This is to certify that the

dissertation entitled

An Experimental Analysis of
Bottlenecks Within a Theoretical
Job Shop: A Simulation Study

presented by

Young Jin Ahn

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Management

Major professor

Date June 11, 1987

AN EXPERIMENTAL ANALYSIS OF BOTTLENECKS WITHIN A THEORETICAL JOB SHOP: A SIMULATION STUDY

By

Young Jin Ahn

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Management

1987

ABSTRACT

AN EXPERIMENTAL ANALYSIS OF BOTTLENECKS WITHIN A THEORETICAL JOB SHOP: A SIMULATION STUDY

by

Young Jin Ahn

The purpose of this study was to identify and assess the problems present when trying to manage a bottleneck job shop in which one of the work centers experiences consistently higher machine loads. The bottleneck job shop, while fairly common in practice, has received little attention from researchers.

Due to the lack of detailed knowledge surrounding bottlenecks, combined with their crucial impact on shop performance, the first step in the research was to develop a theoretical framework of a bottleneck job shop. This framework provided the basis of the study.

The control procedures examined were dispatching rules and order review/release mechanisms. The two bottleneck characteristics studied were location of the bottleneck and prevalence or extent of the bottleneck.

The research vehicle for the study was a computer simulation of a quasi-random job shop which was modeled using SLAMII. Analysis was conducted using primarily analysis of variance.

Several conclusions can be drawn from the findings of the study. The selection of dispatching rules had a greater impact on system performance than that of order review/release mechanisms. Specifically, the SPT rule consistently performed well under almost all conditions tested in this study.

The use of order review/release mechanisms, when compared to the immediate release mechanism, resulted in an improvement in the level of lead time and work-in-process. However, its use did result in degradation in both the levels of mean tardiness and the percentage of jobs tardy.

Shop performance was significantly influenced by both of the bottleneck characteristics: location and prevalence. In addition, there existed many higher significant interactions among experimental factors. Furthermore, the presence of the bottleneck affected the performance of not only bottleneck jobs but also non-bottleneck jobs.

In summary, the results of the study suggest that both managers and researchers must first describe the bottlenecks in terms of their characteristics and, then, apply the most adequate control procedures.

To My Family

ACKNOWLEDGMENTS

This dissertation could not be completed without the contribution of many people. I wish to express my sincere appreciation and thanks for the people who made this study possible.

I would like to thank the members of my dissertation committee for their support and valuable ideas.

Dr. Steven A. Melnyk, the Chairman of the Dissertation Committee and Associate Professor of Department of Management, stimulated the initial idea for this research. His probing suggestions, continuing interest, and personal concerns provided a needed impetus for this research. He provided invaluable encouragement and constructive criticism at every stage of the project. He meticulously edited this paper with warm and enthusiastic support. He helped me believe in my ability. His contribution to my professional development is acknowledged with sincere gratitude.

Dr. Phillip L. Carter, a member of the Dissertation Committee and Associate Dean of College of Business, provided valuable comments and suggestions. He met each of the countless interruptions with a willingness to help. His in-depth knowledge and wisdom made a significant contribution to this research study. I am grateful.

Dr. Gary L. Ragatz, a member of the Dissertation Committee and Assistant Professor of the Department of Management, spent countless hours of reading and discussing the initial drafts of this research. His valuable comments, corrections, and above all his in-depth knowledge of the methodology and analysis portion of the research was an asset to the investigation. His contribution is greatly appreciated.

My gratitude extends to Dr. Ram Narasimhan, the Academic Advisor and the Chairman of the Department of Management. He provided significant financial support. His continuous interest, guidance, and encouragement were invaluable. His support and help during my stay at Michigan State is greatly appreciated.

Also, I wish to express my sincere appreciation to my parents, Dr. Sang Yong Ahn and Mrs. Hae Kyung Kim. They supplied the opportunity for higher education. They provided incredible support, confidence, and inspiration from tens of thousands miles away.

Most of all, I wish to express my sincere appreciation to my wife, Kyu Sook. Without her devotion, inspiration, and above all her sacrifice, this dissertation could never be completed. Also I appreciate the involuntary sacrifices of my two sons, Kyung Seon and Kyung Min.

Of course, I, alone, am fully responsible for any errors and omissions of this paper.

TABLE OF CONTENTS

Page

LIST OF TABLES

TABLE		Page

TABLE Page

LIST OF FIGURES

FIGURE | Page

FIGURE		Page

CHAPTER 1

BOTTLENECK JOB SHOP

1.1 Introduction

Effective shop floor control[1] plays a critical role in any successful manufacturing system. As pointed out by Melnyk, Carter, Dilts and Lyth (1985), effective shop floor control is the necessary complement to good planning. Shop floor control is primarily concerned with the smooth flow of materials, orders and information to satisfy customer needs (as represented by the production schedules) in a timely and cost effective manner. To meet these objectives, the shop floor control system draws on a wide range of different activities.

Traditionally, the focus has been directed at the detailed scheduling phase of the shop floor control system. For example, Melnyk, Carter, Dilts, and Lyth (1985) noted that of over 1200 articles on shop floor control, 213 dealt primarily with issues involving scheduling, sequencing, and dispatching. The primary emphasis among these articles was

1. Melnyk and Carter (1985) define shop floor control as the very detailed short-term planning, execution and monitoring activities needed to control the flow of an order from the moment the order is released by the planning system for execution until the order is filled and its disposition completed.

placed on dispatching rules. Recently, however, researchers and practicing managers have begun shifting their attention away from the dispatching function to other activities (such as order review/release). This shift in attention is also taking place in other areas such as capacity management.

Traditionally, questions involving shop floor control activities were studied within the context of a very specific manufacturing setting: the job shop manufacturing setting.[2] Under this setting, researchers made several general but key assumptions about the nature of the setting. One such crucial assumption was that the shop was essentially "balanced." This implied that while there were short-term work imbalances, in the long run, no one machine or work center persistently constrained the operation of the other work centers. In other words, a "balanced" shop was one in which the long term workload was randomly but evenly distributed across the various work centers. Such a shop setting, while important, is not necessarily representative of all possible job shop settings.

There exists another category of job shop. This is one which is not "balanced." Consideration should be given to such a shop for several reasons. It is a better representation of the reality encountered on the shop floor. (Prather 1983) Bottlenecks, a critical characteristic of the unbalanced job shop, also have a significant impact on the operation of entire shop floor control system. In this shop,

2. A job shop is a shop in which routings of orders are distributed randomly.

there exists one or more constraining machines or work centers which significantly affect the flow of work through the system. These are bottleneck machines or work centers. The presence of bottleneck work centers in a job shop manufacturing system can and does create a unique set of problems, which otherwise would not happen in balanced job shop settings.

Wight (1970) noted that any small capacity bottleneck is followed by an aggravation of the backlog situation in the shop. This is followed by an increased level of expediting activities. It is not expected, however, that the increased level of expediting is a desirable resolution to this bottleneck shop.

Goldratt and Cox (1984, pp. 138) also recognized the importance of bottleneck resources. They noted that it was the type of bottleneck resources which determined the effective capacity of the system to be managed.

Despite their potential and crucial importance, bottleneck job shops have been largely ignored in the study of shop floor control. Very little is known about how to manage a shop floor control system in the presence of bottleneck operations. The study on bottlenecks is further complicated by the lack of general framework for understanding or for providing insight into bottlenecks.

There are three important reasons why research is needed on the bottleneck job shop. First, bottleneck job shops are fairly common in practice. Prather (1983) observed that most factories have bottlenecks. The capacity of these bottlenecks ultimately determines the total level of shipments or output.

However, as pointed out previously, our knowledge of bottlenecks, their critical characteristics, and the impact of bottleneck operations on the performance of the shop floor is relatively limited. Research is needed to identify the unique characteristics of bottleneck operations and to help clarify how their presence affects the shop floor.

Second, there is a growing awareness of the role played by the presence of bottleneck work centers. Managers and researchers are beginning to recognize that the presence of one or more bottleneck work centers affects the resulting operation of the shop floor. As pointed out by Goldratt and Cox (1984), bottlenecks must be recognized within the scheduling system.

Third, research is needed to evaluate the effectiveness of practices developed specifically for "balanced" shops when they are applied to bottleneck shops. Practices and procedures which do not recognize the presence of bottlenecks may create more problems than they solve when used to manage bottleneck operations.

The lack of detailed knowledge surrounding bottlenecks combined with their potential importance forms a major foundation of the justification for the research study. In the following sections, the research premise and specific research objectives underlying this study will be presented.

1.2 The Research Premise

This study is specifically concerned with evaluating the following premise:

> The development of an effective shop floor control system can not be done without first understanding the manufacturing environment in which it must operate and the resulting requirements and constraints imposed by this environment. The process of developing an effective shop floor control system then focuses on identifying and selecting those control procedures which best satisfy the particular requirements of the given manufacturing environment. A key characteristic which shapes the specific nature of the manufacturing environment is the presence or absence of bottleneck operations.

1.3 The Research Objectives

This study will address the following research questions. These questions will form the major objectives of the study.

1. What major characteristics of a bottleneck job shop must be considered when studying their impact on the operation of the shop floor?

2. Which control procedures (dispatching rules or order review/release mechanisms) have a greater effect on a bottleneck work center (and under what conditions)?

3. Can usage of information about workload for a bottleneck work center significantly improve shop performance?

4. In a bottleneck job shop, where there is a mixture of bottleneck and non-bottleneck jobs, how does the presence of a bottleneck work center influence these two types of jobs? Bottleneck jobs are those requiring the operation of a bottleneck work center.

5. How do such bottleneck characteristics as prevalence (i.e., does the bottleneck work center affect the routings of all jobs or just a portion) and the location of the bottleneck (does the bottleneck always occur at the start of the routing, the end or is it randomly distributed?)

affect shop floor operations and the performance of dispatching rules and order review/release mechanisms?

6. Can we identify any general guideline which can be used when dealing with a bottleneck job shop?

To answer the first question, a framework for the bottleneck job shop will be developed. In this study, the framework will look at four different dimensions: causes of the bottleneck, status of the bottleneck, location of the bottleneck, and prevalence. Definition for these various dimensions will be provided later in this thesis.

To answer the second question, this study will look at two fundamental control procedures: local dispatching rules and order review/release mechanisms.

To answer the third question, this study will present various alternative order review/release mechanisms which will utilize a wide range of information for releasing orders.

To answer the fourth question, this study will divide incoming orders into two categories (bottleneck orders and non-bottleneck orders). Information about both types of orders will be separately collected and analyzed.

To answer the fifth question, this study will evaluate and compare various performance measurements gathered for shops having a bottleneck operating at three different locations (front, exit, and mixed) and operating at two different levels of prevalence (100% and 50%).

To answer the final question, this study will analyze and compare three well-known dispatching rules (the first-come-first-served rule, the shortest processing time rule, and the slack per remaining operation rule).

These questions reflect the writer's concern to understand the problems created by a bottleneck operation and to develop effective control procedures to cope with those problems in the job shop manufacturing setting.

1.4 The Organization of the Study

This dissertation has been divided into six chapters. In this first chapter, a rationale for the study on the bottleneck job shop and a description of the objectives has been presented.

In the second chapter, the conceptual considerations of bottleneck operations are examined. The chapter begins with a literature review pertaining to bottleneck operations, and provides the theoretical basis for the development of the bottleneck job shop framework. The definition of a bottleneck work center is presented. Problems created by bottlenecks and tactics used to manage them are also presented.

Chapter three contains the research methodology used in the dissertation. The simulated shop is described in detail. Included is the description of "quasi-random" job shop, the operating logic of the model, the shop size, the characteristics of orders, the assumptions of the model, and the simulation model.

In chapter four, the experimental design of the study is presented. The experimental factors and levels of each factor are presented. Statistical problems pertaining to the simulation model, which is stochastic and dynamic in nature, are examined. The hypotheses and the performance criteria of this study are also presented.

The examination of the simulation results is presented in chapter five. The primary research procedure is that of the analysis of variance (ANOVA). This procedure is used to determine if any of the control procedures or bottleneck characteristics have a significant impact on the observed performance measurements. In analyzing the results, we focus our attention on six major performance measures. The major performance measures consist of work-in-process, mean flow time in the shop, variance of flow time in the shop, mean tardiness, variance of tardiness, and the percent of jobs tardy. The results of this analysis are used to test the hypotheses presented in Chapter four.

Chapter six presents the major findings and managerial implications of the study and suggests future research areas relevant to the bottleneck job shop.

CHAPTER 2

BOTTLENECKS: CONCEPTUAL CONSIDERATIONS

2.1 Introduction

As noted in the preceding chapter, there are several important reasons for studying in detail the bottleneck job shop. To date, however, little research has been devoted to examining bottleneck models in a job shop setting. Little has been made to develop models which adequately represent more realistic job shops and to investigate problems encountered in such settings. As a result, there is little known about the nature of bottlenecks and their problems. This chapter explicitly examines manufacturing systems with bottleneck operations. The primary purpose of this chapter is to develop a framework of a bottleneck job shop. This framework helps provide insight and a more detailed understanding of the bottleneck job shop. It also provides a theoretical basis for this study and the resulting structure of the experiment.

The chapter starts with a literature review regarding bottleneck operations in a wide range of manufacturing configurations. The review provides a background for the development of the framework for the bottleneck job shop. As will be shown, this framework is based on four dimensions.

In order to define the bottleneck work center, the concept of the load-capacity coefficient is presented.

The uniqueness of the bottleneck job shop, when compared to a pure random job shop and project scheduling, is described. Problems created by the presence of a bottleneck work center are discussed. To cope with these problems, several tactics are presented. Specifically, emphasis is placed on dispatching rules and order review/release mechanisms.

2.2 Literature Review

Despite the potential importance of bottlenecks, research to date on bottlenecks is very limited compared to the extensive body of the traditional job shop. There are currently very few works specifically dealing with manufacturing system in which one or more bottleneck operations are located. Within these works, there is little agreement over the type of manufacturing setting to be examined. Each work describes a different type of bottleneck operation or system. This lack of agreement indicates that bottlenecks are diverse and may be drawn from a broad spectrum of configurations. In each work, the importance of bottlenecks in the system is recognized and some procedures are attempted to control problems created by bottleneck operations.

Solberg (1981) raised an issue of the bottleneck model for capacity planning. Solberg defined the bottleneck work center to be that work center for which the workload per server is greatest. Solberg argued that the bottleneck model, for purposes of capacity estimation, suffered from the false assumption that it systematically overestimated true capacity. Even the most heavily loaded servers at times were idled. Therefore, it was sensible to use a more realistic model, called a stochastic model, for estimating capacity planning. Although Solberg did not directly deal with the operation of bottleneck shops, he noted the importance of the bottleneck station by describing that in a flow shop, or one in which all processes pass through the bottleneck station, it was rather obvious that the productive capacity of the system was equal to that of the bottleneck station.

Huang, Rees, and Taylor (1983) recognized the critical aspects of bottlenecks in their simulation analysis of the Japanese Kanban system. Like Solberg, the primary research focus was not on the operation of a bottleneck shop. In the second phase of their simulation experiments, they examined the transition period when the Just-in-Time system was implemented. It was then that the problems of dealing with bottlenecks were raised. The problems resulted from the system's unbalanced condition in which processing times were not the same at each work station. They created a bottleneck operation by altering processing times at each stage. The experimental results implied that additional kanbans, i.e., buffer, would not solve a bottleneck situation. A bottleneck must be dealt with by reducing the bottleneck itself (i.e., setup time reduction at the bottleneck work center, bottleneck capacity expansion, or intensive worker training and cross training).

Prather (1983) emphasized the importance of bottlenecks by stating the capacity of bottleneck work centers ultimately determined the total level of shipments or output. In his presentation of good production control practices, he provided two approaches to identify bottlenecks.

One approach was to calculate an average percentage of utilization of work centers in one year. Work centers with over 90 percent utilization were designated as bottlenecks. The other approach was to review completed work orders and find the work centers where orders sat in the longest queue. Since the capacity of bottleneck work centers limited total system output, it was critical to fully utilize bottleneck work centers. To do so, queues, workload, and priorities of orders at bottleneck work centers were reviewed daily.

Another important factor identified by Prather involved what portion of all fabricated parts was supposed to go through bottleneck work centers. This was important for two reasons. First, it was possible to predict the loading of bottleneck work centers in advance. Second, it was possible to evaluate the impact of order release on the bottleneck work centers before release. Prather also suggested an A-B-C classification analysis of resource utilization of all work centers.

Fogarty and Hoffmann (1983, pp. 18) also suggested such an A-B-C control scheme to the control and management of bottlenecks.

Recently, there has been a growing interest in a scheduling simulation procedure called OPT (Optimized Production Technology). The OPT first was developed by Goldratt and Pazgal in Israel. It has been marketed in the United States since 1979. The goal of the OPT was to make money through simultaneously increasing throughput, reducing inventory, and cutting operating expenses. To accomplish this goal, ten OPT rules were developed. (see Fox 1982b) Among these rules, the key ingredient was the focus of the OPT on the bottleneck resources as the basis for production scheduling and capacity planning.

Goldratt and Cox (1984, pp. 138) defined a bottleneck as any resource with capacity equal to or less than the demand placed upon it. When bottlenecks exist, managers used information about them to control the flow through the system and into the market. Since the capacity of bottleneck resources determined the capacity of the system, it was critical to utilize bottleneck resources to their full potential.

