufacturer	Verify	1
Manufacturer	Transfer	1
Manufacturer	Release	4
Manufacturer	Produce	11
Manufacturer	Package	1
Manufacturer	Stage	1
Manufacturer	Deliver	5
Warehouse	Receive	1
Warehouse	Verify	1
Warehouse	Transfer	1
Warehouse	Release	1
Warehouse	Package	1
Warehouse	Stage	1
Warehouse	Deliver	4

Table 4.16. Server Capacities at the Manufacturer and the Warehouse

Participant	Stage	Capacity (Number of servers)
Retailer 1	Receive	1
Retailer 1	Verify	1
Retailer 1	Transfer	1
Retailer 1	Release	1
Retailer 1	Package	1
Retailer 1	Stage	1
Retailer 1	Deliver	2
Retailer 2	Receive	1
Retailer 2	Verify	1
Retailer 2	Transfer	1
Retailer 2	Release	1
Retailer 2	Package	1
Retailer 2	Stage	1
Retailer 2	Deliver	2

Table 4.17. Server Capacities at the Retailers

4.3.2.5 Lead Times

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,

$$\mathrm{LT}_{\mathrm{Retailer1,\ Product3}} = k(CT_{Manufacturer} + CT_{Warehouse} + CT_{\mathrm{Re}tailer1})$$

In the simulation experiments, k has been set at 1.5. Table 4.18 gives the values for the lead times.

Participant	Product	Lead Time (Days)
Supplier 1	Component 1	4
Supplier 2	Component 2	4
Supplier 3	Component 3	4
Supplier 4	Component 4	4
Manufacturer	Product 1	9
Manufacturer	Product 2	9
Manufacturer	Product 3	13
Warehouse	Product 1	4
Warehouse	Product 2	4
Warehouse	Product 3	4
Retailer 1	Product 1	5
Retailer 1	Product 2	9
Retailer 1	Product 3	18
Retailer 2	Product 1	6
Retailer 2	Product 2	10
Retailer 2	Product 3	19

Table 4.18. Lead Times for Participants and Products

4.3.2.6 Design of Experiments

The analyses of scenarios is very similar to the one carried out for Supply Chain One. We consider three rescheduling periods, and for each scenario, ten replications are carried out to get the value for 90% confidence interval.

One of the objectives of the experiments is to analyze the effect of synchronization on the performance of the system. This work considers two kinds of synchronizations: backward and forward. In backward synchronization, we time the decisions so that upstream decisions will be able to include the downstream decisions without much time delay. Upstream decisions are timed at a specific offset from the downstream decisions, so that, when an upstream decision is taken, the downstream decision-making process has already been carried out. The opposite of this is forward synchronization. Here, we time the upstream decisions ahead of the downstream decisions. This research also analyzes the effect of varying the rescheduling period of one particular activity while keeping the rescheduling periods of the other activities fixed in the supply chain. The third objective is to check if changing the rescheduling period of one retailer independent of the other leads to any significant change in the performance of the system, compared to the performance when both the retailers have the same rescheduling period.

We consider three levels of rescheduling periods. They are: 4 hours (low), 24 hours (medium), and 72 hours (high). These numbers correspond to the intervals at which the decisions are made for sourcing, production, or delivery.

This work considers six different scenarios for analyzing the effects of synchronization. These scenarios correspond to low, medium, and high rescheduling periods for all the rescheduling activities. One set of three scenarios is carried out with backward synchronization, while another set of three scenarios is carried out with forward synchronization. For analyzing the effects of varying the rescheduling period of one particular activity, we vary the manufacturer's production rescheduling period, while maintaining the rescheduling periods for all the other activities in the supply chain at 24 hours. This is done for both backward synchronized and forward synchronized cases. This leads to a total of six different scenarios. But two of these (rescheduling period of 24 hours for all the activities, forward synchronized and backward synchronized) have already been included in the first set of experiments. For the third case, we vary the rescheduling period for each activity at the two retailers independently, while maintaining all the other rescheduling periods at 24 hours. With three activities and three different values for rescheduling periods for each retailer, we get eighteen different combinations, nine with backward synchronization, and nine with forward synchronization. Out of these eighteen, we have already analyzed two scenarios in the previous cases. Tables 4.19, 4.20, and 4.21 summarize the scenarios analyzed.

In all the cases, we take the cycle times and percent tardy measures as the performance measures. We collect the performance measures for the manufacturer, the warehouse, and the retailers. Since the customer interacts with the retailers, the measures at the retailer give the performance of the supply chain as seen by the end customer.

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

Table 4.19. Effect 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 4.20. Effect of Varying Production Rescheduling Period at 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 4.21. Varying the Rescheduling Periods of Retailers Independent of Each Other

4.4 Simulation Results

This section gives the results of the simulation runs for the two supply chains. For Supply Chain One, we analyze the results from varying the three rescheduling periods. In addition, we also analyze the effects of varying the inventory policy and production heuristic. For Supply Chain Two, the results include the effects of forward and backward synchronization, effects of varying the rescheduling period of a single activity, and the effects of varying the rescheduling periods of the retailers independent of each other.

4.4.1 Supply Chain One

4.4.1.1 Effect of Varying Sourcing Rescheduling Period

The results from varying the sourcing rescheduling period are presented in Table 4.22. We vary the rescheduling period for sourcing in the range of 0.1 to 120 hours, keeping the rescheduling period for the other activities at 4 hours. Sourcing rescheduling period affects the inventory performance and hence the availability of raw materials for production.

In the table, the various columns correspond to the stages involved between the customer placing the order and the manufacturer delivering it. All the entries are average values obtained from simulation. *Order receipt to release for production* is the average time between the manufacturer receiving an order from the customer and the actual release of that order for production in the shop floor. *Start build to ready for shipment* cycle time gives the average time between an order getting released for production in the shop floor and it's reaching the finished goods inventory. The processing times at various stages and congestion in the shop floor affect this. The cycle time between *ready for shipment to release for shipment* is determined by the average time it takes for an order in the finished goods inventory to get approved for shipment. The final stage, that is, the transportation of the finished goods from the manufacturer site to the customer site, is dependent on the transportation time and the availability of transporters. We keep track of this in the *release for shipment to delivery at customer* column. The model assigns a due date to each order and records the percentage of orders that were not fulfilled on time, as percent tardy. In addition to the average values for the simulation runs, the table also gives the half width for 90 percent confidence interval.

Rescheduling Period (Hrs)	Category	Order Receipt to Start build (Days)	Start build to ready for shipment (Days)	Ready for Shipment to Release for Shipment (Days)	Release for Shipment to Delivery at Customer (Days)	Average Cycle Time	% Tardy
0.1	Average	0.0840	3.25	0.0838	0.2235	3.64	21.14%
	Half Width	0.0013	0.41	0.0009	0.0125	0.41	5.44%
1	Average	0.0832	3.41	0.0834	0.2223	3.80	24.35%
	Half Width	0.0014	0.55	0.0010	0.0131	0.56	7.75%
2	Average	0.0833	3.58	0.0825	0.2172	3.96	25.87%
	Half Width	0.0007	0.60	0.0008	0.0069	0.60	8.35%
4	Average	0.0837	3.04	0.0824	0.2145	3.42	18.37%
	Half Width	0.0011	0.27	0.0007	0.0080	0.27	2.54%
8	Average	0.0828	3.37	0.0836	0.2247	3.76	22.40%
	Half Width	0.0013	0.42	0.0007	0.0116	0.42	5.33%
16	Average	0.0833	3.19	0.0834	0.2244	3.58	20.62%
	Half Width	0.0013	0.49	0.0010	0.0075	0.49	6.18%
24	Average	0.0924	3.88	0.0830	0.2295	4.28	30.55%
	Half Width	0.0143	0.67	0.0012	0.0120	0.67	11.40%
48	Average	0.2785	3.30	0.0827	0.2209	3.88	24.26%
	Half Width	0.1098	0.24	0.0007	0.0064	0.29	3.79%
72	Average	0.5909	4.77	0.0836	0.2199	5.67	46.83%
	Half Width	0.2083	1.13	0.0009	0.0128	1.30	13.18%
96	Average	1.8238	5.73	0.0842	0.2267	7.87	83.32%
	Half Width	0.4925	0.51	0.0008	0.0083	0.76	9.89%
120	Average	4.4369	7.74	0.0838	0.2458	12.51	96.88%
	Half Width	1.2160	1.02	0.0006	0.0184	1.52	2.85%

Table 4.22. Effect of varying sourcing rescheduling period

Figure 4.5 gives the bar chart representation of the average values in Table 4.22. A stage by stage representation is given in Figure 4.6. We notice that 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 a queue build up and increased shop floor times.

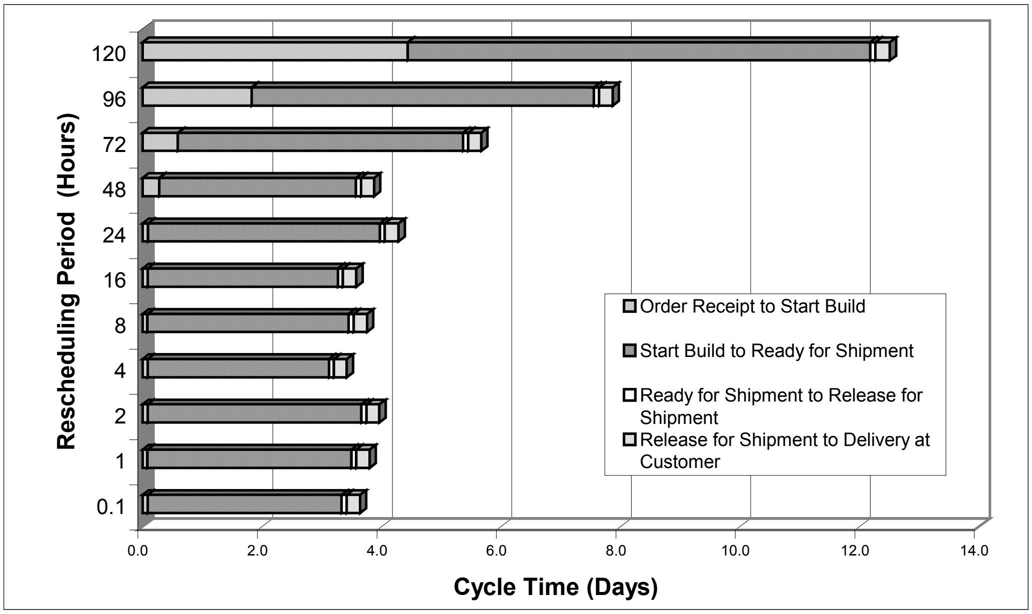

Figure 4.5. Cycle time and sourcing rescheduling period

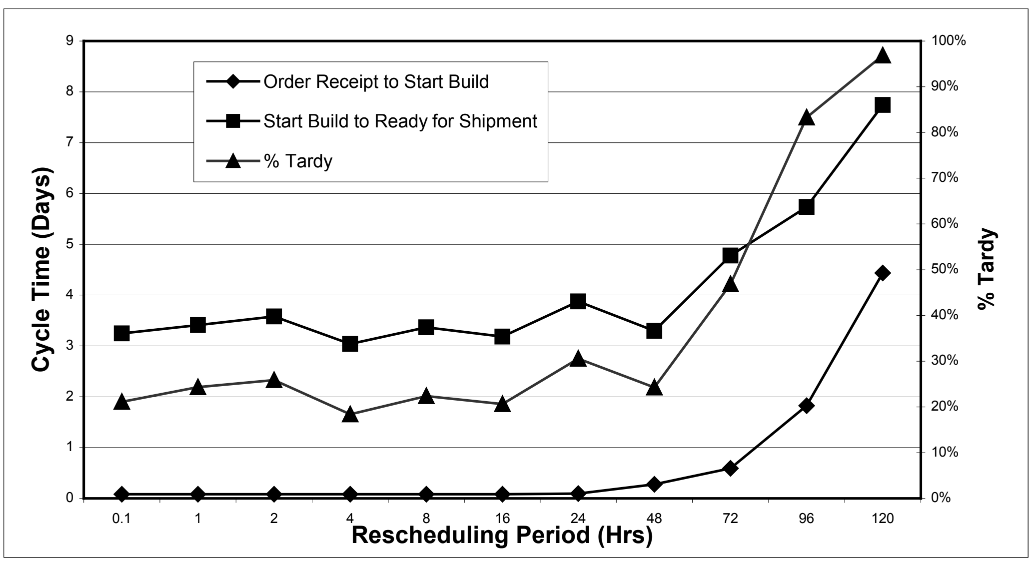

Figure 4.6. Effect of sourcing rescheduling period on raw material availability, production variability and due date performance

4.4.1.2 Effect of Varying Production Rescheduling Period

Table 4.23 gives the performance of the manufacturer under different production rescheduling periods. The various entries are similar to the ones in Table 4.22. Here the manufacturer varies the intervals at which the customer orders that are pending for production are checked. The manufacturer varies the production rescheduling period between 0.1 hours and 120 hours.

Rescheduling Period (Hrs)	Category	Order Receipt to Start build (Days)	Start build to ready for shipment (Days)	Ready for Shipment to Release for Shipment (Days)	Release for Shipment to Delivery at Customer (Days)	Average Cycle Time	% Tardy
0.1	Average	0.0021	3.18	0.0829	0.2289	3.50	19.35%
	Half Width	0.0000	0.31	0.0010	0.0116	0.30	3.29%
1	Average	0.0211	3.56	0.0839	0.2355	3.90	25.45%
	Half Width	0.0002	0.50	0.0010	0.0171	0.50	8.13%
2	Average	0.0421	3.20	0.0833	0.2304	3.56	20.17%
	Half Width	0.0006	0.16	0.0010	0.0158	0.16	2.01%
4	Average	0.0844	3.69	0.0841	0.2276	4.08	28.42%
	Half Width	0.0015	0.61	0.0005	0.0190	0.63	9.14%
8	Average	0.1661	3.65	0.0823	0.2126	4.11	27.59%
	Half Width	0.0023	0.54	0.0011	0.0089	0.54	7.90%
16	Average	0.3326	3.18	0.0839	0.2148	3.81	21.40%
	Half Width	0.0073	0.21	0.0009	0.0109	0.21	1.81%
24	Average	0.5030	3.44	0.0831	0.2308	4.26	27.90%
	Half Width	0.0097	0.58	0.0010	0.0181	0.58	10.01%
48	Average	1.0013	3.71	0.0833	0.2273	5.02	36.65%
	Half Width	0.0146	0.19	0.0008	0.0079	0.20	3.43%
72	Average	1.4956	4.13	0.0838	0.2279	5.94	54.43%
	Half Width	0.0194	0.44	0.0012	0.0126	0.43	9.74%
96	Average	1.9916	4.61	0.0832	0.2227	6.91	75.10%
	Half Width	0.0393	0.39	0.0005	0.0087	0.41	6.97%
120	Average	2.5381	4.93	0.0835	0.2265	7.78	92.23%
	Half Width	0.0468	0.47	0.0010	0.0157	0.47	2.72%

Table 4.23. Effect of varying production rescheduling period

Varying production rescheduling periods affects the time between order receipt to release for production and the production duration. Figure 4.7 shows that there is no significant effect on the overall performance of the system till about a rescheduling period of 24 hours. From Figure 4.8, it is seen that the order receipt to release for production 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 release for production is linearly dependent on the production rescheduling period. Figure 4.7 illustrates this, as the order receipt to release for production 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 is directly dependent on the production rescheduling period. So at higher rescheduling periods, on average, more orders are released at once to the shop floor. Till a certain level, the shop floor can handle this. But if the number of orders released exceeds the capacity of the system, large queues build up. This results in increased production cycle time. Figure 4.7 shows that there is a rise in production cycle time 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. Increase in cycle times at these two stages also leads to a rise in the percentage of tardy orders.