OPT separated resources into two groups for scheduling purposes: critical and non-critical resources. The first group was finite forward scheduled using a secret central OPT module developed by Goldratt. The second was backward scheduled. This procedure was repeated until all resources were not utilized over 100 percent.

Although some significant successes of the OPT in terms of reduction of work in process inventory and improvement of on-time delivery were reported in a limited number of companies (Meleton 1986), it was too early to appreciate the OPT's true value. This situation was due to the following two reasons: 1) the central OPT module is a 'black box' because its logic is proprietary.; 2) it has a rather short history.

The proponents of the OPT view it as a combination of the best from MRP II (Manufacturing Resource Planning) and Just-in-Time (Fox 1982a; Lundrigan 1986). It eliminates waste more efficiently than JIT and produces more a feasible and efficient schedule than MRP. If the OPT runs as claimed, it will increase system output, reduce work-in-process inventory, improve cycle time, and reduce space requirements. Furthermore, it has the capability of simulating production scheduling, master schedules, workload, and product mix quickly and easily. It provides a new way of looking at manufacturing system.

The OPT system, however, appears to have some drawbacks. It requires huge data maintenance for a tight network organization (Meleton 1986). It does not consider costs (Jacobs 1983). It creates much more work-in-process inventory levels than normal and requires non-bottleneck machines go through many more setups (Aggarwal 1985). It is anything but transparent (Vollmann 1986). It appears the OPT system works best in a high volume, large batch size operation with few individual production operations.

Ow (1985) attempted to use the knowledge of restricted resources to minimize the total weighted tardiness of jobs to be scheduled in the proportionate flow shop. He acknowledged that the order in which jobs eventually come out of the shop depends on which jobs are completed at the bottleneck. He proposed a focused approach which works primarily on the bottleneck work center for the purpose of scheduling. The simulation results indicate the focused approach to scheduling provide the best results when compared with other experimental approaches such as Weighted Shortest Processing Time rule, Earliest Due Date Rule, First Come First Serve rule, COVERT, and Lead Time Iteration. Like Goldratt and Cox (1984), Ow explicitly utilized information on the bottleneck to control scheduling in the special flow shop.

Billington (1985) tested the relative magnitude of cost reduction through capacity expansion of the bottleneck in an assembly system with one bottleneck. The primary performance criterion was the cost. Cost was the combined setup costs and inventory holding costs. Although the paper did not measure customer performance criteria, it had two important implications. First, the location of bottleneck was found to be a significant factor for evaluating bottleneck resources. Second, better scheduling of bottlenecks was more important than mere capacity expansion to reduce production delay.

Billington, McClain and Thomas (1986) investigated a bottleneck shop setting for the purpose of evaluating a heuristic method for multilevel lot-sizing with the extension of Billington's 1985 model. They examined the capacitated lot-sizing problem by introducing a single bottleneck facility. In their study, they ignored capacity limitations at all work centers other than the bottleneck. Test result showed feasible solutions were possible for problems too difficult to solve with exact methods.

As shown in the preceding review, there is a very little agreement over the type of shop setting to be examined. Certain conclusions, however, can be drawn from this limited but diverse body of literature. The most important of these conclusions include the following:

* Bottlenecks are very crucial and pervasive factor which determine the resulting performance of a manufacturing system.

* There is little agreement over the exact definition of bottlenecks.

* Bottlenecks, if any, must be first identified.

* Bottlenecks must be used as the primary basis for production scheduling and capacity planning.

* The location and the condition of bottlenecks are important factors for scheduling.

* The performance of the OPT is yet to be conclusively proven.

2.3 Definition of a Bottleneck Work Center

In the studies on bottlenecks, there was little agreement over the definitions of a bottleneck work center.[3] One view of bottlenecks involves the comparison of input rate with output rate at a work center (Goldratt and Cox 1984, Wallace 1984). A bottleneck work center is then the one where input rate is equal to or greater than output rate. Another method is to examine a work center which has capacity utilization above 90% or the longest queue (Prather 1983). There are, however, some problems with these definitions which must be pointed out.

The first definition is theoretically impossible to apply. It is not feasible to generate a work center in which the input rate exceeds the output rate. The reason is that such a work center would be unstable due to an explosive waiting line. The strict specification of a certain capacity utilization of the second one is relatively artificial. It also offers too broad definition for theoretical application. Both are good terms from a practical standpoint, but are of limited use for theoretical research.

2.3.1 Definition of a Bottleneck Work Center in this Study

The definition of a bottleneck work center used in this study differs somewhat from those two above. Before defining

---

3. A work center is defined as a specific production facility, consisting of one or more people and/or machines, which can be considered as one unit for purposes of capacity requirements planning and detailed scheduling. (APICS dictionary 1984)

a bottleneck work center, let us consider what really creates it. In general, a bottleneck is created by two factors: inadequate capacity and/or high workload. Here, capacity may include machines, manpower, and tooling. An insufficient amount of capacity to be able to process existing and planned workload is the major cause of bottlenecks. Note that the relative value, not the absolute value, of capacity of resources and workload is of importance. Whether or not the capacity of a work center is sufficient depends upon the amount of workload imposed in a certain time period. The ratio of these two factors determines the condition of a bottleneck. To define the bottleneck, therefore, the concept of the load-capacity coefficient is introduced.

A load-capacity coefficient (Aij) can be defined as follows:

$$Aij = Lij/Cij$$

where:

Lij = the workload planned to be completed for work center i in the planning period j.

Cij = the capacity (in standard hours - demonstrated or effective) of machine hours for work center i in the planning period j.

Lij is the sum of setup and processing times of jobs planned to be completed for work center i in the planning period j.

Cij is the number of standard machine hours for work center i in planning period j. For example, the weekly capacity of a work center i consisting of only one machine is 40 hours.

For each work center in the shop, a load-capacity coefficient is calculated. A load-capacity coefficient takes the value between 0 and 1, inclusive.

Formally defined, a bottleneck is the work center with the highest load-capacity coefficient over the long run. In other words, we define a bottleneck operation as one at which the average workload is persistently high, when compared to other work centers.

This definition does have some advantages over others previously discussed. It considers both capacity and workload in a relative manner when identifying a bottleneck. It also identifies the most critical work center. The most critical work center is the one which has the highest load-capacity coefficient. This is the major work center which most significantly affect the flow of work through the system. Finally, it provides a definition for theoretical study.

This is, however, a very restrictive conceptual definition. It is of limited significance for practical purposes. For example, a job shop has four work centers with the Aij of each work center A, B, C, and D for the period j is .57, .35, .37,and .33, respectively. By definition, work center A is designated as the bottleneck, because it has the highest Aij. Practically, none will be considered as a bottleneck work center. As a result, additional quantifying conditions are described below in order to make the definition significant practically as well as theoretically.

* The bottleneck work center at which Aij is significantly deviated from 1.0 is not regarded as a bottleneck. Here, we have no bottleneck.

* Any non-bottleneck work center at which Aij is smaller than Aij of the bottleneck but close to 1.0 is also considered as a bottleneck. Here, we have multiple bottlenecks.

2.4 The Framework of a Bottleneck Job Shop

As seen in 2.2, no general universally accepted scheme has yet been presented in the literature for categorizing a bottleneck. The intent of categorization is to help identify understanding of the problem inherent in the study of bottlenecks and important theoretical developments for those specific areas. A bottleneck can be described using three major classification dimensions in the context of a job shop which is the main setting for this study:

1. Cause of a bottleneck
   a. A systematic bottleneck
   b. A random bottleneck
2. Status of a bottleneck
   a. Stationary
   b. Floating
3. Location of a bottleneck in the routing
   a. Front
   b. Exit
   c. Mixed

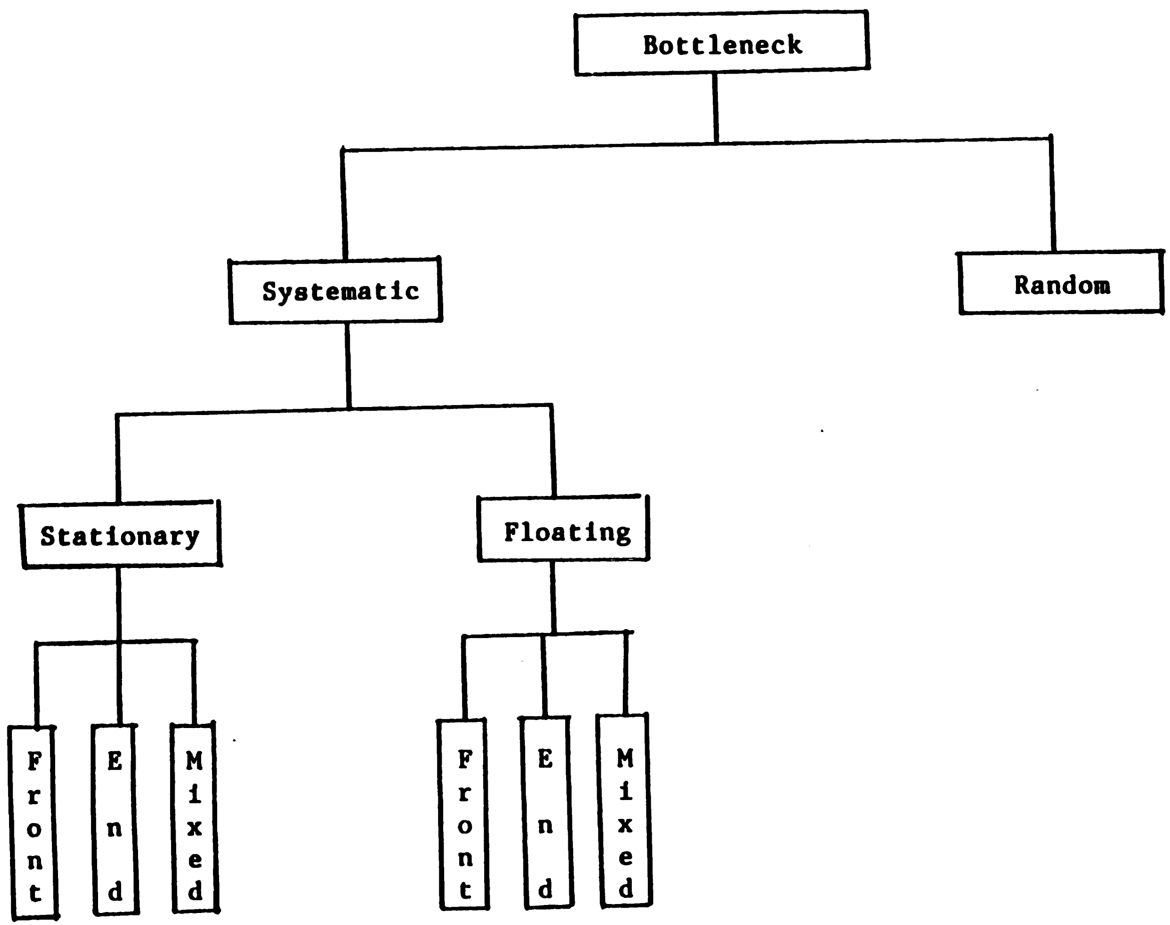
2.4.1 Cause of a Bottleneck

In Figure 2-1, a bottleneck is first divided into two groups in terms of the cause of a bottleneck. The first group is systematic; the second is the random bottleneck. This is a key distinction for control purposes. A systematic bottleneck results from two factors. The workload for a specific work center is too high (due to problems with product mix or scheduling), or, a bottleneck may result from the lack of adequate capacity. Either of these two factors (alone or together) creates a systematic bottleneck. The systematic bottleneck persistently exists and limits the total output of the system over the long run.

As the name implies, a random bottleneck occurs in a random fashion in the shop. It exists temporarily in the system, then disappears. A random bottleneck results from the following factors:

* Machine breakdown
* Employee absenteeism
* Reworks due to defects
* Unexpected temporary large demand
* Tooling breakdown
* Expediting
* Product mix

A ràndom bottleneck is ever changing across machines in the system. The problems created by a random bottleneck may be solved by relatively naive procedures (for example, overtime).



THE FRAMEWORK OF A BOTTLENECK JOB SHOP

FIGURE 2-1

In this study, we focus exclusively on problems created by the presence of a systematic bottleneck. It is the systematic bottleneck which constrains and restricts the performance of shop floor.

2.4.2 Status of a Bottleneck

A systematic bottleneck can be further divided into two categories in terms of the bottleneck status: stationary and floating. The status of the bottleneck identifies the extent to which a bottleneck is fixed at one specific work center. If a bottleneck does not move across work centers, it is stationary. The bottleneck work center is fixed. On the other hand, a floating bottleneck moves across work centers. The bottleneck work center is floating due to changes in demand pattern, capacity expansion, or scheduling problems.

2.4.3 Location of a Bottleneck in the Routing

A stationary or floating bottleneck is further divided into two categories in terms of the bottleneck's location: front, exit, and mixed. The location of the bottleneck refers to the relative location of the bottleneck in the routings of orders. The location is frequently seen in the front of or at the end of order routings in practice. As an example of the exit location of the bottleneck, a final inspection operation, packaging, or coating would be the cases. Examples of a front location for the bottleneck may include milling machine or lathe. Also considered is a mixed location in which the bottleneck can appear anywhere in the routings of orders.

Specifically, systematic and stationary bottleneck along with three bottleneck locations in Figure 2-1 is the primary focus of this study. In addition, another dimension which should be considered when studying a bottleneck job shop is that of prevalence. Prevalence refers to the extent to which orders are subject to pass through the bottleneck. Specifically, prevalence is the percent of all orders which must go through the bottleneck operation. For example, 100% prevalence means that all incoming orders to the system must go through the bottleneck operation. On the other hand, 0% prevalence represents a shop in which a bottleneck operation does not exist. Prevalence is a continuous term.

2.5 Uniqueness of a Bottleneck Job Shop

The main manufacturing setting to be dealt with in this study is a job shop having a bottleneck work center. It is called a bottleneck job shop. In this section, the unique characteristics of the bottleneck job shop are discussed. In addition, the bottleneck job shop is compared with a pure job shop and project scheduling.

The key difference between the bottleneck job shop and the pure job shop is that in the bottleneck job shop there exists one or more dominant resources which determines the level of overall system performance measurement. The bottleneck work center's capacity is the system's capacity. The utilization of the bottleneck work center is relatively high compared to other non-bottleneck work centers. In the pure job shop, the average capacity utilization across all work centers is approximately the same in the long run.

The bottleneck job shop scheduling appears similar to the project scheduling in that both have constraining resources which affect system performance. However, they differ from each other in that the bottleneck job shop scheduling has the continuous nature of work input and flow to the system (Davis 1973). Therefore, it is more difficult to manage the bottleneck job shop than the project.

2.6 Impact of Bottleneck Operations on Shop Floor

The bottleneck work center is a major dominant work center in influencing the shop performance. It aggravates the shop floor by creating a set of unique problems. This section looks at the impact of bottleneck work center on shop floor and system performance. It is critical for several significant reasons.

* It hinders the smooth flow of orders through the shop.
* It lengthens manufacturing lead times.
* It persistently constrains the operation of other work centers.
* It increases the number of expediting.
* It increases work-in-process inventory levels.
* It increases variance of load balancing.
* It determines the overall output of the system.

When a bottleneck work center exists, the effectiveness of shop floor control is directly affected by the manager's ability to control the bottleneck.

2.7 Tactics to Cope with Bottlenecks

After identifying a bottleneck work center, the next question faced by researchers and practicing managers is how to tackle the problems created by this bottleneck operation. In order to cope with these problems, it is reasonable to look at what really causes the bottleneck work center to exist in the first place. As discussed previously in 2.3 and 2.4, there are two systematic factors for the real causes of the bottleneck: inadequate capacity of resources and high workload. To reduce the impact of a bottleneck operation on shop floor, therefore, researchers and managers must either expand the capacity of bottleneck resources or reduce the workload for the bottleneck work center or both. In this section, these two tactics are discussed in more detail.

2.7.1 Tactics to Manage Capacity

The decision of how to manage inadequate capacity basically concerns the expansion of capacity of bottleneck resources. This decision generally takes time and demands a high price to implement. Potential tactics to expand the capacity of critical resources are as follows:

* Purchase of a bottleneck machine
* Subcontracting
* Setup reduction of a bottleneck work center
* Cross worker training
* Additional tooling
* Increase of employment

These tactics are long-term solutions and may not be feasible or may be excessively expensive in the short time.

2.7.2 Tactics to Manage Workload

Tactics for solving problems created by insufficient capacity of a bottleneck work center may take relatively long or medium time to implement. On the other hand, tactics used to manage workload for a bottleneck work center may be quickly implemented. As pointed out by Melnyk and Carter (1987), shop floor control deals with very detailed short-term planning, execution and monitoring activities needed to control order flows. Shop floor control is primarily concerned with the operation of the order flows, not the expansion of capacities. One of the goals of shop floor control is how to utilize given resources in a most efficient and cost-effective manner. Therefore, this study explicitly looks at tactics used to manage workload.

One approach to reduce workload for the bottleneck work center is the use of alternative routings. The change of routings containing the bottleneck operation definitely helps reduce the current workload as well as the planned workload. In this study, we assume the use of alternative routings is infeasible. Specifically, this study examines two control procedures: dispatching rules and order review/release mechanisms.