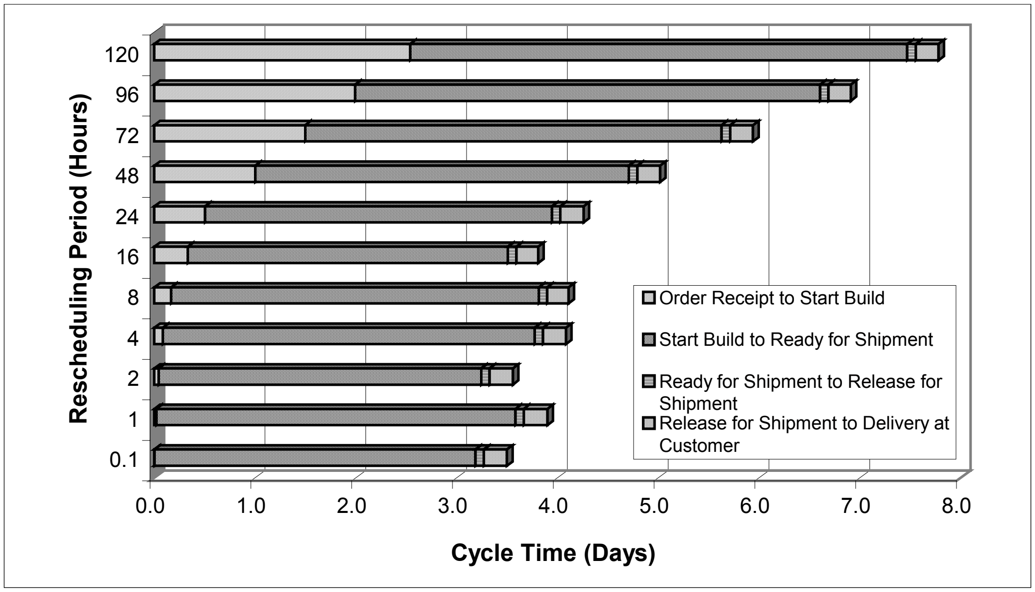

Figure 4.7. Cycle time and production rescheduling period

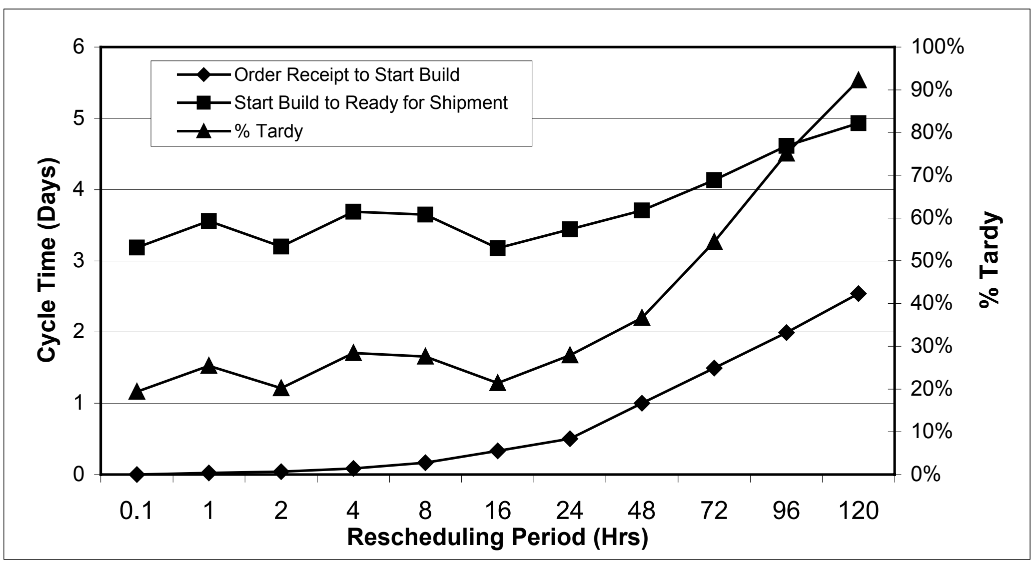

Figure 4.8. Effect of production rescheduling period on order release delay, production variability and due date performance

4.4.1.3 Effect of Varying Delivery Rescheduling Period

Table 4.24 gives the performance of the system under varying delivery rescheduling periods. The delivery rescheduling period refers to the interval at which the delivery management system checks the finished goods inventory to release orders for delivery. Every time the system checks the finished goods inventory for delivery, all the orders in the finished goods inventory are released for production. Since the number of transporters is limited, if too many orders are released for delivery at once, it leads to a queue build up. This leads to an increased cycle time for delivery, rising the overall cycle time.

Rescheduling Period (Hrs)	Category	Order Receipt to Start build (Days)	Start build to ready for shipment (Days)	Ready for Shipment to Release for Shipment (Days)	Release for Shipment to Delivery at Customer (Days)	Average Cycle Time	% Tardy
0.1	Average	0.0824	2.98	0.0021	0.2148	3.28	17.62%
	Half Width	0.0011	0.23	0.0000	0.0063	0.23	2.44%
1	Average	0.0832	3.40	0.0210	0.2220	3.73	22.85%
	Half Width	0.0013	0.58	0.0002	0.0121	0.58	7.46%
2	Average	0.0831	3.27	0.0418	0.2124	3.60	21.48%
	Half Width	0.0010	0.27	0.0005	0.0092	0.27	4.68%
4	Average	0.0836	3.42	0.0826	0.2139	3.80	24.37%
	Half Width	0.0015	0.52	0.0010	0.0071	0.52	7.01%
8	Average	0.0838	3.18	0.1677	0.2382	3.67	21.29%
	Half Width	0.0014	0.31	0.0022	0.0094	0.31	4.32%
16	Average	0.0834	3.52	0.3308	0.3179	4.25	28.91%
	Half Width	0.0010	0.68	0.0029	0.0093	0.68	11.09%
24	Average	0.0831	3.41	0.5027	0.4065	4.40	29.60%
	Half Width	0.0010	0.42	0.0063	0.0080	0.43	7.91%
48	Average	0.0833	3.06	1.0002	0.7138	4.86	33.65%
	Half Width	0.0006	0.27	0.0139	0.0306	0.29	6.14%
72	Average	0.0836	3.07	1.5086	1.0586	5.72	53.79%
	Half Width	0.0016	0.22	0.0225	0.0414	0.24	6.90%
96	Average	0.0836	3.44	2.0072	1.3700	6.90	79.43%
	Half Width	0.0011	0.46	0.0178	0.0413	0.50	7.64%
120	Average	0.0830	3.32	2.5177	1.6738	7.60	91.37%
	Half Width	0.0015	0.55	0.0239	0.0729	0.58	2.94%

Table 4.24. Effect of varying delivery rescheduling period

Figure 4.10 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.

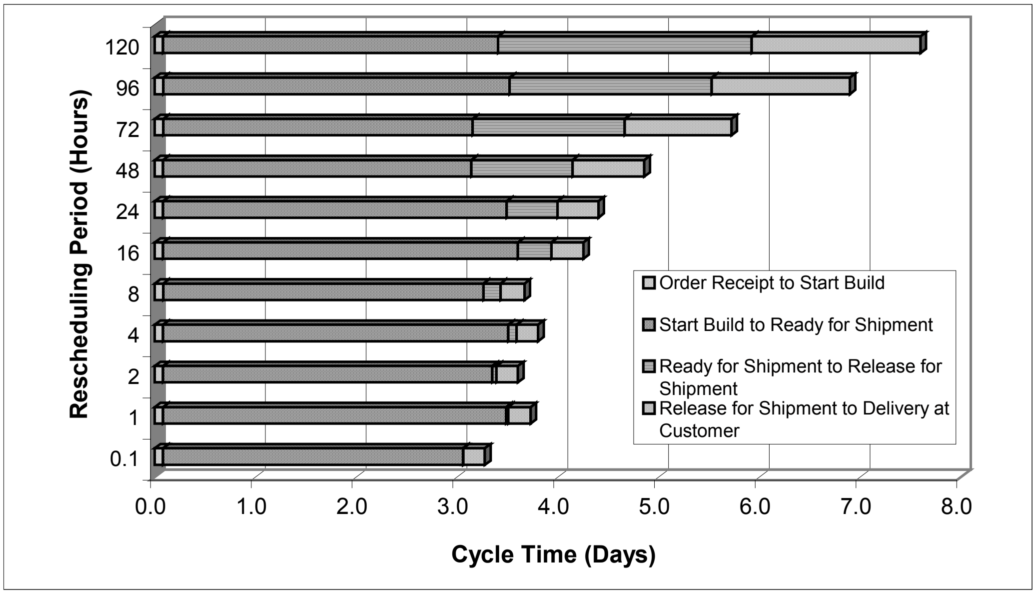

Figure 4.9. Cycle time and delivery rescheduling period

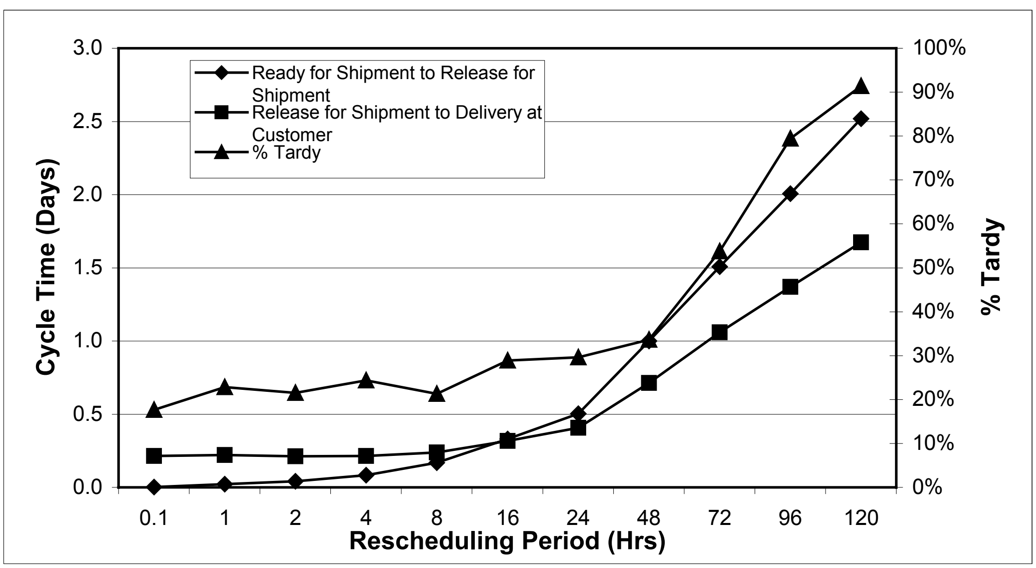

Figure 4.10. Effect of delivery rescheduling period on delivery release delay, delivery variability and due date performance

4.4.1.4 Effect of Varying Inventory Policy

Figure 4.11 compares the effect of changing the inventory policy on the performance of the manufacturing system. We reduce the reorder point to five days worth of inventory from the original value of seven days, keeping the order up to quantity at the same level. The effect on the performance is not very significant 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.

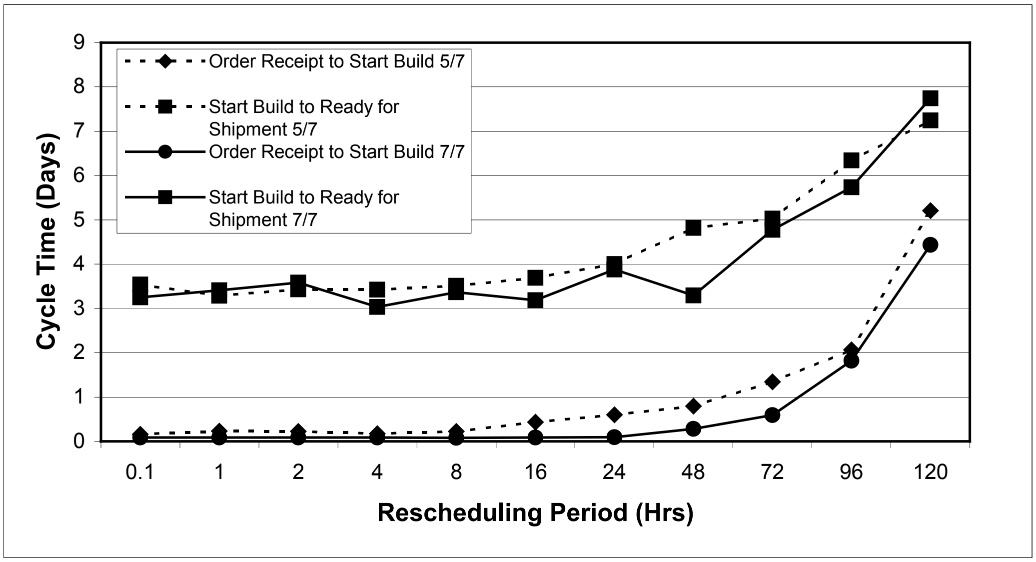

Figure 4.11. Comparing the performance under two different inventory policies

.

4.4.1.5 Effect of Varying Production Policy

In order to compare the effects of production policy on the system performance, we consider two alternatives. First-in-first-out (FIFO) heuristic releases orders to the shop floor in the order they were received. Shortest-processing-time (SPT) heuristic sends the orders in the increasing order of their processing times. Figure 4.12 compares the results for the two alternatives. We analyze two of the performance measures: One is the average time the order spends in the shop floor and the other is the percent tardy measure. These two performance measures get affected directly with a change in the production policy.

Figure 4.12 shows that for lower rescheduling periods, there is no significant difference between the performances of the two systems. At high rescheduling periods, the system with SPT heuristic performs better than the system with the FIFO heuristic. This can be explained as follows: At very high production rescheduling periods, the system releases more orders for production at a time than the system can handle with its limited resources. This leads to a queue build up. 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 get tardy mainly due to the queue build up. Speeding up 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.

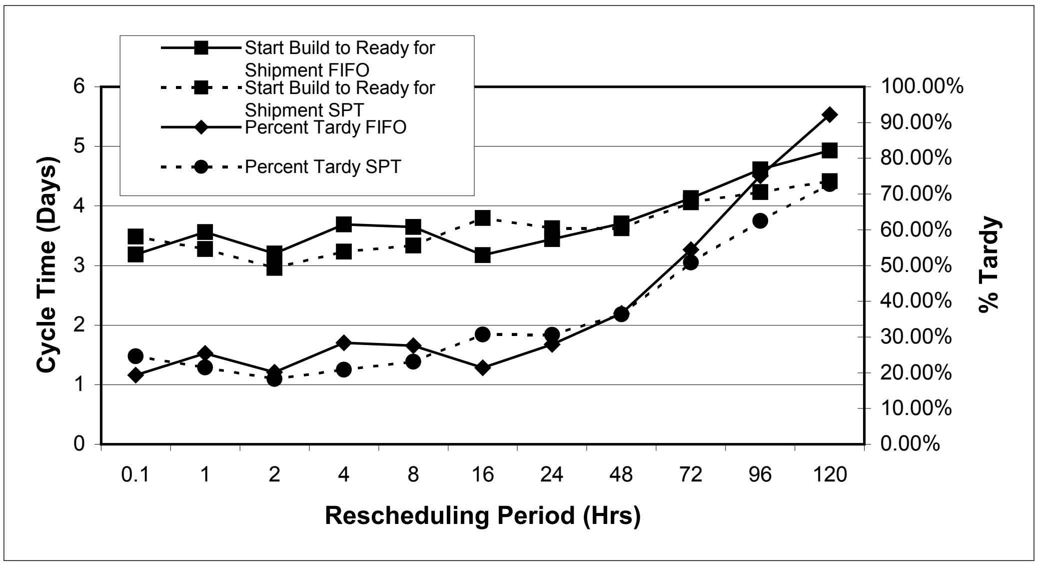

Figure 4.12 Performance of the manufacturing system under two different production policies

4.4.2 Supply Chain Two

4.4.2.1 Effect of Synchronization

Here we study the difference in performance of the supply chain under two kinds of synchronization. In forward synchronization, decisions at an upstream participant are made before all the downstream participants. In backward synchronization, decisions at a downstream participant are made earlier than all its upstream participants. The advantage with backward synchronization is that decisions made by a downstream participant get passed onto the corresponding upstream participant at a shorter notice. This effect can be seen in Figures 4.13, 4.14, and 4.15. 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: delay in the processing of information and 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.