2.7.2.1 Dispatching Rules

Dispatching, defined as the activity for selecting the next job in queue for processing on a machine (Melnyk, Carter, Dilts and Lyth 1985), is an essential activity in a production scheduling system. The research on dispatching rules are well documented. Dispatching rules are easy to implement. They affect the performance of the system. They also affect the rate at which each individual job progresses through the system. Therefore, the selection of dispatching rules affects workload for the bottleneck work center. Some "global"[4] dispatching rules are suggested to reduce queue lengths and inventory levels at the overloaded work center. Conway, Maxwell, and Miller (1967, pp. 223) proposed the WINQ (Work in Next Queue) rule and the XWINQ (Expected Work in Next Queue) rule and Schonberger (1979) suggested the clearest-road-ahead-priorities.

2.7.2.2 Order Review/Release Mechanisms

Order review/release was recently attracted the attention of both researchers and managers. Order review/release is the first phase of shop floor control system. It controls the rate of input flow to the shop floor. It is a screening process by which potential problem orders are identified and kept off the shop floor until the underlying difficulties are solved. It links the planning system with the shop floor control system (Melnyk and Carter 1987).

Order review/release controls the total workload in the shop. Order review/release mechanisms thus have the

4. According to Conway and Maxwell (1962), "global" rules are ones which require information about jobs or machine states at other machines.

capability of controlling workload for the bottleneck work center implicitly or explicitly depending on the type of order review/release mechanisms to be implemented. Since the body of knowledge on order review/release is relatively new and less extensive than that of dispatching rules, we review past study on order review/release in the following.

2.7.2.2.1 Past Study on Order Review/Release

Harty (1969) presented the first extensive study of order review/release by focusing on the relationship between order review/release and short-term capacity control. Harty pointed out the fact that the control of input rate into the shop floor affects current capacity requirements. Although Harty did not provide a detailed order review/release mechanism, he identified the importance of order review/release to effective production operating system.

Nicholson and Pullen (1971) also emphasized the importance of order review/release by suggesting a centralized control system. Reduction of control points on the shop floor greatly simplified production scheduling system. They illustrated a very simple example in which all jobs were available at the same time and produced an optimal solution for this simple problem. However, they did not present a clear mechanics of order review/release mechanism.

Irastorza and Deane (1974, 1976) developed a controlled releasing algorithm which attempted to balance workload among machine centers in the computer simulation study of ten machine job shop. Using the pool system concept (Deane and Moodie 1972) and applying a mixed integer linear programming, the algorithm used the information about due dates and work center load level to determine the selection of an order to be released. The results indicated that the use of order review/release reduced work-in-process inventory levels and the variability of queue length.

Sandman and Hayes (1980), based on a study of over 600 job shops, realized that the total lead time of a released job usually takes 10 to 30 times longer than the actual processing time. They identified the reason as a long queue which in turn reduced productivity. To cope with this problem, they recommended the use of order review/release.

Bechte (1982) proposed load-oriented order release mechanism to control manufacturing lead time and work-in-process inventory level in the simulation study of the actual data. Bechte first linked order review/release to planning system through planned orders. The load-oriented order release has two steps. Step one was to establish urgent orders by means of backward scheduling and time limit. Step two released workable orders according to capacity availability. The simulation study showed that the use of load oriented order release algorithm reduced lead-time and inventory up to 60% without noticeable effect on capacity utilization.

Bertrand (1983) investigated the performance of the order release mechanism in terms of the mean and the variance of job lateness in a five-machine job shop simulation model. The order release mechanism attempted to control the amount of workload in the shop by establishing the minimum load level. The simulation result indicated that the controlled release mechanism did not have direct impact on the variance of the lateness. Instead, the use of the order release mechanism did amplify the effect of the sequencing rule and the due-date assignment rule.

Baker (1984) examined the effects of input control in the simulation of one-machine shop in terms of job tardiness. Similar to the approach taken by Bertrand (1983), the releasing mechanism tried to keep the minimum amount of workload in the shop. The main finding was that the use of a job releasing mechanism was far less important to the system performance than was the use of an effective priority scheme. In his explanation of this finding, Baker argued that input control removes some options from the set of choices available to a scheduling system. Although he concluded with a warning that input control can be counter-productive, he suggested that more research on input control was needed to investigate some complex actual system.

Ragatz (1985) conducted a job shop simulation to examine the impact of various job releasing mechanism on system performance and the interaction of dispatching rules with the releasing functions. Ragatz developed several releasing mechanisms which required varying range of information. The result showed that the the use of order release substantially improved shop performance although the effect was not as impressive as the use of dispatching rules. The study also showed that the increasing use of information improved the effectiveness of the order release mechanism.

As can be seen in the literature review thus far, order review/release mechanisms attempt to control lead time, work-in-process inventory level, load leveling, the aggregate workload in the shop and cost. Although there is a very little agreement over the detailed mechanics of order review/release, most researchers agree over the use of order review/release for better production scheduling.

2.7.2.2.2 Potential Benefits of Order Review/Release

Effective order review/release plays a major role in a production operating system. Order review/release operates as a filter through which all orders must pass. Order review/release has final authorization to release jobs to the shop floor. Effective use of order review/release provides following potential benefits. They result from the fact that:

* It reduces work-in-process inventory levels.
* It reduces the mean and variance of queue length.
* It facilitates workload leveling.
* It provides the savings of space and capital.
* It simplifies the shop floor control activities.
* It provides the feasibility and visibility.

As mentioned previously in 2.6, the presence of bottleneck work centers creates severe problems in the shop. These problems could be reduced by the use of order review/release. The input flow of incoming orders which need the operation of a bottleneck work center must be controlled before release because the bottleneck work center is already heavily overloaded.

2.7.2.2.3 Mechanics of Order Review/Release

Any order review/release mechanism must determine what to release and when to release it. The first issue, what to release, selects jobs to be released to the floor while the second issue, when to release, determines the timing of release.

Jobs are selected through the use of a wide range of information, from very simple, like first-come-first-served (Bertrand 1983 and Baker 1984), to very complex like finite loading (Ragatz 1985). Although a complicated mechanism like finite loading does not necessarily always produce best performance, a mechanism which considers both characteristics of the job and shop congestion usually outperforms one which does not. (Ragatz 1985)

The timing of release is categorized into two types: periodic and non-periodic. By periodic release we mean jobs are released into the shop floor every specified period. (See Irastorza and Deane 1974, Bechte 1982, Ragatz 1985) Any release other than periodic can be regarded as non-periodic. Non-periodic is relatively more sensitive to the status of the shop while the time before release is shorter than the former. The preference of one over another type, however, has yet to be examined.

2.8 Summary

In this chapter, the literature review regarding bottleneck operations was described. This review provided a background for the development of the framework for the bottleneck job shop. The definition of a bottleneck work center was also presented using the load-capacity coefficient. Two control procedures to cope with the problems created by the bottleneck work center were were presented.

In Chapter three, a research methodology in this study will be presented. Included there are a quasi-random job shop model, job characteristics, shop characteristics, the assumptions of the model, and a simulation model.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The major technique used in this study is that of computer simulation. The problem examined is in nature dynamic and stochastic. Computer simulation is the most appropriate technique to deal with this nature of the model. The main manufacturing setting of this study is a "quasi-random" job shop. In the following section, the "quasi-random" job shop is described and compared with the traditional job shop. In section three, a detailed description and the operation of this "quasi-random" job shop is presented. Also discussed in this chapter are job and shop characteristics. These include areas such as the shop size, job arrival distribution, routing of jobs, processing times of jobs, and due date setting of jobs. Finally, the underlying assumptions of the model are also described.

3.2 A Quasi Random Job Shop

The shop being modeled in this study is a "quasi-random" job shop. The "quasi-random" job shop differs from the traditional job shop primarily in terms of the routing generated. In the pure job shop, order routing is purely random. Under the "quasi-random" job shop, however, order routing is not completely random. Consistent with the focus of this study, a work center is identified and fixed in advance as the bottleneck. The inclusion of this bottleneck and its location in the routing is a controlled variable. The order routing is then determined by the nature of location of a bottleneck and prevalence in the experimental model.

3.3 The Operating Logic of the Model

The operating logic of this model follows that used by Ragatz (1985). There are three stages to control the flow of orders in the shop. The first stage is the order entry stage at which orders arrive from customers. Once a job enters the order entry stage, job characteristics such as the routing, the processing times at each machine, and the due date are determined. The second stage is the order review/release stage. During this stage, jobs are reviewed every period, eligible jobs are then released onto the shop floor. During the third stage, the flow of released jobs on the shop floor is then controlled by local dispatching rules.

3.4 The Shop Size

The "quasi-random" job shop consists of six work centers. Each work center is treated as a unique machine which is able to process only one job at a time. Machines are the only constraining factor to the production system.

The size of a shop does not significantly affect the result of simulation (Baker and Dzielinski 1960). Buffa (1968, pp. 338) also noted that since shop size has never appeared as a major variable, it seems that we may be able to experiment with relatively small shops and generalize the resulting conclusions.

3.5 Job Arrival Distribution

Job interarrival times are generated using an exponential distribution with mean of 5.263 simulated hours. This mean of 5.263 generated the overall shop capacity utilization at 82%. The use of an exponential distribution does not affect the shop performance since the distribution with respect to shape and range of the arrival rate for incoming jobs is not a significant variable in evaluating shop scheduling. (Elvers 1974).

3.6 Routing of Jobs

In this study, routings are not randomly generated in the strictest sense of the word. Instead, routing is a controlled variable used to create a bottleneck work center. The routing is generated by the combination of location and prevalence of a bottleneck. Here, three types of locations and prevalences are examined. Three types of locations are entry, exit, and mixed. Two levels of prevalence are 100% and 50%. Throughout the simulation run, work center one is designated as a bottleneck in the experiment.

Routings of non-bottleneck work centers are drawn without replacement from a uniform distribution. For these jobs, routing follows a uniform distribution without replacement using five non-bottleneck work centers.

For each job, the number of operations in the routing is uniformly distributed with range running from two to five operations.

3.7 Processing Times of Jobs

Processing times at each work center are drawn from an exponential distribution. The mean processing time at each work center, however, is not the same throughout the simulation run. The mean processing time of the bottleneck and non-bottleneck work centers varies in conjunction with the prevalence of a bottleneck. Such controlled processing time enables the output of the simulation to be evaluated at a stable capacity utilization. Table 3-1 illustrates the mean processing time of the bottleneck and non-bottleneck work centers being used in the experiment. Under this study, the overall capacity utilization is set at 82% while a bottleneck work center is at 95% and non-bottleneck work centers are at 79%.

TABLE 3-1

MEAN PROCESSING TIME OF BOTTLENECK AND NON-BOTTLENECK WORK CENTER

	Mean Processing Time of Bottleneck Work Center	Mean Processing Time of Non-Bottleneck Work Center
100% Prevalence	5.000 Hours	8.358 Hours
50% Prevalence	10.000 Hours	6.965 Hours

3.8 Due Date Setting of Jobs

The due date is set in multiple of the total operation time of the corresponding job (i.e., TWK rule).

Due Date = k * Total Work Content

where k is a controlled factor

Due date setting relating to processing time performs very well when compared to other procedures such as random or total number of operation (Baker and Bertrand 1981). Blackstone, Phillips, and Hogg (1982) also suggested that the TWK method is the most rational method of assigning due dates. Under this simulation run, k is set at eight indicating relatively loose due date. (Elvers 1973)

3.9 The Assumptions of the Model

The general assumptions of the simulation model follow those of conventional hypothetical job shops typified by many simulation studies. The following list includes the assumptions of the model in this study. Some of them are adapted from Baker (1974, pp. 215).

1. Jobs consist of strictly ordered operation sequences.

2. A given operation can be performed by only one type of work center in the shop.

3. There is only one machine per work center in the shop.

4. Processing times as well as due dates are known in advance.

5. Setup times are sequence independent.

6. Once an operation is begun on a machine, it must not be interrupted.

7. An operation may not begin until its predecessors are complete.

8. Each machine can process only one operation at a time.

9. Each machine is continuously available for production.

10. Actual and estimated processing times are identical.

3.10 The Simulation Model

The inherent complexity pertinent to the model being studied prohibits the use of an analytical procedure. A computer simulation is, therefore, the most appropriate vehicle for this study.

The operation of the shop is modeled in the SLAMII (Pritsker 1984) simulation language. SLAMII is an advanced FORTRAN based language which provides the flexibility to combine network, discrete event, and continuous modeling capabilities into a single integrated framework. For the simulated shop of this study, however, the operation is modeled only in discrete-event subroutines.

3.11 Summary

In this chapter, a quasi-random job shop model, as compared to the traditional job shop model, used in this study was described. Shop characteristics as well as job characteristics were also identified. In addition, the assumptions underlying the model were described. In Chapter four, the experimental factors and associated levels of the experimental design will be presented. Included there are discussions of the performance criteria and statistical characteristics of the stochastic model.

CHAPTER 4

EXPERIMENTAL DESIGN

4.1 Introduction

This chapter describes the structure of the research design used in this study. This design forms the foundation for obtaining the data on which this study will base its answers to the major questions posed in Chapter One.

In addition, this chapter identifies the experimental factors and establishes the levels for each factor. The chapter also presents the statistical hypotheses tested in this study. The performance criteria to be collected are also identified and their significance to the study discussed.

The simulation model in this study involves variability inherent to all computer simulation models. As a result, it is also necessary to examine the statistical aspects of the simulation model needed to maintain a certain level of statistical accuracy.

4.2 Experimental Factors

The major purpose of this study is to examine the impact of two control procedures used to manage the bottleneck job shop which is itself characterized by two key environmental variables: location and prevalence. The study is interested in examining not only how these factors influence system performance directly but also the nature of the interactions that exist between the control and environmental factors.

To test these interests of this study, the experimental design, by necessity, must be a full fixed factorial design. A full fixed factorial design is also needed because this study has been described as being an exploratory study. We do not know in advance the nature of the effects of the experimental factors on system performance.

A full fixed factorial design is one in which all levels of a factor are combined with all levels of each of the other factors (Kleijnen 1975, pp. 289). The use of a full factorial design allows the study to not only derive estimates of the main effects but to also identify key interaction effects between the main effects (Kleijnen 1975, pp. 289-290). Both of these effects are of concern to this study.

Furthermore, the term 'fixed' denotes that all possible levels of the factors selected have been included in the study.

This full fixed factorial design used in this study consists of four major qualitative factors - each having different levels. These factors and the associated levels are discussed in the next section.

4.2.1 Dispatching Rules

One control procedure for coping with the problems created by the bottleneck operation is the use of dispatching rules. There are, however, a large number of alternative dispatching rules. The problem facing the researcher is that of picking dispatching rules applicable to the problem setting. Given the need to control the size of the experimental design, it was decided to limit the number of levels for this factor to three. To select the levels, a preliminary study was carried out.

The dispatching rules used in the preliminary study, however, were not selected at random. Several dispatching rules which are commonly well-known in the literature were selected.

In the preliminary study conducted by Ahn, Melnyk, and Ragatz (1987), jobs were immediately released to the shop floor as they arrived to the bottleneck job shop. The purpose of the preliminary study was first to evaluate relative effectiveness of several selected dispatching rules and to select those which should be used in the main experiment. In addition, another purpose of the preliminary study was to investigate the impacts of the environmental factors of the bottleneck job shop on shop performance.

Four dispatching rules were used in the preliminary study:

* The Shortest Processing Time Rule (The SPT rule):

  Job priority equals processing-time of the imminent operation (Conway, Maxwell, and Miller 1967). The SPT rule only considers the operation time (setup plus processing time). It does not consider the due date. The SPT rule is best in terms of the average flow time. (Baker and Dzielinski 1960). One weakness of the SPT is the large variance of the lateness distribution. Conway (1965, pp. 129) felt the SPT rule should be considered the 'standard' in scheduling research.

* The Earliest Due Date Rule (The EDD rule):

  Job priority equals its order due-date (Conway, Miller, and Maxwell 1967). The EDD rule does not consider the operation time. It only considers the due-date. The EDD rule is relatively good in reducing the variance of job lateness (Conway 1965). However, it works poorly when due dates are tight or infeasible.

* The Slack Per Remaining Operations Rule (The S/OPN rule):

  Job priority equals the ratio of job slack-time to the number of remaining operations (Conway, Maxwell and Miller 1967). The S/OPN considers the amount of remaining operations time and the number of remaining operation. The S/OPN works best among due-date oriented rules in minimizing the variance of job lateness and the number of tardy jobs. The S/OPN works best when the due-dates established are either feasible or loose (Conway 1965).

* The Work in Next Queue Rule (The WINQ Rule):

  Job priority equals the sum of the imminent operation processing-times of the other jobs in the queue that this job will next enter. A job waiting for its last operation has a priority of zero (Conway, Maxwell and Miller 1967). In this study, the tie is broken using the earliest due-date. The WINQ rule primarily considers the shop status to reduce the downstream congestion.

The four dispatching rules were evaluated using five performance measures: (1) mean flow time in the shop; (2) variance of flow time in the shop; (3) mean tardiness; (4) variance of tardiness; and (5) percent of jobs tardy. An analysis of variance (ANOVA) was used to evaluate the significance of dispatching rules.

The Duncan multiple comparison procedure was next used to determine whether there was any statistically significant difference present between cell means at the .05 level. Tables 4-1 through 4-5 show that the SPT rule outperformed the EDD rule, the S/OPN rule, and the WINQ rule in reducing mean flow time in the shop, mean tardiness, and the percent of jobs tardy.

The Duncan procedure also confirmed that there was statistically significant difference between the SPT rule and the other dispatching rules with respect to the three performance measures.

The results also indicated that the S/OPN rule performed the best in reducing the variance of flow time in the shop and the variance of tardiness. There was also significant difference between the S/OPN rule and the other dispatching rules for these two performance measures.

TABLE 4-1

MEAN FLOW TIME IN THE SHOP
(PRELIMINARY STUDY)

(Measured in Hours)		Dispatching Rule				
Prev.	Loca.	SPT	EDD	SOPN	WINQ	Avg.
100%	Front	86.31	165.85	163.36	146.17	140.43
	Exit	88.73	164.06	161.30	153.55	141.91
	Mixed	94.27	184.96	176.62	180.30	159.04
	Avg.	89.77	171.62	167.09	160.61	147.13
50%	Front	86.50	154.47	155.68	152.64	137.32
	Exit	83.29	137.75	131.92	126.47	119.86
	Mixed	89.93	163.04	163.90	157.37	143.56
	Avg.	86.57	151.75	150.50	145.49	133.58
Grand Avg.		88.17	161.69	158.80	152.75	140.36

TABLE 4-2

VARIANCE OF FLOW TIME IN THE SHOP
(PRELIMINARY STUDY)

(Measured in Hours)		Dispatching Rule				
Prev.	Loca.	SPT	EDD	SOPN	WINQ	Avg.
100%	Front	26725	21985	18789	20512	22003
	Exit	33522	17372	17069	14663	20657
	Mixed	47033	23555	20266	36471	31831
	Avg.	25873	18809	16840	23882	24830
50%	Front	35504	19679	17823	31141	26037
	Exit	20619	16827	15403	14380	16807
	Mixed	53039	25054	23419	37058	34643
	Avg.	36387	20520	18882	27526	25829
Grand Avg.		31130	19665	17861	25704	25330

TABLE 4-3

MEAN TARDINESS
(PRELIMINARY STUDY)

(Measured in Hours)		Dispatching Rule				
Prev.	Loca.	SPT	EDD	SOPN	WINQ	Avg.
100%	Front	9.02	22.80	21.90	26.84	20.14
	Exit	10.65	22.56	18.93	21.01	18.29
	Mixed	14.25	30.35	26.10	51.05	30.44
	Avg.	11.31	25.24	22.31	32.97	22.96
50%	Front	9.93	24.49	24.98	39.16	24.64
	Exit	6.89	14.17	12.41	16.62	12.52
	Mixed	12.35	32.51	30.74	44.28	29.97
	Avg.	9.72	23.72	22.71	33.55	22.38
Grand Avg.		10.52	24.48	22.51	33.16	22.67

TABLE 4-4

VARIANCE OF TARDINESS
(PRELIMINARY STUDY)

(Measured in Hours)		Dispatching Rule				
Prev.	Loca.	SPT	EDD	SOPN	WINQ	Avg.
100%	Front	16186	1904	2093	5540	6431
	Exit	21641	1254	1125	1535	6389
	Mixed	32213	2857	2625	16287	13496
	Avg.	23347	2005	1948	7787	8772
50%	Front	21323	3127	3743	14829	10756
	Exit	9790	2115	2034	2564	4126
	Mixed	36086	6516	7476	19072	17288
	Avg.	22400	3919	4418	12155	10723
Grand Avg.		22874	2962	3183	9971	9748

TABLE 4-5

PERCENT OF JOBS TARDY
(PRELIMINARY STUDY)

(Measured in Percentage)		Dispatching Rule				
Prev.	Loca.	SPT	EDD	SOPN	WINQ	Avg.
100%	Front	4.22	27.82	25.90	24.64	20.65
	Exit	4.05	29.16	26.93	29.01	22.29
	Mixed	5.22	32.34	28.10	31.09	24.19
	Avg.	4.50	29.77	26.98	28.25	22.38
50%	Front	4.43	20.24	20.98	23.16	17.20
	Exit	3.19	14.17	12.01	17.92	11.82
	Mixed	4.35	22.21	22.04	24.28	18.22
	Avg.	3.99	18.87	18.33	21.79	15.75
Grand Avg.		4.25	24.32	22.66	25.02	19.07

Based on the results of the preliminary study, both the EDD rule and the WINQ rule were discarded in the main experiment. In addition to the SPT and the S/OPN rule, the first-come-first-served rule (FCFS) was introduced in the main experiment. The FCFS rule was used as the base case against which other dispatching rules could be evaluated.

The factor of dispatching rules in the main experiment is tested at three levels: (1) the FCFS; (2) the SPT; and (3) the S/OPN rule.

4.2.2 Order Review/Release Mechanisms

As mentioned previously in 3.4, any order review/release mechanism must answer two fundamental questions: (1) what to release?; and, (2) when to release?

In this study, there are two ways to review and release jobs. The first way is to release jobs immediately as jobs arrive to the system. The backlog file is not needed for this scheme. The second approach, on the other hand, reviews jobs every week. As jobs arrive to the system, they are maintained in the backlog file until the start of next week. At the start of next week, jobs in the backlog file are reviewed and released if eligible.

Order review/release mechanisms are used at the start of each week to determine which jobs are eligible for release. These mechanisms use a wide range of information such as due date, slack, and shop congestion in determining the specific order jobs are to be released to the shop floor. In this study, jobs in the backlog file are released on the basis of minimum SLACK rule (where SLACK is the due date minus time now).

The release of jobs is controlled by a workload limit. A workload limit is set in an effort to control the maximum load either in the shop or at the bottleneck work center. This workload limit is a controlled variable. The determination of this workload limit will be discussed later in this chapter.

4.2.2.1 Control of Workload

The total workload in the shop at time j is divided into two components:

TWLSj = TWLBj + TWLNBj

Where

TWLSj = Total workload in the shop at time j

TWLBj = Total workload for the bottleneck work center at time j

TWLNBj = Total workload for the non-bottleneck work centers at time j

TWLBj includes both current and future bottleneck workload of jobs already released into the shop and passing through the bottleneck work center. The workload in the shop other than TWLBj becomes TWLNBj. For example, suppose there are five jobs in a shop consisting of six work centers. Each work center consists of a unique machine. Work center one is designated as a bottleneck. The job characteristics and location of each job is shown in Table 4.6 below:

TABLE 4-6

EXAMPLE FOR CALCULATING TWLS AND TWLB

Job #	Type	Routing and Processing Time				
001	B	1(20)	3(15)	5(10)		
002	NB	2(5)	6(10)	4(5)	3(12)	
003	B	3(5)	4(10)	6(7)	1(25)	
004	NB	5(10)	6(3)	2(4)	4(10)	
005	B	2(7)	3(4)	1(23)	6(10)	5(3)

Type represents whether a job is bottleneck (B) or non-bottleneck (NB) job. Routing and processing time is shown in the next column. For example, Job 001 first requires the operation of 20 hours at Work Center 1, then the operation of 15 hours at Work Center 3 and, finally, 10 hours of operation at Work Center 5. The underline indicates the completion of operation at that Work Center. Therefore, Job 001 is currently at Work Center 3.

According to this example, TWLS = 134 hours and TWLB = 48 hours. The current workload at the bottleneck work center is 23 hours while the future workload for the bottleneck work center is 25 hours. The difference between TWLS and TWLB is TWLNB (86 hours).

In this research study, three order review/release mechanisms were developed:

1. Immediate release (NOR)
2. Aggregate release (AR)
3. Bottleneck release (BR)

4.2.2.2 The Immediate Release Mechanism

The immediate release (NOR) mechanism releases jobs immediately as jobs arrive to the system. No backlog file is needed. The NOR represents a system in which no order review/release mechanism is present. As such, it is the base case - the standard against which the other order review/release mechanisms can be evaluated.

4.2.2.3 The Aggregate Release Mechanism

The aggregate release (AR) mechanism releases jobs in the backlog file based on TWLS. That is, the AR mechanism is designed to control only TWLS. The AR mechanism completely ignores the presence of any bottleneck work center in the shop. The AR mechanism is similar to that used by Bertrand (1983) and Baker (1984).

At the start of each week, the AR mechanism releases a job with the highest rank to the shop floor if current TWLS is below the predetermined workload level set by the experimenter. Jobs are prioritized on the basis of the SLACK rule. The ranked jobs become eligible in order for release until the updated TWLS meets the predetermined limit. The flowchart for the AR mechanism is provided in Appendix A.

4.2.2.4 The Bottleneck Release Mechanism

As discussed previously in Chapter 2 (see Goldratt and Cox 1983, and Ow 1985), one of the conclusions drawn was that the knowledge about the bottleneck should be used for bottleneck production scheduling. As such, the bottleneck release (BR) mechanism attempts to control the bottleneck work center by recognizing the impact of the bottleneck work center on shop performance.

The BR mechanism releases jobs based on TWLB alone. It does not consider TWLS. At the start of each week, the BR mechanism releases prioritized jobs by rank until the updated TWLB satisfies the planned workload level for the bottleneck work center. Jobs are again prioritized on the basis of the SLACK rule. The flowchart for the BR mechanism is illustrated in Appendix B.

4.2.2.5 Determination of Load Limit Level

A predetermined load limit must be set for the operation of both the AR and the BR mechanism. Specifically, the AR mechanism requires a load limit level for TWLS while the BR mechanism needs that for TWLB.

A load limit level is defined as the amount of load in the shop as a percentage of theoretical capacity. The setting of load limit level is expected to significantly affect the performance of order review/release mechanisms. Therefore, it is important to establish a reasonable range of values for the load limit level.

To identify such a range, the operating logic of these two mechanisms is further examined in light of bottleneck location. The location of the bottleneck does not affect the determination of load limit level for the AR mechanism. As previously noted, the AR mechanism is completely ignorant of the presence of the bottleneck.

The BR mechanism, on the other hand, does require some elaborate considerations. The bottleneck location has considerable influence on the determination of load limit level for the BR mechanism. This is best illustrated by considering an example.

Suppose the bottleneck is located in the front with 100% prevalence. 100% prevalence is used because it is the most restricted situation. Under this situation, there is no time delay between job release time to the shop floor and job arrival time to the bottleneck work center. As contrasted to this, there exists a time delay between job release and job arrival to the bottleneck when the bottleneck is at the end.

If the same load limit level for release is imposed on both locations, then more jobs tend to be released when the bottleneck is located in the front. Because TWLB for the front location, as compared to the exit, rapidly decreases. This results in the release of more jobs into the shop floor.

For the mixed location of the bottleneck, the position of the bottleneck in the routing is purely random. It is determined based on the uniform distribution. In the mixed location, the load limit level for the front and the exit location can provide the lower and upper limits. Therefore, an average of lower and upper limit level provides that load limit level for the mixed location.

To establish these limits, several pilot runs were conducted only for the following three cases. They were:

(1) The AR with the front location and 100% prevalence;

(2) The BR with the front location and 100% prevalence;

(3) The BR with the exit location and 100% prevalence.

In each case, seven different load limit levels, ranging from 100% to 700%, were tested. Five measurements were used as the performance criteria: (1) mean flow time in the shop; (2) variance of flow time in the shop; (3) mean tardiness, (4) variance of tardiness; and, (5) percent of jobs tardy. The FCFS rule was used for all cases.

Table 4-7 summarizes the results for the case (1). Both 100% and 200% load limit level turned out to be theoretically infeasible because of instability of the shop. For these two limits, the waiting line of the backlog file was growing continuously. Therefore, these two load limit levels were not used in the main experiment.

TABLE 4-7

LOAD LIMIT LEVEL DETERMINATION
FOR AR/FCFS/100%/FRONT

Load Limit Level	(Hours) Mean Flow Time in the Shop	(Hours) Variance of Flow Time in the Shop	(Hours) Mean Tardi-ness	(Hours) Variance of Tardiness	(Percent) Percent of Jobs Tardy
300%	118.94	34020	186.52	420967	61.10
400%	147.30	76300	75.56	62778	36.00
500%	165.30	134083	82.43	117271	31.30
600%	181.20	287671	93.14	266309	28.50
700%	189.70	324925	99.52	304326	27.50

It was evident from Table 4-8 that at the 600% and above load limit level, the mechanism tended to dump most jobs in the backlog file at the start of each week. Jobs spent little or no time in the backlog file. Therefore, this led to the use of two load limit levels in the main experiment: 300% (tight) and 500% (loose).

TABLE 4-8

AVERAGE JOB WAITING TIME
IN THE BACKLOG FILE

Experimental Design Cell Number	AR/Front 600% Load Limit Level	BR/Front 500% Load Limit Level	BR/Exit 700% Load Limit Level
1	21 hours	21 hours	21 hours
2	20 hours	21 hours	21 hours
3	32 hours	30 hours	25 hours
4	89 hours	49 hours	52 hours
5	20 hours	20 hours	20 hours
6	21 hours	23 hours	21 hours
7	20 hours	20 hours	20 hours
8	21 hours	20 hours	20 hours
9	20 hours	20 hours	22 hours
10	20 hours	21 hours	21 hours
11	48 hours	35 hours	35 hours

The results for the second case is shown in Table 4-9. Although 100% is feasible, it was not used in the main experiment because of the extremely high percentage of jobs tardy. Table 4-8 also indicates that the load limit level of 500% and above were loose enough to release most jobs at the very next review time. Therefore, two levels were selected for use in the main experiment: 200% (tight) and 400% (loose).

TABLE 4-9

LOAD LIMIT LEVEL DETERMINATION
FOR BR/FCFS/100%/FRONT

Load Limit Level	(Hours) Mean Flow Time in the Shop	(Hours) Variance of Flow Time in the Shop	(Hours) Mean Tardi-ness	(Hours) Variance of Tardiness	(Percent) Percent of Jobs Tardy
100%	99.64	23398	716.23	37349	93.50
200%	150.78	176571	71.96	1632692	31.80
300%	167.62	274740	82.97	256726	29.50
400%	183.25	340930	95.32	319923	27.60
500%	192.30	362178	102.70	340511	27.10
600%	196.52	360699	105.82	337629	27.30
700%	201.27	369092	110.00	345656	27.50

The performance measurements for the case (3) is shown in Table 4-10. As expected, 100% and 200% was theoretically infeasible due to the increasing number of jobs accumulating in the backlog file. Although 300% was feasible, it was not used in the main experiment due to the high number of jobs tardy and extremely long waiting time experienced by jobs in the backlog file. The load limit level of 700% and above were also considered too loose to be used in the main experiment. (See Table 4-8) There was no significant difference in performance between 700% load limit level and above. Therefore, the following two levels were identified as suitable for the main experiment: 400% (tight) and 600% (loose).

TABLE 4-10

LOAD LIMIT LEVEL DETERMINATION
FOR BR/FCFS/100%/EXIT

Load Limit Level	(Hours) Mean Flow Time in the Shop	(Hours) Variance of Flow Time in the Shop	(Hours) Mean Tardiness	(Hours) Variance of Tardiness	(Percent) Percent of Jobs Tardy
300%	104.56	27320	425.62	33895	89.10
400%	135.28	58404	79.83	46336	42.20
500%	152.52	109355	77.37	88607	32.50
600%	162.45	138604	80.97	114833	28.70
700%	171.13	166363	85.92	138737	26.90

For the mixed location, an average of the front and the exit location was used as the load limit level.

In the main experiment, the same load limit level was used across all levels of the prevalence.

Table 4-11 presents tight and loose load limit levels for release which are used in the main experiment under the AR and BR mechanism.

TABLE 4-11

LOAD LIMIT LEVELS IN THE MAIN EXPERIMENT

		Tight	Loose
AR		300.00%	500.00%
BR	Front	200.00%	400.00%
	Mixed	300.00%	500.00%
	Exit	400.00%	600.00%

The combination of the order review/release mechanism and the two load limit levels resulted in a factor having 5 levels:

1. NOR
2. AR with tight load limit level (ART)
3. AR with loose load limit level (ARL)
4. BR with tight load limit level (BRT)
5 BR with loose load limit level (BRL)

4.2.3 The Location of a Bottleneck

The location of a bottleneck work center is expected to affect the system performance. This factor occurred in three levels: front, exit, and mixed.

4.2.4 The Prevalence of a Bottleneck

The extent to which jobs go through the operation of bottleneck work center is expected to influence the system performance. The two levels were set in the main experiment: 100% and 50%.

4.2.5 Summary of experimental design

In this study, a full fixed factorial design is used to evaluate the effects of not only main factors but also the interactions among factors on shop performance. Therefore, the dimensions of the factorial experiment of this study are indicated by 3 (dispatching rule) * 5 (order review/release mechanism) * 3 (location) * 2 (prevalence) full factorial experiment. When combined, the resulting number of simulation runs, without replication, required by this study is 90.

The entire sample size is further increased by the number of replications required. There are eleven replications or repetitions of each of the combinations discussed previously. (The determination of replications will be discussed in 4.9.) As a result, the experimental design for this study requires 990 simulation runs.

4.3 Hypothesis Testing

In evaluating the impact of alternative control procedures on the management of the bottleneck job shop, the study focuses its attentions on testing the following hypotheses:

Main effects: Under this study the bottleneck is characterized by the location and prevalence. To cope with the problems created by the bottleneck, two control procedures (dispatching rules and order review/release mechanisms) have been proposed. We will test whether the characteristics of the bottleneck and proposed control alternatives have any significant impact on system performance (as measured in six major performance criteria). Each performance is measured in aggregate terms. To test the main effects, the following hypotheses are used:

H1a: The dispatching rule by itself will not have a significant impact on system performance.