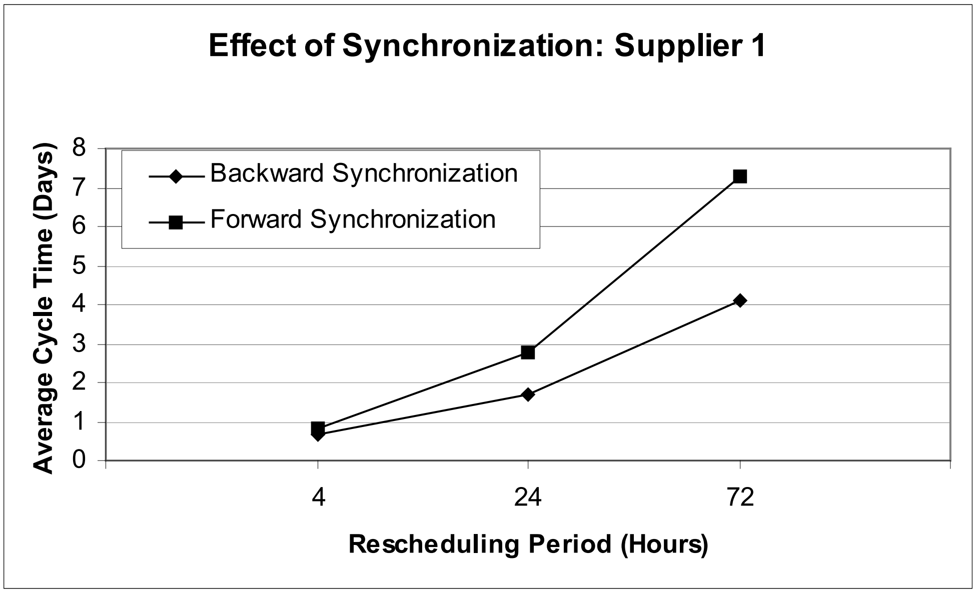

Figure 4.13. Effect of Synchronization: Supplier 1

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 delay in the processing of information and shortage of raw materials. As the supplier does not experience shortage of raw materials, this additional difference is not seen in Figure 4.13.

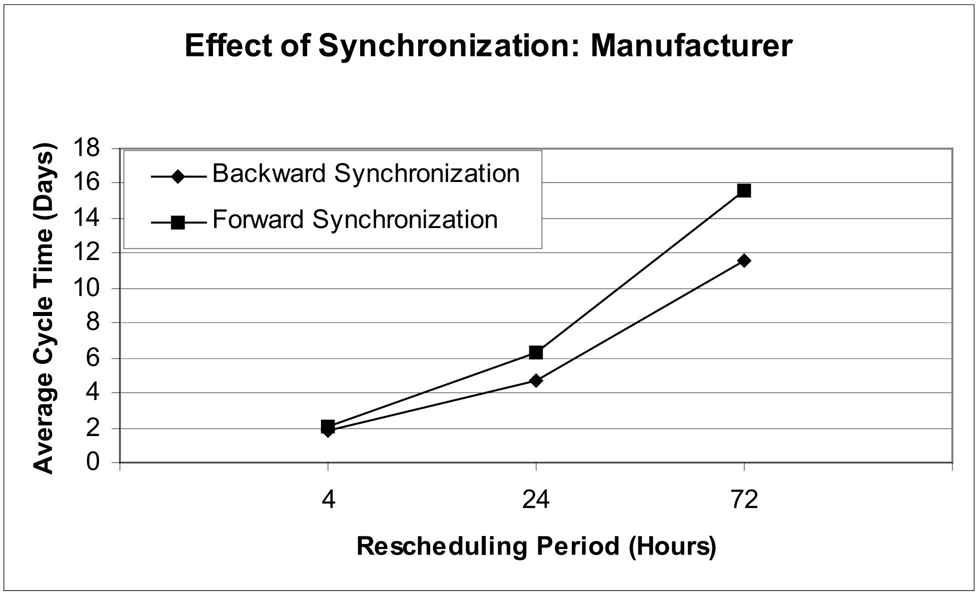

Figure 4.14. Effect of Synchronization: Manufacturer

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.

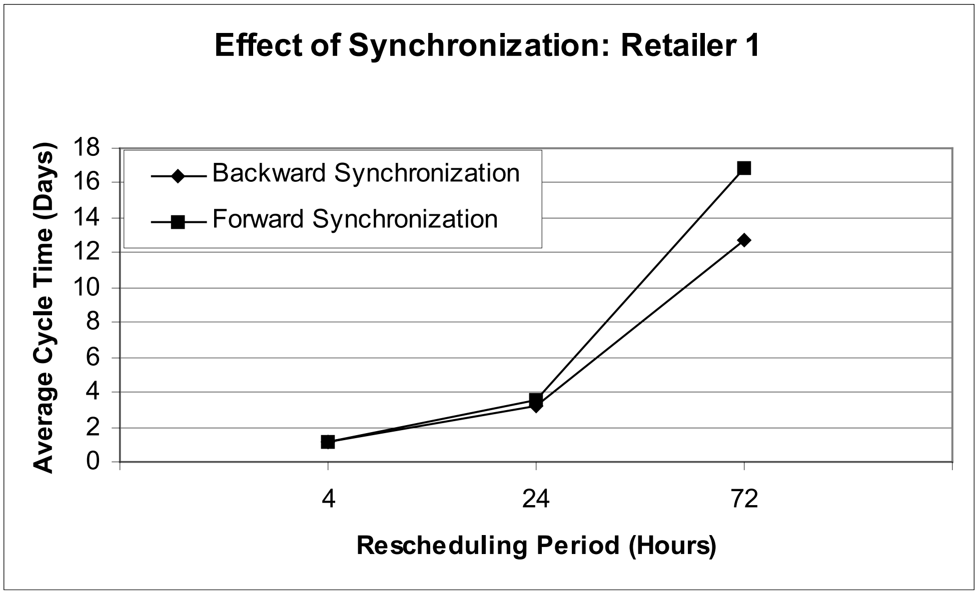

Figure 4.15. Effect of Synchronization: Retailer 1

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.

4.4.2.2. Effect of Varying Manufacturer's Production Rescheduling Period

In this section, we discuss the results obtained by 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.

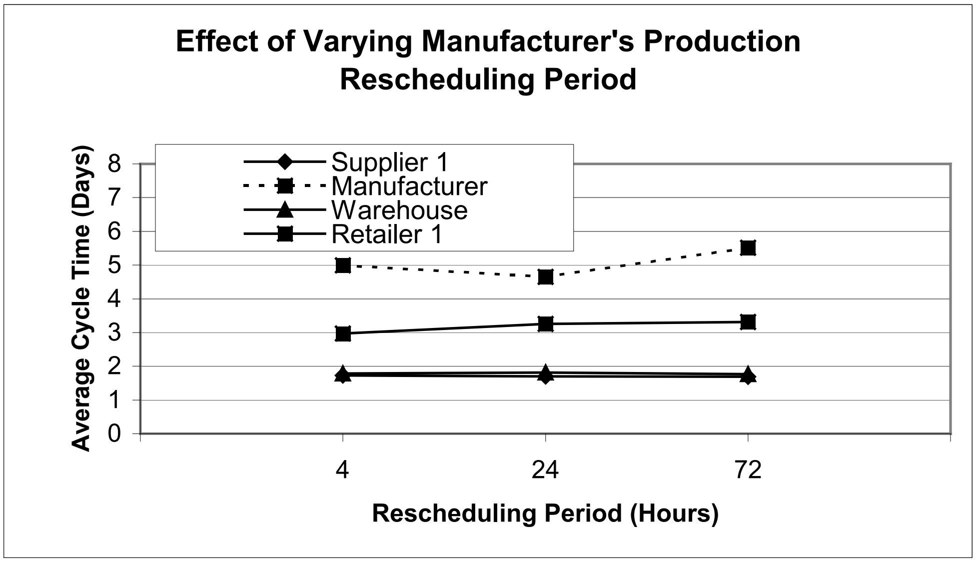

Figure 4.16. Effect of Varying Manufacturer's Production Rescheduling Period

As we see from Figure 4.16, 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. There is no increase due to lumping, as the average number of orders processed during each cycle in the 72 hours case is lower than the capacity of the system. So an average utilization of 85% is ensured without much queue build up in the shop floor. A much larger rescheduling period would have led to a lumping effect. Equivalently, lumping would have occurred if the rescheduling periods at the warehouse and retailers were much smaller.