H1b: The order review/release mechanism by itself will not have a significant impact on system performance.

H1c: The location of the bottleneck by itself will not have a significant impact on system performance.

H1d: The prevalence of the bottleneck by itself will not have a significant impact on system performance.

Method of analysis: analysis of variance

Initial expectation: Each main factor will have a significant impact on system performance.

First-order interaction effects: When we apply two control procedures to the management of bottlenecks, the impact of these two procedures on system performance may be affected by the characteristics of the bottleneck. We will test whether these is any potential interaction between the characteristics of the bottleneck and two control alternatives. To test these interaction effects, the following hypotheses are used:

H2a: The location of the bottleneck will not have a significant impact on the performance of the dispatching rules.

H2b: The location of the bottleneck will not have a significant impact on the performance of the order review/release mechanisms.

H2c: The prevalence of the bottleneck will not have a significant impact on the performance of the dispatching rules.

H2d: The prevalence of the bottleneck will not have a significant impact on the performance of the order review/release mechanisms.

Method of analysis: analysis of variance

Initial expectation: unknown

First-order interaction effect: Regardless of the type of order review/release mechanisms in use, one of the dispatching rules must be used. We will test if the type of dispatching rules used on the shop floor has any significant impact on the operation of the various order review/release mechanisms. To test this interaction effect, the following hypothesis is used:

H3: The dispatching rules will not have any significant impact on the performance of order review/release mechanisms.

Method of analysis: analysis of variance

Initial expectation: unknown

First-order interaction effect: The bottleneck is characterized by one of the six combinations of the location and prevalence. The performance measured at one particular type of bottleneck location may be affected by the type of the prevalence in use. We will test this possible interaction effect. To test this interaction effect, the following hypothesis is used:

H4: The type of prevalence in use will not have any significant impact on the performance of the location.

Method of analysis: analysis of variance

Initial expectation: unknown

Second-order interaction effects: The performance of the control procedures (as described in terms of order review/release mechanism and dispatching rule) may be influenced by the specific combination of the location and prevalence of the bottleneck. We will test if there is any combinatorial impact of these three factors on system performance. To test these interaction effects, the following hypotheses are used:

H5a: The performance of the dispatching rules will not be affected by the specific type of the location and prevalence of the bottleneck.

H5b: The performance of the order review/release mechanisms will not be affected by the specific type of the location and prevalence of the bottleneck.

Method of analysis: analysis of variance

Initial expectation: unknown

Main effects for non-bottleneck jobs: Up to this point, the performance measures we have dealt with are aggregate. This implies that we combine the performance measures of bottleneck jobs and non-bottleneck jobs. For the following hypotheses, we separate jobs into bottleneck and non-bottleneck jobs. There are two reasons for this separation. First, we try to examine how the presence of a bottleneck work center does influence these two types of jobs. Second, the separation of jobs into two types will facilitate the understanding of what type of job is most influenced by the presence of a bottleneck operation and control procedures.

Therefore, we collect data separately for bottleneck and non-bottleneck jobs, where it is possible (i.e., when we have 50% prevalence). First, we consider non-bottleneck jobs in association with the characteristics of a bottleneck operation and the control procedures.

To test these main effects, the following hypotheses are used:

H6a: The location of a bottleneck operation will not have a significant impact on the system performance of non-bottleneck orders.

H6b: The prevalence of a bottleneck operation will not have a significant impact on the system performance of non-bottleneck orders.

H6c: The dispatching rules will not have any significant impact on the the system performance of non-bottleneck jobs.

H6d: The order review/release mechanisms will not have any significant impact on the system performance of non-bottleneck jobs.

Method of analysis: analysis of variance

Initial expectation: unknown

Main effects for bottleneck jobs: Now, we shift our attention on bottleneck jobs in conjunction with the characteristics of a bottleneck operation. To test these main effects, the following hypotheses are used:

H7a: The location of a bottleneck operation will not have any significant impact on the system performance of bottleneck jobs

H7b: The prevalence of a bottleneck operation will not have any significant impact on the system performance of bottleneck jobs

H7c: The dispatching rules will not have any significant impact on the system performance of bottleneck jobs.

H7d: The order review/release mechanisms will not have any significant impact on the system performance of bottleneck jobs.

Method of analysis: analysis of variance

Initial expectation: Each main factor will have a significant impact on system performance of bottleneck jobs.

The full fixed factorial experiment: As mentioned earlier, the full fixed factorial experiment as a design was selected for this study. In a full fixed factorial experiment, all levels of a given factor are combined with all levels of every other factor in the experiment. The observations obtained in the full fixed factorial experiment can be used to test the significance of the main effects and interactions. This is done by the Analysis of Variance (ANOVA).

ANOVA - an overview: The analysis of variance is used to determine if there are significant differences between the cells, and if so, whether these differences can be attributed to either the main effects (the impact of each factor alone) or to the interactions effects. However, the analysis of variance is a limited test. It does not tell the researcher which levels of a specific factor are significant. Furthermore, it does not estimate the response of the of the primary performance criterion to a given factor or its levels (Kleijnen 1975, pp. 295-307). The analysis of variance, as a result, gives some insight into the nature of the relationships present between the factors and system performance, but it does not provide complete insight.

Multiple comparison procedure: Linear contrasts (or pairwise multiple comparisons) on group means are performed. The purpose of these comparisons is to determine which levels of a specific factor are significantly different from the other levels of that factor. The linear contrast test achieves this goal by ranking the cell means from high to low and indicating how these cell means are grouped statistically. While differentiating the various levels, this comparison does not indicate how much more effective one level or factor is than any other.

The comparison of means can be done on either an 'a priori' (planned comparison) basis or on an ' a posteriori' basis (data exploration). Given the exploratory orientation of this project, the 'a posteriori' approach is used. This method of contrasting cell means systematically compares all possible pairs of group means. The result of these comparisons are then used in identifying the homogeneous subsets (i.e., the set of all group means where the difference between the means of any two groups is not significant at some specified level).

Of the various procedures available for comparing group means, Duncan's multiple range test is used in this research (Winer 1971, pp. 196-201).

Finally, as part of this procedure, a test of homogeneity of variance is run on all groups, using Cochran's C (Winer 1971, pp. 205-210).

4.4 Performance Criteria

A shop floor control system attempts to achieve a smooth flow of orders and to minimize work-in-process inventory while meeting planned customer delivery promises in most cost effective manner. In general, using this perspective, the performance of a shop floor control system can be measured along three dimensions: lead-time, inventory, and customer service. For each dimension, performance can be measured using either cost or non-cost yardsticks. Non-cost measures of performance were chosen because of problems inherent to cost structure assumptions used in various studies. In those studies, the performance was significantly affected by the specific structure of the cost function.

To capture adequately all three type of non-cost performance, the following performance measures were selected:

Lead-time measures

* Mean flow time in the shop
* Variance of flow time in the shop

Inventory measure

* Mean work-in-process inventory in the system

Customer service measures

* Mean tardiness
* Variance of tardiness
* Percent of jobs tardy

In addition to these six major performance measures, other performance measures were also recorded. These minor measures provide further more detailed insight into how each factor affected the shop floor. These measures included the following:

* Mean flow time in the system
* Variance of flow time in the system
* Average waiting time in the backlog file
* Average waiting time at the bottleneck work center
* Average waiting time at the non-bottleneck work center
* Average total workload in the shop
* Average workload at the bottleneck work center
* Average workload at the non-bottleneck work center

Where possible (i.e., when prevalence is 50 percent), information was collected on both the bottleneck jobs and the non-bottleneck jobs.

4.5 Initial Condition Setting

The research study deals with a system operating in the steady-state. The steady-state, however, is frequently affected by the initial conditions of the simulation. In this section, initial simulation settings are examined.

In most stochastic models there is an initial bias not typical of steady-state conditions. This is because it takes some time for the model to overcome the atypical or artificial situations created by the starting condition of the simulation. (Shannon 1975, pp. 182) Conway (1963) suggested three approaches for the initial condition setting:

(1) Test each system starting "empty and idle."

(2) Test each system using a common set of starting conditions that is essentially a compromise between the two different sets of reasonable starting conditions.

(3) Test each system with its own "reasonable" starting conditions.

In general, it was more efficient to use (2) or (3) than (1). In this study, however, approach (1) was used since it was difficult to obtain good initial condition data for this bottleneck operation model.

4.6 Test for Independence

For the statistical analysis to be valid, the samples in each run must be independent of each other (i.e., uncorrelated). Correlated and dependent samples violate the assumptions of many statistical tests. Analysis based on such data provides results which are unreliable for drawing statistical inferences.

Shannon (1973) listed two methods of dealing with autocorrelated data.

(1) Dividing the simulation run into equal subgroups and treat each subgroups as a single independent observation.

(2) Estimate the autocorrelation function and include its effects in the estimation of the parameters.

For this study, (1) was selected. In order to decide the number of observations per batch which is uncorrelated and independent, the technique suggested by Fishman (1978) was employed. Fishman's method groups the observations on a run into batches and determines the size of a batch which is independent of each other. These batches then are used as the basic data for analysis.

Several computer simulation runs were conducted initially with 128 batches, each consisting of 100 completed jobs (i.e., each simulation run has 12800 completed jobs). Using Fishman's method, the number of batches was reduced by half each time until each batch is independent of each other. The necessary number of observations per batch was found to be 1600 completed jobs. Therefore, a batch of 1600 completed jobs which were uncorrelated and independent of each other were used in the main experiment.

4.7 Steady-State Equilibrium

This research was interested in studying the behavior of a non-terminating system operating in its steady-state. Since the system starts initially "empty and idle", there was a transient state before the system reached the steady-state. Steady-state defines a situation in which performance measurements are independent of the initial condition setting. In the previous section, the number of jobs comprising a batch which were independent of each other was determined. Each batch was independent of each other. As a result, the first batch was regarded as the transient period and discarded before doing the statistical analysis. Once steady-state has been attained, the terminal conditions of one subrun forms excellent candidates for the optimal conditions of the next. (Kaczka 1970)

4.8 Variance Reduction Technique

It is desirable to reduce the variance of the data for statistical analysis. There are two approaches. The first is to increase the sample sizes. The other is to use variance reduction techniques.

Since the research being studied was concerned with evaluating and comparing several competing alternatives, it was reasonable to do the simulation using the same operating environments.

A technique called blocking was used to provide a reduction of variance in the experimental errors. Under blocking, common random number streams were used for all alternatives. If common random numbers were used, the performance measurements for different alternatives were positively correlated. This reduced the variance of the difference between the alternatives.

In this study, the common random number streams were used for all the simulation models as the variance reduction technique.

4.9 The Sample Size

Since the simulation model being studied dealt with random samples, the result had some degree of imprecision associated with the measurements. It was therefore necessary either to estimate the confidence interval attributable to the conclusions with a given sample size or determine the sample size with a desired precision.

There are two approaches, replicated runs and continued runs, to do this for nonterminating systems. (Kleijnen, 1974, pp.86) Although replication of runs using different sequence of pseudo-random numbers was more desirable for statistical analysis than continued runs, it was very expensive and had to discard the transient observations at the beginning of each run. With this respect, it was decided to conduct a continued run with batch sampling.

To determine the appropriate sample size at the .05 level, several computer runs were conducted. For purposes of estimating the variability of results, the batch mean was considered as the single observation. This satisfied the assumption of normality because of the central limit theorem. A studentized t distribution was applied to determine the adequate sample size using the following formula. (Shannon, 1975, pp. 189)

N = T*T*S*S/D*D

Where:

N = The sample size

T = Tabulated t value for the desired confidence level and the degree of freedom of the initial sample

D = The half-width of the desired confidence interval

S = The estimate of the variance obtained in pilot run

Table 4-12 illustrates the appropriate sample size where D equals +- 15% of the mean. The appropriate sample size had wide values ranging from 1 to 53 depending on the type of load limit level, order review/release mechanism, and the performance measurement being used. However, the procedure of how the sample sizes were determined in Table 4-12 ignored the efficiency of the blocking factor used to reduce the error variability. The efficiency of the blocking factor reduced the sample size without affecting statistical significance.

In an effort to reduce the sample size of the main experiment, the efficiency of the blocking factor as identified by Ragatz (1985) was consulted. The simulation model used by Ragatz was very similar to the model of this study in terms of operating logic, relative shop size, and use of order review/release mechanisms. The efficiency factor in Ragatz's model was approximately 3.5. Since the reduction of experimental error variance through the blocking factor can lead to a reduction in sample size without losing a power of the test, the sample size could be reduced in the main experiment.

In the main experiment, each run had 11 independent subruns, each of which had 1600 completed jobs. The first subrun was discarded since this represented the transient state. As the result, each run had 10 independent subruns with 16000 completed jobs.

TABLE 4-12

SAMPLE SIZE DETERMINATION

	Mean Flow Time in the Shop	Variance of Flow Time in the Shop	Mean Tardi- ness	Variance of Tardiness	Percent of Jobs Tardy
Run 1	16.45	43.19	48.20	52.39	1.56
Run 2	1.19	5.56	33.38	6.76	32.24
Run 3	12.01	37.67	32.83	45.08	0.57

Run 1 : The NOR/FCFS/100%/Mixed
Run 2 : The ART/FCFS/100%/Mixed
Run 3 : The ARL/FCFS/100%/Mixed

4.10 Summary

In this chapter, the factors and levels of each factor of the experimental design were described. Also discussed were the statistical hypotheses and performance criteria in this study. The statistical aspects of the simulation model was also discussed. In the next chapter, the results of this study will be analyzed. In addition, the appropriateness of the ANOVA model will be examined.

CHAPTER 5

ANALYSIS OF THE SIMULATION RESULTS

5.1 Introduction

This chapter describes the analysis of the experimental results. The simulation results are evaluated by an analysis of variance procedure to determine the statistical significance. The assumptions underlying the analysis of variance are tested in section 2. Original model, if necessary, is transformed. Section 3 presents detailed analysis of significant main and interaction effects of the experimental design in light of aggregate performance measurements. In section 4, then, the performance of bottleneck jobs is compared with that of non-bottleneck jobs.

5.2 Assumptions in an Analysis of Variance

Univariate 5-factor analysis of variances was used to determine if any of the experimental factors had a significant effect on the major performance criteria at the .05 level. The data analysis was performed using the Statistical Package for Social Sciences (SPSS), release 9.0 MANOVA package on the CDC Cyber 750 at Michigan State University.

The results of the ANOVA, as measured by the six major performance measurements, are presented in Appendix C. It was assumed that all interactions involving the blocking factor, Jobset, were to be zero and included in the experimental error. Summary tables of the results of the main experiment are presented in Tables 5-1 through 5-6.

Before going on to an analysis of the statistical inferences, one factor must be examined. This is the appropriateness of the assumptions in the ANOVA to assure conformity to F-test assumptions. Each six ANOVA model is examined separately. The basic assumptions in the ANOVA are as follows:

(1) Each experimental observation should be independent.

(2) Distributions of experimental errors should be normal.

(3) Experimental errors should be homogeneous in their variance.

The independence of each experimental observation was satisfied by using independent subruns previously mentioned in 4.6.

Deviations from the assumptions about normality and homogeneity of variance of experimental errors were detected by the analysis of standardized residuals. The assumption of normality of experimental errors were tested using bar chart of the standardized residuals and through a Chi-square goodness of fit test. The assumption of homogeneity of variance of experimental errors were examined using standardized residual plots by each cell and the use of Cochran's test for homogeneity at the .01 level.

TABLE 5-1

SUMMARY TABLES FOR WORK-IN-PROCESS
(ORIGINAL MODEL: 10 OBSERVATIONS)

(Measured in Hours)

100% Prevalence — Order Review/Release Mechanism

Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	302.61	271.36	302.92	317.92	316.15	302.19
	SPT	149.22	145.22	148.64	154.17	150.32	149.51
	SOPN	271.80	256.20	266.10	267.49	266.37	265.59
Exit	FCFS	817.91	745.71	790.08	518.04	656.84	705.72
	SPT	217.49	210.96	216.64	182.14	201.60	205.77
	SOPN	609.76	536.35	609.52	328.63	446.63	506.18
Mixed	FCFS	787.64	557.83	731.02	552.37	632.52	652.28
	SPT	185.10	173.93	182.51	172.98	179.92	178.89
	SOPN	449.74	363.76	412.38	332.80	383.15	388.37
	Avg.	421.25	362.37	406.65	314.06	359.28	372.72

50% Prevalence — Order Review/Release Mechanism

Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	322.90	306.16	307.02	341.46	330.60	321.63
	SPT	138.44	134.52	136.58	154.40	149.27	142.64
	SOPN	250.60	255.33	242.77	297.54	274.03	264.05
Exit	FCFS	555.76	455.37	510.63	376.31	451.02	469.82
	SPT	181.93	177.60	183.30	160.70	172.70	175.25
	SOPN	413.89	380.51	413.00	296.30	316.97	364.13
Mixed	FCFS	647.94	453.21	580.49	403.55	518.50	520.74
	SPT	166.85	157.55	164.38	163.55	167.52	163.97
	SOPN	396.14	334.14	367.28	352.78	337.78	357.62
	Avg.	341.61	294.93	322.83	282.95	302.04	308.87

TABLE 5-2

SUMMARY TABLES FOR MEAN FLOW TIME IN THE SHOP
(ORIGINAL MODEL: 10 OBSERVATIONS)

(Measured in Hours)

100% Prevalence — Order Review/Release Mechanism

Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	196.48	118.93	165.34	150.77	183.24	162.95
	SPT	86.31	88.74	92.84	86.99	90.13	89.00
	SOPN	163.36	134.37	154.78	134.28	157.77	148.91
Exit	FCFS	197.88	163.72	189.55	132.58	162.45	169.24
	SPT	88.73	88.46	90.57	83.72	88.26	87.95
	SOPN	161.31	156.04	166.11	131.46	145.51	152.09
Mixed	FCFS	220.69	151.20	215.00	150.97	186.65	184.90
	SPT	94.28	89.59	95.43	86.88	90.96	91.43
	SOPN	176.62	150.75	169.67	139.60	157.35	158.80
	Avg.	153.96	126.87	148.81	121.92	140.26	138.36

50% Prevalence — Order Review/Release Mechanism

Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	183.10	123.39	158.31	128.44	151.26	148.90
	SPT	86.51	83.47	88.05	85.85	87.53	86.28
	SOPN	155.68	135.05	148.54	132.05	137.52	141.77
Exit	FCFS	165.88	142.97	166.12	125.61	144.51	149.02
	SPT	83.28	83.53	85.65	83.47	84.72	84.13
	SOPN	131.91	135.81	135.55	140.19	131.63	135.02
Mixed	FCFS	203.05	141.68	187.95	131.17	153.02	163.37
	SPT	89.95	86.01	90.49	87.68	89.68	88.76
	SOPN	163.90	145.05	158.03	150.45	148.26	153.14
	Avg.	140.36	119.66	135.41	118.32	125.35	127.82

TABLE 5-3

SUMMARY TABLES FOR VARIANCE OF FLOW TIME IN THE SHOP
(ORIGINAL MODEL: 10 OBSERVATIONS)

(Measured in Hours)

100% Prevalence — Order Review/Release Mechanism

Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	449451	34026	134202	176573	340937	227038
	SPT	26724	15205	25962	9243	18803	19188
	SOPN	18792	7355	13663	9838	15045	12939
Exit	FCFS	293140	164374	248459	58404	138604	180596
	SPT	33520	29923	32610	10201	23870	26025
	SOPN	17068	12101	17305	5586	10976	12607
Mixed	FCFS	401611	107197	366025	118410	285405	255730
	SPT	47028	31122	46586	13879	27117	33147
	SOPN	20266	9210	16364	8625	13432	13580
	Avg.	145290	45613	100131	45640	97133	86761

50% Prevalence — Order Review/Release Mechanism

Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	367105	58027	273876	56969	205659	192327
	SPT	35505	17733	34459	8881	14757	22267
	SOPN	17829	8522	13132	8551	9765	11560
Exit	FCFS	170395	110692	166067	43295	86103	115310
	SPT	20621	20259	22117	8625	13920	17108
	SOPN	15402	12236	16100	7229	8867	11967
Mixed	FCFS	531833	142354	372075	57450	153541	251450
	SPT	53034	27555	50694	10560	17633	31895
	SOPN	23417	12641	20259	10233	10829	15476
	Avg.	137238	45558	107643	23533	57898	74374

TABLE 5-4

SUMMARY TABLES FOR MEAN TARDINESS
(ORIGINAL MODEL: 10 OBSERVATIONS)

(Measured in Hours)

100% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	105.60	186.51	82.43	71.94	95.31	108.36
	SPT	9.01	10.52	11.29	15.18	11.14	11.43
	SOPN	21.90	53.33	30.14	31.01	30.15	33.31
Exit	FCFS	102.16	76.94	98.50	79.81	80.97	87.68
	SPT	10.63	11.88	12.26	14.54	12.64	12.39
	SOPN	18.92	31.32	29.04	120.02	30.66	45.99
Mixed	FCFS	121.27	93.91	122.74	87.83	104.56	106.06
	SPT	14.24	14.43	15.65	25.56	17.33	17.44
	SOPN	26.09	62.59	35.33	63.99	38.89	45.38
	Avg.	47.76	60.16	48.60	56.65	46.85	52.00

50% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	93.47	125.87	82.33	106.79	101.00	101.89
	SPT	9.94	19.62	11.34	68.71	42.92	30.51
	SOPN	24.98	87.05	40.40	94.58	65.22	62.45
Exit	FCFS	72.90	60.31	77.40	158.29	66.86	87.15
	SPT	6.91	8.30	8.53	22.39	13.00	11.83
	SOPN	12.41	32.36	17.50	172.82	37.64	54.55
Mixed	FCFS	109.07	102.96	102.86	194.54	110.74	124.03
	SPT	12.34	21.33	13.46	63.33	41.84	30.46
	SOPN	30.73	77.85	36.42	204.91	93.29	88.64
	Avg.	41.42	59.52	43.36	120.71	63.61	65.72

TABLE 5-5

SUMMARY TABLES FOR VARIANCE OF TARDINESS
(ORIGINAL MODEL: 10 OBSERVATIONS)

(Measured in Hours)

100% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	420975	35211	117273	163282	319916	211331
	SPT	16185	8067	15964	4619	11316	11230
	SOPN	2093	4052	2789	2841	2784	2912
Exit	FCFS	251379	137321	214054	46342	114833	152786
	SPT	21640	19819	21348	4604	14863	16455
	SOPN	1124	1599	1550	9515	1681	3094
Mixed	FCFS	356029	91017	329161	103291	259075	227715
	SPT	32216	21784	32868	8359	18132	22672
	SOPN	2624	6165	3649	6653	4251	4668
	Avg.	122697	36115	82073	38834	82984	72541

50% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	337742	52944	254948	54425	194204	178853
	SPT	21323	10921	21633	9979	11494	15070
	SOPN	3741	7952	5071	9084	6442	6458
Exit	FCFS	142222	90944	142018	42595	69267	97409
	SPT	9792	10822	11304	5168	6903	8797
	SOPN	2034	4064	2652	12570	4039	5072
Mixed	FCFS	494484	129556	344791	63332	144518	235336
	SPT	36093	18808	35078	12793	15211	23597
	SOPN	7478	11166	8013	19918	12351	11785
	Avg.	117213	37464	91725	25541	51604	64709

TABLE 5-6

SUMMARY TABLES FOR PERCENT OF JOBS TARDY
(ORIGINAL MODEL: 10 OBSERVATIONS)

(Measured in Percentage)

100% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	19.60	61.10	31.30	31.80	27.60	19.60
	SPT	4.00	13.90	12.10	21.80	14.00	13.16
	SOPN	25.20	44.90	35.40	36.20	35.40	35.42
Exit	FCFS	18.60	24.60	25.10	42.40	28.70	27.88
	SPT	4.10	10.10	10.20	18.20	13.20	11.16
	SOPN	27.30	40.40	37.40	59.80	37.90	40.56
Mixed	FCFS	20.60	40.50	27.00	38.40	31.80	31.66
	SPT	4.60	14.10	11.10	26.50	18.50	14.96
	SOPN	27.90	48.40	36.50	50.10	36.90	39.96
	Avg.	16.88	33.11	25.12	36.13	27.11	27.67

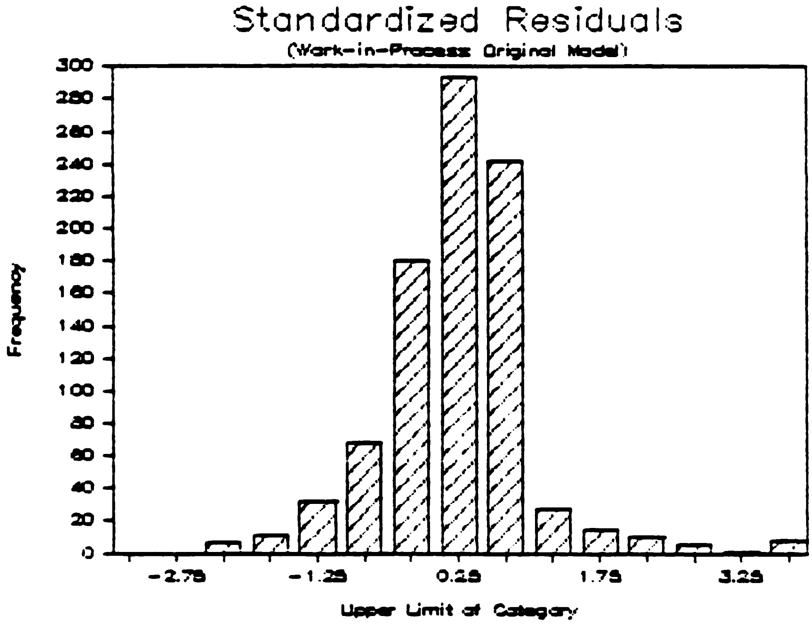
50% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	17.30	48.90	28.00	45.00	39.50	35.74
	SPT	3.90	18.80	9.40	39.50	29.80	20.28
	SOPN	20.60	45.70	32.00	50.20	39.80	37.66
Exit	FCFS	18.30	24.20	24.80	57.70	29.80	30.96
	SPT	3.70	8.90	8.80	21.60	15.00	11.60
	SOPN	12.00	28.70	19.80	72.90	34.70	33.62
Mixed	FCFS	18.50	41.10	26.30	57.40	41.60	36.98
	SPT	4.30	15.20	9.50	39.90	28.10	19.40
	SOPN	21.50	43.80	28.70	68.40	47.70	42.02
	Avg.	13.34	30.59	20.81	50.29	34.00	29.81

Figures 5-1 through 5-6 illustrate the bar charts of the standardized residuals and the Chi-square goodness of fit tests, and standardized residual plots by experimental design cell number and Cochran's tests for each of the six major performance measurements.

The ANOVA model with respect to the percent of jobs tardy was the only one which, although slightly violating the assumption of nomality, satisfied the assumption of homogeneity of variance of experimental residuals (see Figures 5-1 through 5-6). The failure to meet the assumptions of normality and homogeneity of variance for other ANOVA models indicated that the original data should be transformed in order for each ANOVA to produce meaningful results.

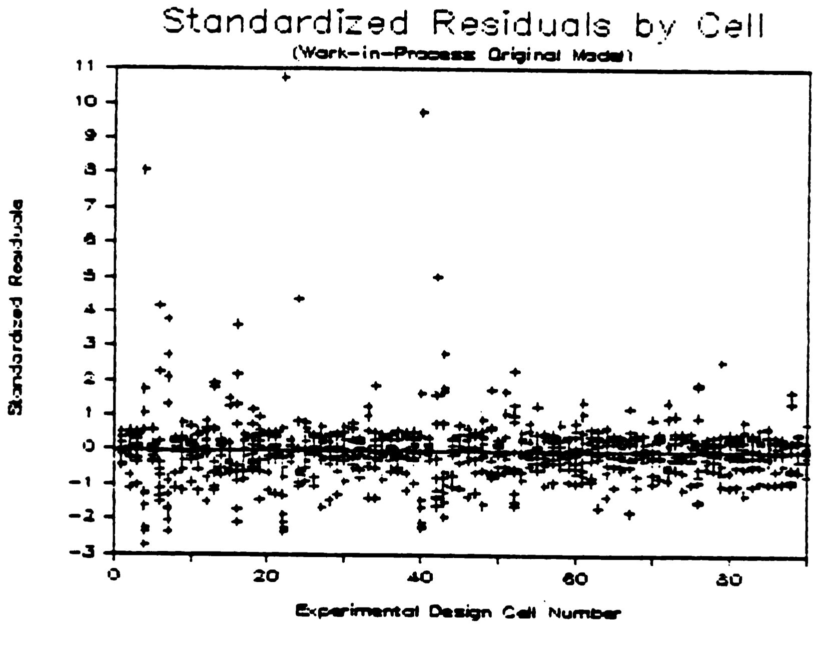
Since heterogeneity of error variance usually arose from a relationship of variance to mean (Kempthorne 1966, pp. 155), the choice of appropriate transformation for each ANOVA model was determined by examining the relationship between cell variance, or cell standard deviation, and cell mean, or square of cell mean.

To the ANOVA models for work-in-process and mean flow time, an inverse or reciprocal transformation was applied to reduce the variability of experimental errors. Figures 5-7 and 5-8 show plots of cell standard deviation versus square of cell mean of the ANOVA models for work-in-process and mean flow time in the shop, respectively. When the standard deviation is proportional to the square of the mean, the



SKEWNESS = 3.932 KURTOSIS = 38.705

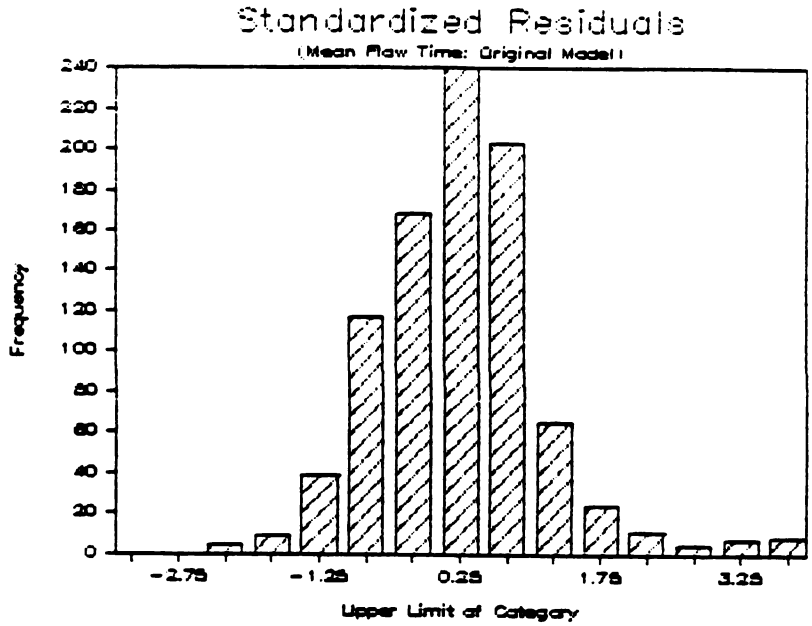
CHI-SQUARED = 314.692 D.F. = 14 SIGNIF. = .000



COCHRAN'S C = 0.172
CRITICAL VALUE (a = .01) = 0.047

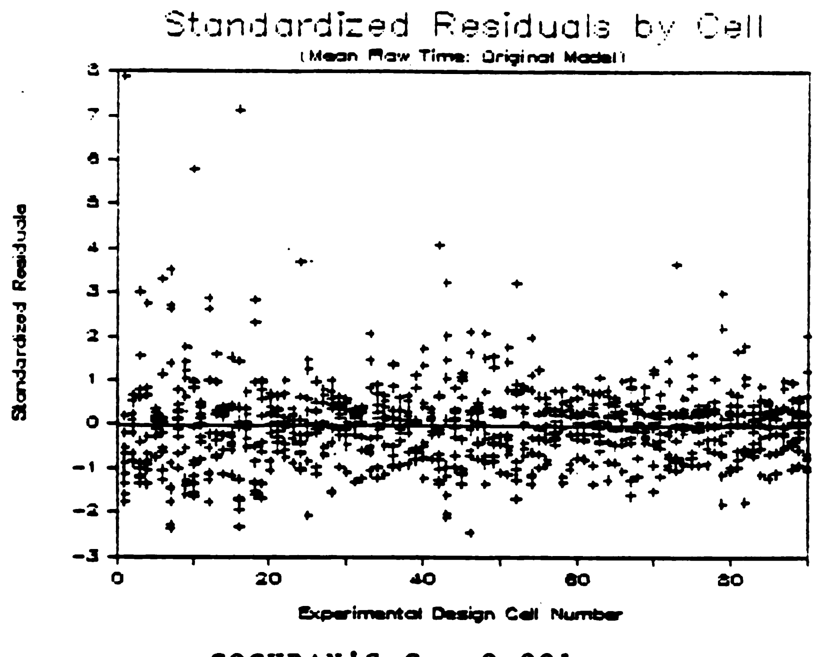
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(WORK-IN-PROCESS: ORIGINAL MODEL)

FIGURE 5-1



SKEWNESS = 1.896 KURTOSIS = 11.434

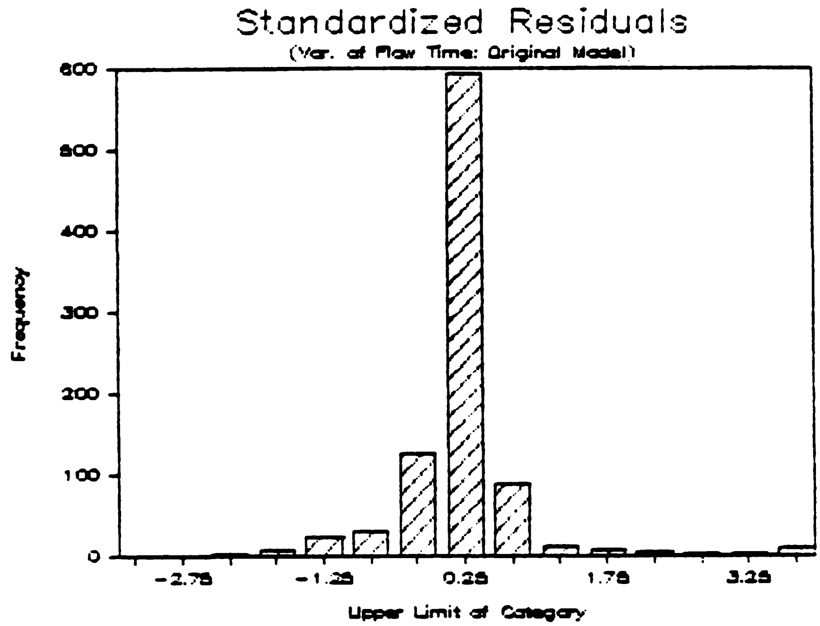
CHI-SQUARED = 168.461 D.F. = 14 SIGNIF. = .000