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.

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

Here we discuss the results of the performance of the supply chain when the rescheduling periods at the retailers are varied independent of each other. The results correspond to backward synchronization. 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.

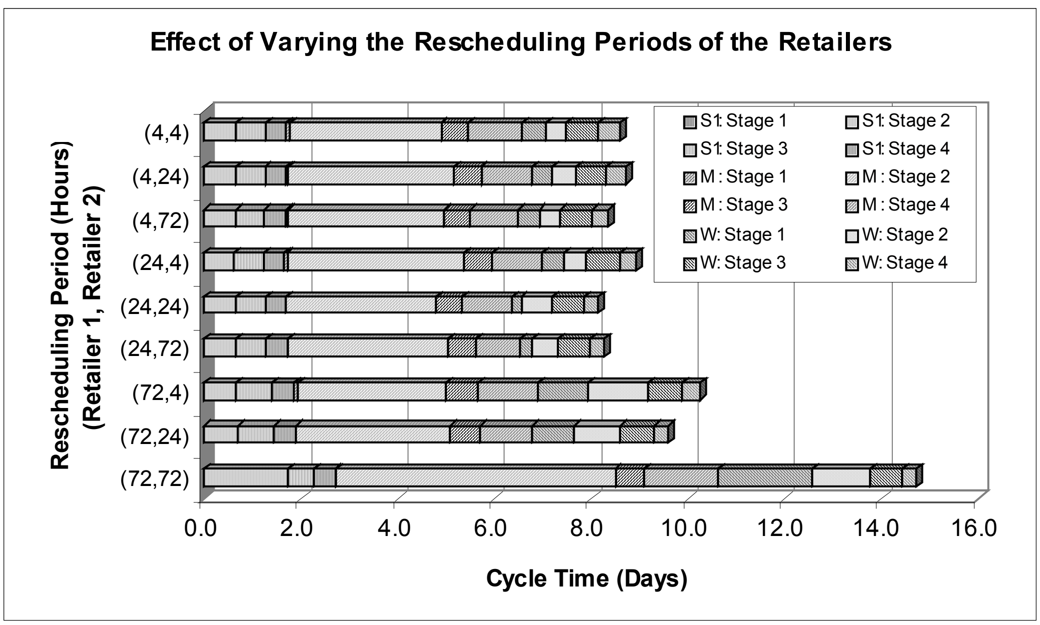

Figure 4.17. Effect of Varying the Rescheduling Periods at the Retailers

Figure 4.17 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 average time between the receipt of an order and the release of production order. Stage 2 is the average time the order spends in the shop-floor during production, packaging, and staging. Stage 3 is the average time an order spends in the finished goods inventory. Stage 4 corresponds to the average time between the release of an order for delivery and the delivery at the customer site.

From figure 4.17, we observe that the sum of the average cycle times remain approximately the same for all the scenarios where both the retailers have a rescheduling period less than 72 hours The remaining three scenarios, where Retailer 1 has a rescheduling period of 72 hours, 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 last three bars in Figure 4.17 correspond to high rescheduling period for Retailer 1. 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 4.17, the increase in the cumulative cycle times is largely due to the increase in the production cycle times at the manufacturer. We notice that 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.

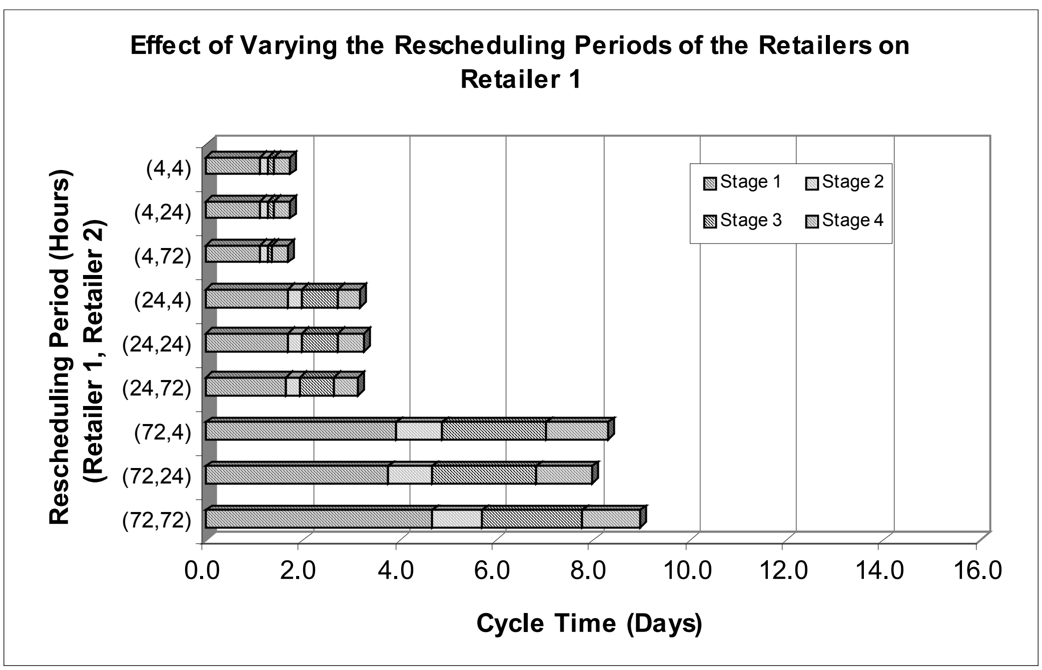

Figure 4.18 Effect of Varying the Rescheduling Periods at the Retailers on Retailer1

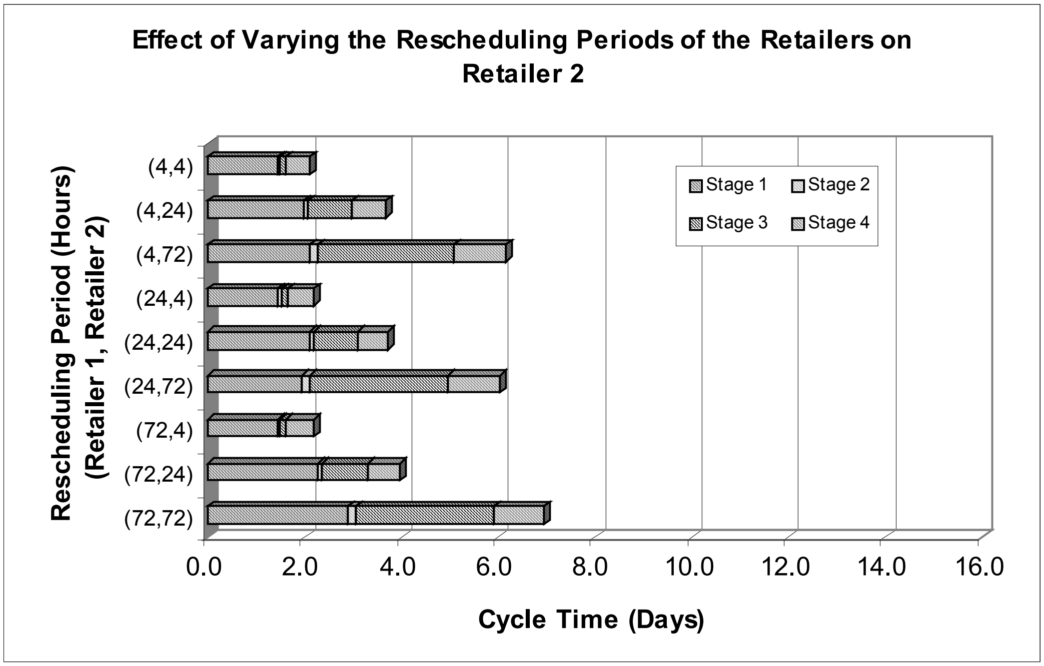

Figure 4.19 Effect of Varying the Rescheduling Periods at the Retailers on Retailer2

Figures 4.18 and 4.19 show the average cycle times at the retailers. We see that 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 found to be 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.