COCHRAN'S C = 0.091
CRITICAL VALUE (a = .01) = 0.047

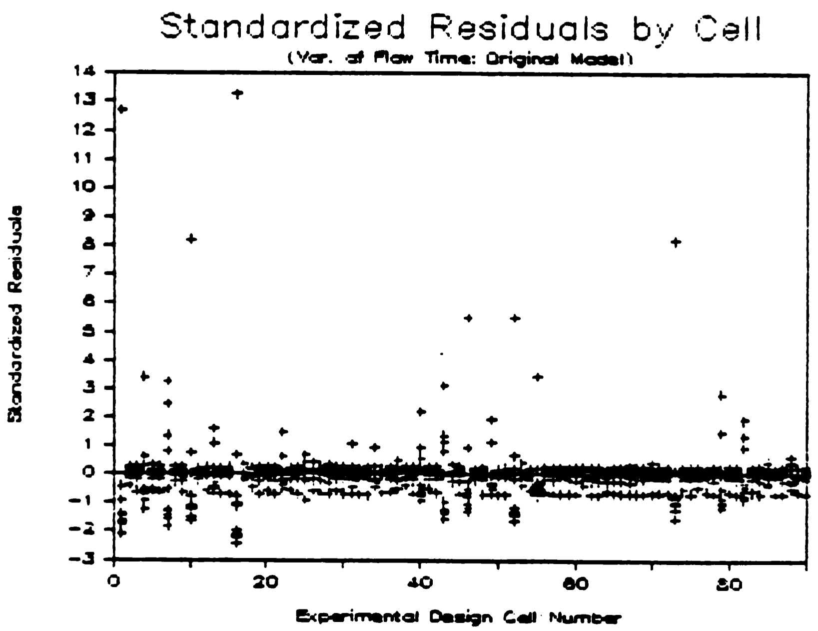
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(MEAN FLOW TIME IN THE SHOP: ORIGINAL MODEL)

FIGURE 5-2



SKEWNESS = 7.789 KURTOSIS = 94.446

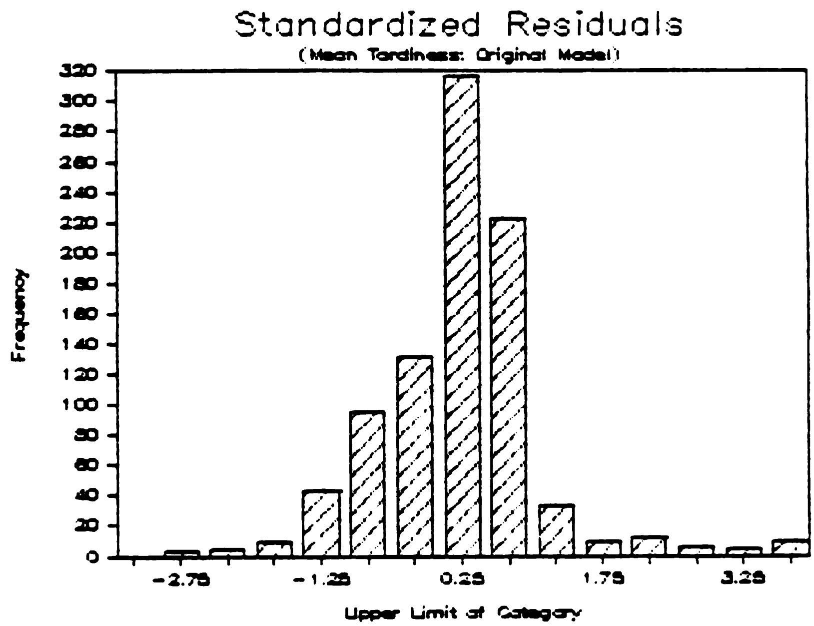
CHI-SQUARED = 1342.414 D.F. = 14 SIGNIF. = .000



COCHRAN'S C = 0.255
CRITICAL VALUE (a = .01) = 0.047

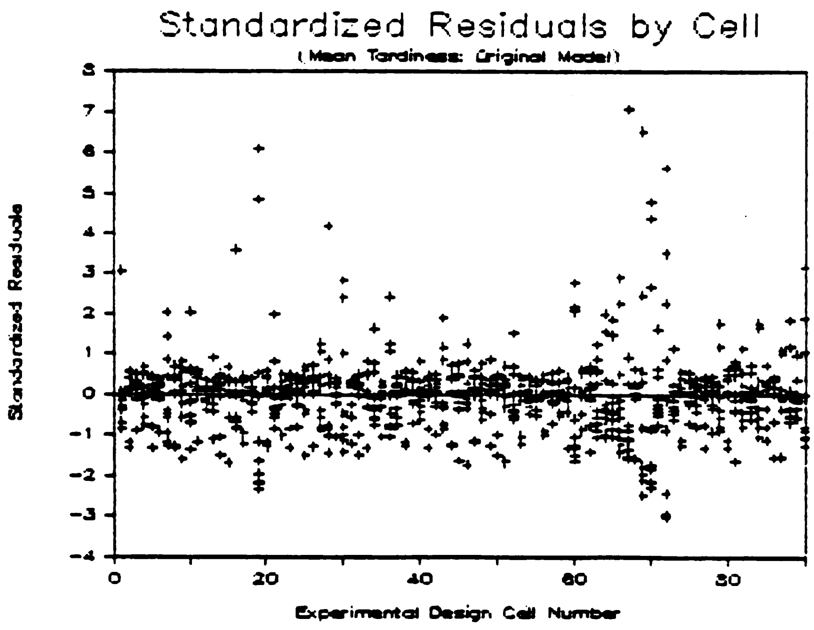
NORMALITY AND HOMOGENEITY OF VARIANCE TEST (VARIANCE OF FLOW TIME IN THE SHOP: ORIGINAL MODEL)

FIGURE 5-3



SKEWNESS = 1.936 KURTOSIS = 11.875

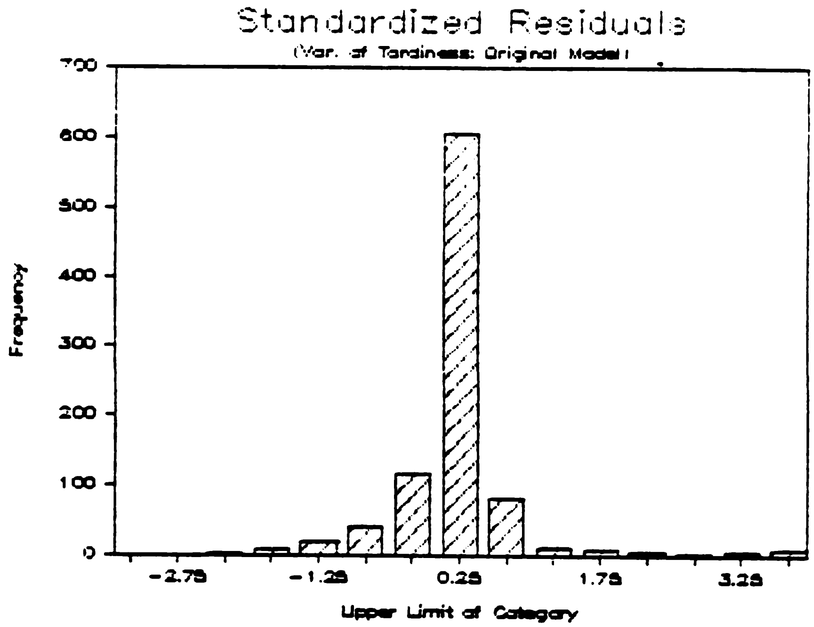
CHI-SQUARED = 347.438 D.F. = 14 SIGNIF. = .000



COCHRAN'S C = 0.105
CRITICAL VALUE (a = .01) = 0.047

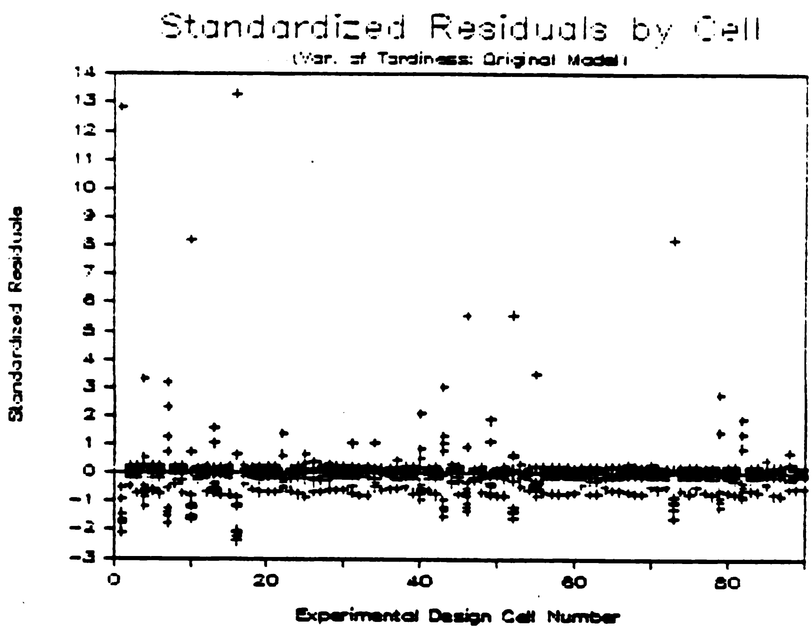
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(MEAN TARDINESS: ORIGINAL MODEL)

FIGURE 5-4



SKEWNESS = 7.924 KURTOSIS = 96.637

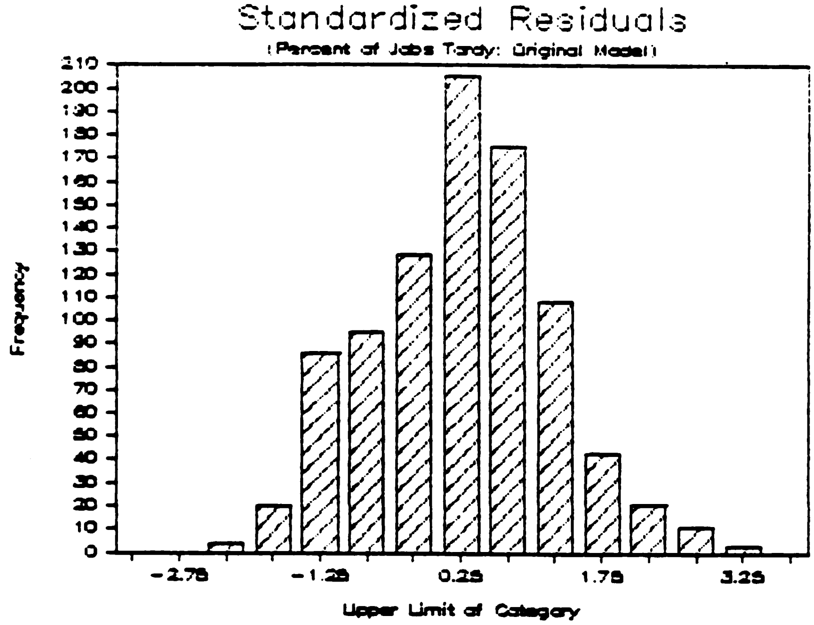
CHI-SQUARED = 1377.67 D.F. = 14 SIGNIF. = .000



COCHRAN'S C = 0.263
CRITICAL VALUE (a = .01) = 0.047

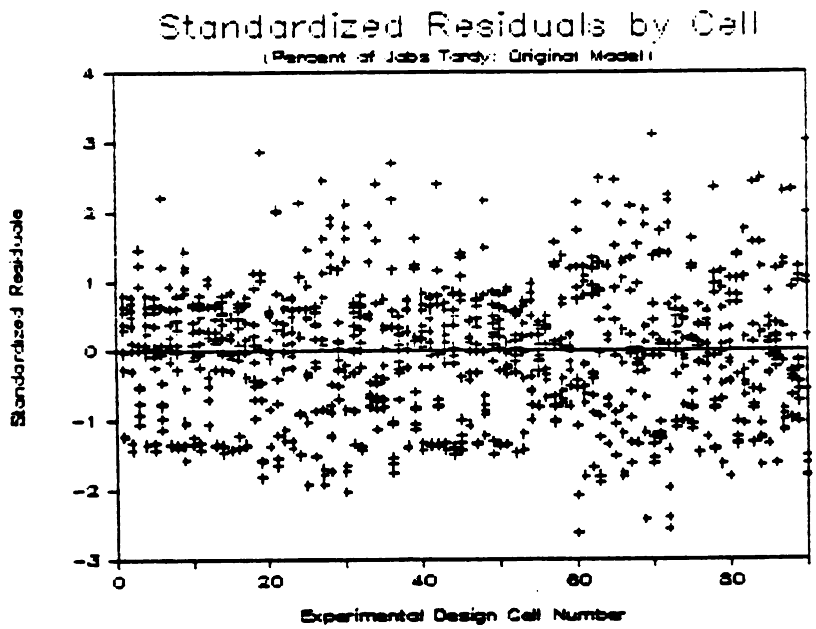
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(VARIANCE OF TARDINESS: ORIGINAL MODEL)

FIGURE 5-5



SKEWNESS = 0.135 KURTOSIS = 0.023

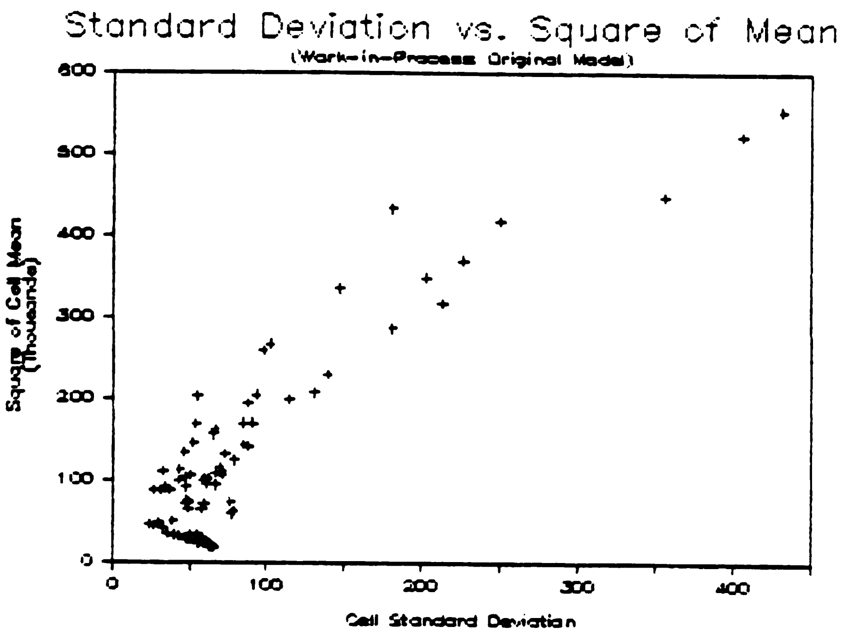
CHI-SQUARED = 38.920 D.F. = 14 SIGNIF. = .000



COCHRAN'S C = 0.042
CRITICAL VALUE (a = .01) = 0.047

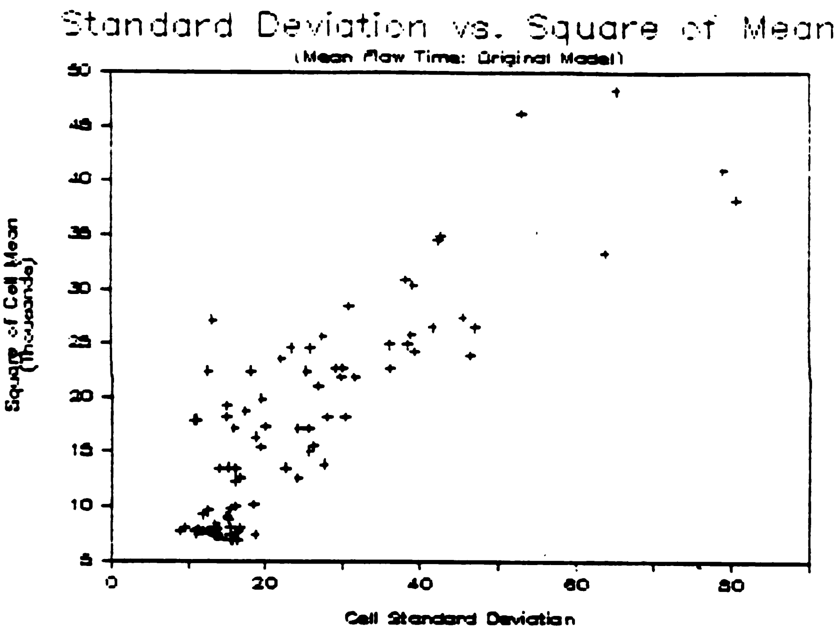
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(PERCENT OF JOBS TARDY: ORIGINAL MODEL)