4.5. Summary and Conclusions

In this chapter, we designed and analyzed the performance of two different supply chains under varying conditions of rescheduling periods. The first supply chain had five participants, including two suppliers, one manufacturer, and two customers. The second supply chain had ten participants, including four suppliers, one manufacturer, one warehouse, two retailers, and two customers. In both the supply chains, the customers placed orders for various products at random intervals and the products were 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.

In Supply Chain 1, we analyzed the performance of the manufacturer under eleven different rescheduling periods. We also analyzed the effect of varying the inventory policy and production policy. Whereas inventory and production policies had an impact on the performance, it was observed that rescheduling periods play a much more important role. A high rescheduling period at a particular activity may have adverse effect on the performance at downstream activities too. From the simulation runs, one may conclude that very low rescheduling periods are always good for the system. But from the results, we also notice that the marginal improvements obtained by reducing the rescheduling periods are not significant beyond some point. In fact, reducing the rescheduling periods to very low values may have other adverse effects. One of them is the increased effort to arrive at new plans more frequently. Also, too frequent change of plans will complicate the operations of the firm. Plans have to be changed every now and then and this may lead to too much confusion at the implementation level.

Supply Chain 2 was much more complicated with ten participants. Here we analyzed the effects of synchronization and interdependence of activities in the supply chain. We observed that synchronization of activities across participants of the supply chain has significant impact on the performance. We analyzed two extreme cases of synchronization. In backward synchronization, whenever an upstream participant takes planning decisions, all the downstream participants would already have carried out their planning activities. In such a scenario, the upstream participant can include all the requirements of the downstream activities without any time delay. Forward synchronization is exactly the opposite. Here, an upstream participant carries out the planning activities before all his downstream participants. This is a very inefficient way of implementation. The results showed that backward synchronization improves the performance of the system significantly.

Backward synchronization can be implemented with the help of a supply-chain wide database. Here, all the participants should be willing to share information with their upstream participants and then the participants can coordinate in a way that would benefit the performance of the entire supply chain. For this kind of coordination to happen through information sharing, all the participants should have significant incentives. This is important since each participant would value his or her benefits more than that of the entire supply chain. Moreover, some of the participants may not want to go for this extent of information sharing in order to get an edge over the competitors.

In Supply Chain 2, like 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 the 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.

5. Summary and Conclusions

This chapter reviews the work carried out in this thesis, describes the contributions of the results, and discusses opportunities for further work.

5.1 Supply Chain Simulation

A typical supply chain consists of participants such as suppliers, producers, warehouses, and retailers. All the participants of the supply chain have some activities in common and by defining a level of detail, it is possible to build modules that can be put together to represent the entire supply chain. We tried to build reusable modules that could be used to represent these activities. The Supply Chain Operations Reference model was used as the basis for standardizing the modules. The modules were implemented in Arena and Microsoft Excel. To build the simulation model, the user has to put together the modules for each participant. Each participant is associated with a Microsoft Excel file. Parameters such as resource capacity and inventory holding cost for each participant are entered through the Microsoft Excel file and the Arena modules. Planning activities are achieved through Microsoft Excel Macros.

Once the model has been developed, the user can specify the replication length and the number of replications. The simulation model keeps track of the results obtained during each replication and uses this information to give a 90% confidence interval for the performance measures. The output includes performance measures such as cycle times at various stages, overall cycle time, percent tardy performance measures, cost of goods sold, and resource utilization.

We noticed that the development time for building the simulation models using these modules was very short. Even complicated supply chains with many participants could be built in a short time. The modules can be used to represent various kinds of participants of the supply chain including manufacturers, warehouses, and retailers.

5.2 Rescheduling Periods and Supply Chain Performance

The supply chain simulation modules were used in developing models to analyze the importance of information flow and rescheduling periods in supply chains. We analyzed two different supply chains. One supply chain had five participants while the other had ten. The study considered rescheduling periods at three different activities: sourcing, production, and delivery.

The emphasis in the analysis of Supply Chain 1 was to find out how increasing the rescheduling periods affects the performance of the participants of the supply chain. In addition to affecting the performance of the corresponding activity, in some cases, high rescheduling periods at a particular activity had a negative impact on the performance of the downstream activities too. This was due to the lumping of orders under high rescheduling periods. Reducing the rescheduling period beyond a point did not improve the performance significantly. Planning activity leads to change of existing plans and too frequently changing plans could lead to chaos on the shop floor. There is cost associated with every planning activity. So if the planning activities were carried out more frequently, that would lead to increased expenses. So it is necessary to strike a balance between the costs and the benefits. While the values obtained in this set of simulations is specific to the problem considered, it can be concluded that the insight of the results can be applied to other supply chain systems.

A comparison was also made to determine the effects of production and sourcing policies on the performance of the system. It was found that in the case of sourcing, the rescheduling period had the greatest impact and the effect of reducing the reorder point did not lead to any significant change in the performance. On the other hand, it was noticed that for production rescheduling period, at very high values of rescheduling period, switching from FCFS to SPT rule improved the performance of the system.

In Supply Chain 2, we analyzed the effects of synchronization and interdependence of activities in the supply chain. The analysis showed the importance of timely exchange of information. Two extreme cases were considered: in one, downstream participants carried out planning activities before the upstream participants while in the other, upstream participants carried out the planning activities before their downstream participants. In the first case, the upstream participants get to process the information from the downstream participant without much time delay. This had a considerable positive impact on the performance of the supply chain.

We also saw how demand pattern at a downstream participant can affect the cycle time performance at an upstream participant. This shows how important it is for all the participants to function in a coordinated manner to obtain a good overall supply chain performance.

5.3 Contributions

With increasing competition in the manufacturing industry, it has become important for every company to have an efficient supply chain. Industries have begun to realize that managing information flow is as important as managing material flow in the supply chain. Simulation plays an important role in decision-making. Systems such as supply chains are too complicated to analyze through analytical modeling. Simulation models can represent the uncertainty and variability in the supply chains in an effective way. With the advent of more and more powerful computers, it has become easy to simulate complex systems. But the amount of time needed to develop the simulation model from scratch can be quite high. Most of the discrete event simulation packages available today are not suitable for modeling supply chains. There is a need for constructing libraries that can be used to build supply chain models.

This project created templates that can be used to construct supply chain simulation models with great ease. In addition to the material flow in the model, the supply chain simulation templates take into account information flow and cash flow, which is not easy to implement in standard discrete event simulation software. These simulation modules reduce the time and cost needed to develop supply chain simulations. We addressed two important and conflicting issues in simulation: standardization and customization. The modules were standardized by building them based on the SCOR model. The modules constitute a transparent layer of Visual Basic code over Arena and Microsoft Excel. This allows for any customization that the industry might think necessary in implementing the supply chain.

The experimental studies yielded insights into an important, yet often overlooked factor in the design of supply chain management systems. While a great deal of effort is spent in developing sophisticated planning and scheduling algorithms, little work is done to consider how scheduling frequency and information synchronization affect the supply chain performance. The results reported here clearly show that these factors could have significant impacts.

5.4 Scope for Further Work

Scope for further work lies in implementing more complicated planning logic in Excel using VBA. Since the planning activities are also modular, one can replace a part of the existing framework with suitable procedure to implement different planning logic. One example is inventory management. In the present model, *(R, s, S)* policy has been followed. If the user wants to implement some other inventory management policy, it can be easily done by replacing the VBA procedure in Excel that takes care of sourcing for raw materials. This kind of approach makes the modules very flexible in terms of their logic.

Another drawback of using the supply chain simulation modules in its present form is the huge amount of output data that is made available at the end of simulation runs. Though the program tries to simplify the output by automatically calculating the mean and 90% confidence interval for each performance measure, it is not an easy task to go through the Excel files corresponding to each participant to analyze the outputs. Moreover, the analyst may be interested in some performance measures more than the others. So he may want to check only a subset of the total results. A way to do this is to provide an output analyzer that can be used to extract necessary results and present them in a graphical format. Hewitt (2002) has created a tool that could be modified to perform this function.

In the simulation models analyzed, emphasis was given to the cycle time performance measures. Another way of analyzing the performance would be through financial performance measures. Simulation models can be built with proper pricing data to obtain realistic estimates for the financial performance measures such as cost of goods sold. This way, the change in profit with various modifications in the supply chain can be analyzed.

REFERENCES

[1] Austin, M., and Frankpitt, B.A., 2000, *Lecture Notes for ENSE 621: Systems Engineering Principles,* University of Maryland, College Park.

[2] Barnett, M.W., and Miller, C.J., 2000, "Analysis of the virtual enterprise using distributed supply chain modeling and simulation: An application of e-SCOR", *Proceedings of the 2000 Winter Simulation Conference*, 352-355.

[3] Bean, J. C., Birge, J.R., Mittenthal, J., and Noon, C.E., 1991, "Matchup scheduling with multiple resources, release dates, and disruptions," *Operations Research*, 39 (3), 470-483.

[4] Bhaskaran, S., 1998, "Simulation analysis of a manufacturing supply chain", *Decision Sciences*, 29(3), 633-657.

[5] Blanchard, Benjamin S., and Fabrycky, W.J., 1998, Systems Engineering and Analysis, Third Edition, Prentice Hall Inc., New Jersey.

[6] Church, L. K., and Uzsoy, R., 1992. "Analysis of periodic and event-driven rescheduling policies in dynamic shops", *International Journal of Computer Integrated Manufacturing,* 5, 153 – 163.

[7] Cohen M. and Lee, H., 1988, "Strategic analysis of integrated production – distribution systems: models and methods", *Operations Research*, 36, 216 – 228.

[8] Dhaenens – Flipo, C., and Finke, G., 2001, "An integrated model for an industrial production – distribution problem", *IIE Transactions*, 33, 705 – 715.

[9] Eliter, T., Subrahmanian, V.S., and Pick, G., 1998, "Heterogeneous active agents", *Computer Science Technical Report Series*, University of Maryland, College Park.

[10] Farn, C.K., and A.P. Muhlemann., 1979, "The dynamic aspects of a production scheduling problem," *International Journal of Production Research*, Volume 17, 15-21.

[11] Folie, M., andTiffin, J., 1976, "Solution of a multi – product manufacturing and distribution problem", *Management Science*, 23, 286 – 296.

[12] Herrmann, J., 2001, *ENSE 622 Course Notes*, University of Maryland, College Park.

[13] Hewitt, S., 2002, "Comparing analytical and discrete-event simulation models of manufacturing systems", Master's Thesis: University of Maryland, College Park.

[14] Hopp, W. J., and Spearman, M. L., 2000, *Factory Physics*, Irwin McGraw-Hill.

[15] Jain, S., Workman, R.W., Collins, L.M., and Ervin, E.C., 2001, "Development of a high-level supply chain simulation model", *Proceedings of the 2001 Winter Simulation Conference*, 1129-1137.

[16] Kelton, W.D., Sadowski, R.P., and Sadowski, D.A., 1998, *Simulation with Arena*, McGraw-Hill.

[17] Kim, M. H., and Kim, Y.-D., 1994, "Simulation-based real-time scheduling in a flexible manufacturing system" *Journal of Manufacturing Systems*, 13, 85-93.

[18] Law, A.M., and Kelton, W.D, 1991, *Simulation Modeling and Analysis*, Second Edition, McGraw-Hill, Inc., New York.

[19] Martin, *Management Accounting Concepts Techniques and Controversial Issues*, http://home.att.net/~jvmartin/MAWTextbookMain.htm

[20] Mehta, S. V., and Uzsoy, R. M., 1998, "Predictable scheduling of a job shop subject to breakdowns", *IEEE Transactions on Robotics and Automation*, 14, 365-378.

[21] *Microsoft Visual Basic Language Reference*, 1995, Microsoft Corporation.

[22] Muhlemann, A.P., Lockett, A.G., and Farn, C.K., 1982, "Job shop scheduling heuristics and frequencies of scheduling," *International Journal of Production Research*, 20, 227-241.

[23] Pichler, F., and Schwartzel, H., 1992, *CAST methods in modeling,* Springer-Verlag, Berlin-Heidelberg.

[24] Poirier, Charles C., 1999, *Advanced supply chain management: how to build a sustained competitive advantage*, Berrett-Kochler Publishers.

[25] Riggs, 1994, *Financial and Cost Analysis for Engineering and Technology Management*, John Wiley and Sons.

[26] Sabuncuoglu, I., and Karabuk, S., 1999, "Rescheduling frequency in an FMS with uncertain processing times and unreliable machines", *Journal of Manufacturing Systems*, 18 (4), 268-283.

[27] Shafaei, R., and Brunn, P., 1999, "Workshop scheduling using practical (inaccurate) data - Part 1: The performance of heuristic scheduling rules in a

dynamic job shop environment using a rolling time horizon approach", *International Journal of Production Research*, 37 (17), 3913-3925.

[28] Shafaei, R., and Brunn, P., 1999, "Workshop scheduling using practical (inaccurate) data - Part 2: An investigation of the robustness of scheduling rules in a dynamic and stochastic environment", *International Journal of Production Research*, 37 (18) 4105-4117.

[29] Silver, E.A., Pyke, F.D., and Peterson R., 1998, *Inventory management and production planning and scheduling*, Third edition, John Wiley and Sons.

[30] Smiley, J., 1998, *Learn to Program with Visual Basic 6*, Activepath Ltd.

[31] *Supply Chain Operations Reference – Model*, SCOR Version 4.0, August 2000, Supply Chain Council.

[32] Swaminathan, J.M., Smith, S.F., and Sadeh, N.M., 1998, "Modeling Supply Chain Dynamics: A Multiagent Approach", *Decision Sciences*, 29 (3), 607-631.

[33] Towill, D.R., Naim, M.M., and Wikner, J., 1992, "Industrial dynamics simulation models in the design of supply chains", *International Journal of Physical Distribution and Logistics Management*, 22(5), 3 – 13.

[34] Vieira, G. E., Herrmann, J. W., and Lin, E., 2000, "Analytical models to predict the performance of a single-machine system under periodic and event-driven rescheduling strategies." (This paper is being published at the *International Journal of Production Research.)*

[35] Vieira, G. E., Herrmann, J. W., and Lin, E., 2000, "Analytical models to predict the performance of parallel-machine systems under three different rescheduling

strategies." (This paper has being submitted for publication at the *Journal of Manufacturing Systems.)*

[36] Vollmann, T. E., Berry, W. L., and Whybark, D. C., 1988, *Manufacturing Planning and Control Systems*, Dow Jones-Irwin.

[37] Vondermbse, M.A., and White, G.P., 1987, *Operations Management: Concepts, Methods and Strategies*, West Publishing Company.

[38] Williams, J., 1981, "Heuristic techniques for simultaneous scheduling of production and distribution in multi – echelon structures: theory and empirical comparisons", *Management Science*, 27, 336 – 351.

[39] Wu, S. David, Byeon, Eui-Seok, and Storer, Robert H., 1999, "A graph-theoretic decomposition of the job shop scheduling problem to achieve scheduling robustness," *Operations Research*, 47 (1), 113-124.