FIGURE 5-6



CELL STANDARD DEVIATION VS. SQUARE OF CELL MEAN
(WORK-IN-PROCESS: ORIGINAL MODEL)

FIGURE 5-7



CELL STANDARD DEVIATION VS. SQUARE OF CELL MEAN
(MEAN FLOW TIME IN THE SHOP: ORIGINAL MODEL)

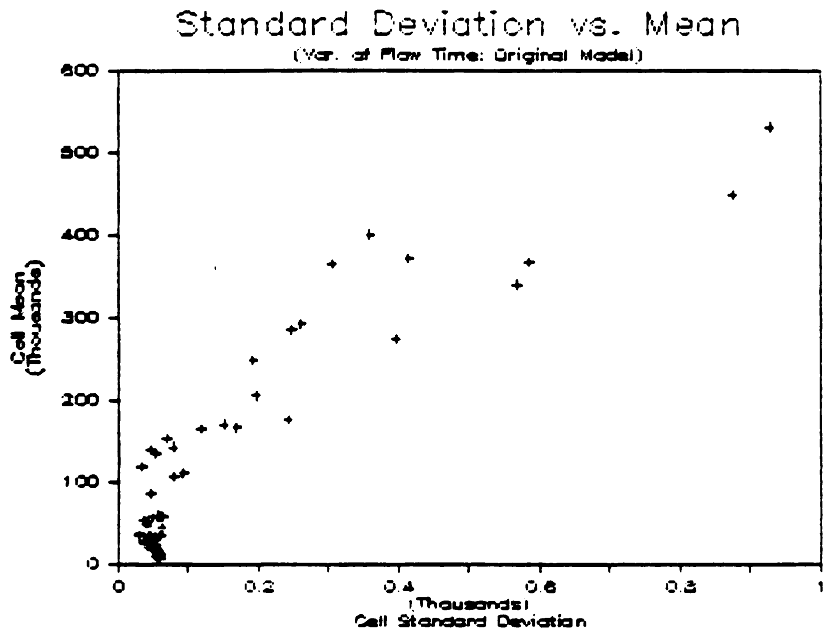
FIGURE 5-8

reciprocal transformation of the original data was recommended. (Anderson and McLean 1974, pp. 25)

A logarithmic transformation was used for the ANOVA models for the variance of flow time in the shop, mean tardiness, and the variance of tardiness. When the cell mean is approximately proportional to its standard deviation, the logarithmic transformation is effective. (Walker and Lev 1953, pp. 424) Figure 5-9 through 5-11 illustrate the plots of cell standard deviation versus cell mean of the ANOVA models for variance of flow time in the shop, mean tardiness, and the variance of tardiness measures, respectively. The logarithmic transformation is also particularly effective in normalizing distributions which have high positive skewness. (Winer 1971, pp. 400) The skewness of these criteria were relatively high as compared to other dependent variables (see Figure 5-3 and 5-5).

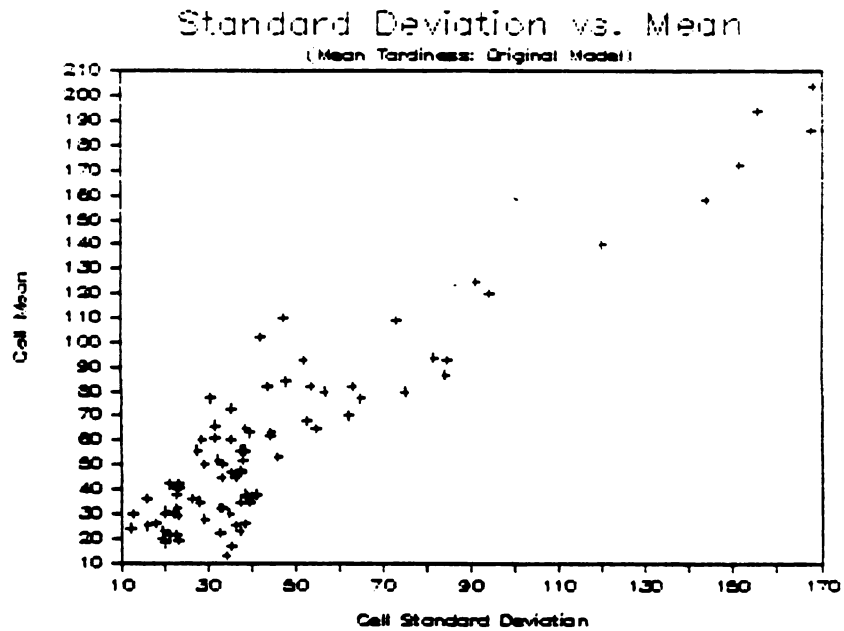
The ANOVA results on the transformed data for the five major performance measurements are given in Table 5-7 through 5-11.

Figure 5-12 through 5-16 show the results of the bar chart of the standardized residuals, the Chi-square goodness of fit test, the plot of standardized residuals by experimental design cell number and Cochran's test on the transformed data for the five performance measures. Although the Chi-square test for variance of flow time in the shop again indicated non-normality of the residuals, it was evident that both the skewness and kurtosis had been



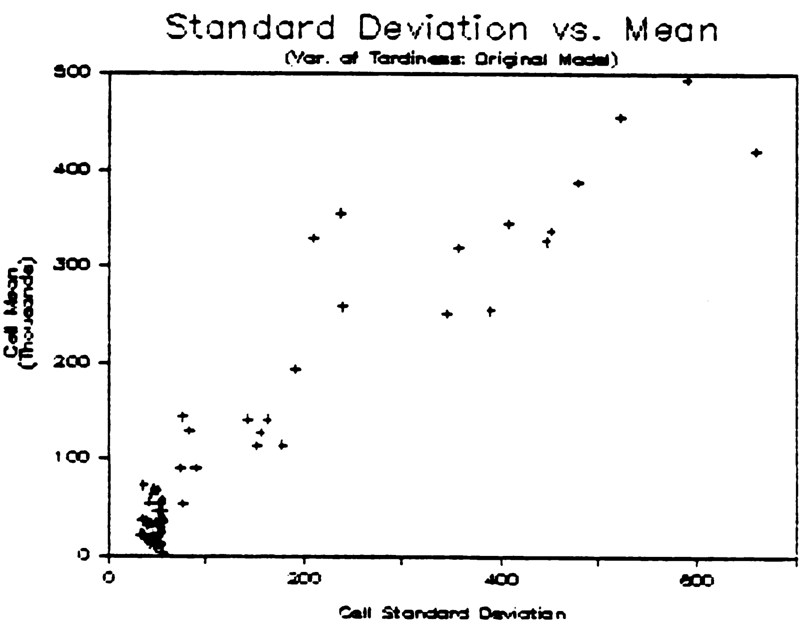
CELL STANDARD DEVIATION VS. CELL MEAN
(VARIANCE OF FLOW TIME IN THE SHOP: ORIGINAL MODEL)

FIGURE 5-9



CELL STANDARD DEVIATION VS. CELL MEAN
(MEAN TARDINESS: ORIGINAL MODEL)

FIGURE 5-10



CELL STANDARD DEVIATION VS. CELL MEAN
(VARIANCE OF TARDINESS: ORIGINAL MODEL)

FIGURE 5-11

TABLE 5-7

ANALYSIS OF VARIANCE
(WORK-IN-PROCESS: INVERSE MODEL)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR INWIP USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	.00017	801	2.16718E-007		
JOBSET	.00029	9	.00003	148.24369	0
ORR	.00001	4	2.95894E-006	13.65340	0
DISPATCH	.00240	2	.00120	5527.68820	0
LOCATION	.00033	2	.00016	756.02341	0
PREVALEN	.00004	1	.00004	166.25449	0
ORR BY DISPATCH	2.89341E-006	8	3.61676E-007	1.66887	.10224
ORR BY LOCATION	.00003	8	3.15582E-006	14.56183	0
ORR BY PREVALEN	1.37364E-006	4	3.43409E-007	1.58459	.17641
DISPATCH BY LOCATION	.00001	4	2.24477E-006	10.35801	3.49959E-008
DISPATCH BY PREVALEN	2.68008E-006	2	1.34004E-006	6.18333	.00216
LOCATION BY PREVALEN	.00002	2	.00001	35.75940	0
ORR BY DISPATCH BY LOCATION	1.91728E-006	16	1.19830E-007	.55293	.91847
ORR BY DISPATCH BY PREVALEN	1.80573E-006	8	2.25717E-007	1.04152	.40284
ORR BY LOCATION BY PREVALEN	1.26110E-006	8	1.57637E-007	.72738	.66742
DISPATCH BY LOCATION BY PREVALEN	2.66189E-006	4	6.65472E-007	3.07068	.01589
ORR BY DISPATCH BY LOCATION BY PREVALEN	6.62495E-007	16	4.14060E-008	.19106	.99980
(MODEL)	.00313	98	.00003	147.16657	0
(TOTAL)	.00330	899	3.66983E-006		

R-SQUARED = .94738
ADJUSTED R-SQUARED = .94095

- -

TABLE 5-8

ANALYSIS OF VARIANCE
(MEAN FLOW TIME IN THE SHOP: INVERSE MODEL)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR INMFT USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	.00074	801	9.27023E-007		
JOBSET	.00111	9	.00012	132.91106	0
DDR	.00011	4	.00003	29.86542	0
DISPATCH	.00445	2	.00222	2399.28937	0
LOCATION	.00005	2	.00002	26.33390	0
PREVALEN	.00007	1	.00007	75.90779	0
DDR BY DISPATCH	.00006	8	.00001	8.38633	0
DDR BY LOCATION	.00002	8	2.27405E-006	2.45307	.01258
DDR BY PREVALEN	.00001	4	1.73967E-006	1.87662	.11256
DISPATCH BY LOCATION	.00001	4	1.86357E-006	2.01027	.09119
DISPATCH BY PREVALEN	2.13448E-006	2	1.06724E-006	1.15125	.31676
LOCATION BY PREVALEN	1.62264E-006	2	8.11321E-007	.87519	.41718
DDR BY DISPATCH BY LOCATION	.00002	16	1.12512E-006	1.21369	.25071
DDR BY DISPATCH BY PREVALEN	.00001	8	1.32344E-006	1.42762	.18094
DDR BY LOCATION BY PREVALEN	.00001	8	8.57605E-007	.92512	.49473
DISPATCH BY LOCATION BY PREVALEN	8.55146E-007	4	2.13787E-007	.23062	.92123
DDR BY DISPATCH BY LOCATION BY PREVALEN	3.81994E-006	16	2.38746E-007	.25754	.99863
(MODEL)	.00593	98	.00006	65.22873	0
(TOTAL)	.00667	899	.00001		

R-SQUARED = .93865
ADJUSTED R-SQUARED = .87502

\- -

TABLE 5-9

ANALYSIS OF VARIANCE
(VARIANCE OF FLOW TIME IN THE SHOP: LOGARITHMIC MODEL)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR LOVFT USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	295.01125	801	.36830		
JOBSET	160.14873	9	17.79430	48.31422	0
ORR	87.35628	4	21.83907	59.29636	0
DISPATCH	906.48143	2	453.24072	1230.61686	0
LOCATION	18.04140	2	9.02070	24.49257	0
PREVALEN	4.27179	1	4.27179	11.59854	.00069
ORR BY DISPATCH	8.07820	8	1.00977	2.74169	.00546
ORR BY LOCATION	10.34962	8	1.29370	3.51260	.00053
ORR BY PREVALEN	2.78204	4	.69551	1.88841	.11050
DISPATCH BY LOCATION	2.53276	4	.63319	1.71920	.14370
DISPATCH BY PREVALEN	1.30745	2	.65372	1.77496	.17016
LOCATION BY PREVALEN	1.86597	2	.93299	2.53320	.08004
ORR BY DISPATCH BY LOCATION	6.05510	16	.37870	1.02822	.42360
ORR BY DISPATCH BY PREVALEN	1.98518	8	.24815	.67376	.71496
ORR BY LOCATION BY PREVALEN	2.90327	8	.36291	.98535	.44591
DISPATCH BY LOCATION BY PREVALEN	1.92410	4	.48102	1.30606	.26606
ORR BY DISPATCH BY LOCATION BY PREVALEN	.62153	16	.03885	.10547	1.00000
(MODEL)	1216.70893	98	12.41540	33.70967	0
(TOTAL)	1511.72018	899	1.68156		

R-SQUARED = .80485
ADJUSTED R-SQUARED = .78097

TABLE 5-10

ANALYSIS OF VARIANCE
(MEAN TARDINESS: LOGARITHMIC MODEL)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR LOMTA USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	654.22513	801	.81676		
JOBSET	622.78454	9	69.19828	84.72286	0
DDR	96.81474	4	24.20369	29.63376	0
DISPATCH	772.93998	2	386.46999	473.17421	0
LOCATION	32.12683	2	16.06341	19.66723	0
PREVALEN	.27693	1	.27693	.33905	.56054
DDR BY DISPATCH	78.63257	8	9.82907	12.03421	1
DDR BY LOCATION	8.43658	8	1.05457	1.29117	.24449
DDR BY PREVALEN	23.46186	4	5.86547	7.18138	.00001
DISPATCH BY LOCATION	4.55259	4	1.13815	1.39349	.23437
DISPATCH BY PREVALEN	.94328	2	.47164	.57745	.56156
LOCATION BY PREVALEN	5.40597	2	2.70298	3.30940	.03704
DDR BY DISPATCH BY LOCATION	16.91657	16	1.05729	1.29449	.14332
DDR BY DISPATCH BY PREVALEN	2.63380	8	.32923	.40302	.91909
DDR BY LOCATION BY PREVALEN	.39642	8	.04955	.06067	.99988
DISPATCH BY LOCATION BY PREVALEN	2.42403	4	.60601	.74196	.56352
DDR BY DISPATCH BY LOCATION BY PREVALEN	1.13707	16	.07107	.08701	1.00000
(MODEL)	1669.88374	98	17.03963	20.86246	0
(TOTAL)	2324.10887	899	2.58522		

R-SQUARED = .71950
ADJUSTED R-SQUARED = .69406

\- -

TABLE 5-11

ANALYSIS OF VARIANCE
(VARIANCE OF TARDINESS: LOGARITHMIC MODEL)

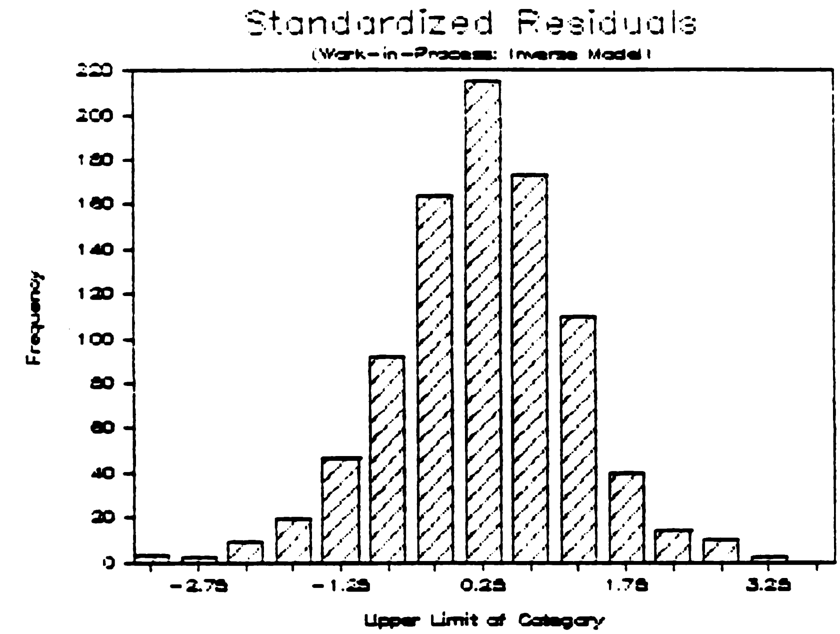
* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR LOVTA USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	1382.74112	801	1.72627		
JOBSET	1182.91203	9	131.43467	76.13862	0
ORR	14.18607	4	3.54652	2.05444	.09499
DISPATCH	3208.77410	2	1604.38705	929.39597	0
LOCATION	99.85695	2	49.92848	28.92277	0
PREVALEN	.02180	1	.02180	.01263	.91054
ORR BY DISPATCH	218.92050	8	27.36506	15.85215	0
ORR BY LOCATION	9.93218	8	1.24152	.71919	.67472
ORR BY PREVALEN	7.67771	4	1.91943	1.11189	.34962
DISPATCH BY LOCATION	13.02511	4	3.25628	1.88631	.11066
DISPATCH BY PREVALEN	11.20742	2	5.60371	3.24614	.03944
LOCATION BY PREVALEN	10.12568	2	5.06284	2.93282	.05382
ORR BY DISPATCH BY LOCATION	26.93658	16	1.68354	.97525	.48203
ORR BY DISPATCH BY PREVALEN	9.05399	8	1.13175	.65560	.73085
ORR BY LOCATION BY PREVALEN	.91211	8	.11401	.06605	.99983
DISPATCH BY LOCATION BY PREVALEN	2.22062	4	.55515	.32159	.86359
ORR BY DISPATCH BY LOCATION BY PREVALEN	2.83806	16	.17738	.10275	1.00000
(MODEL)	4818.60891	98	49.16948	28.48305	0
(TOTAL)	6201.34203	899	6.89804		

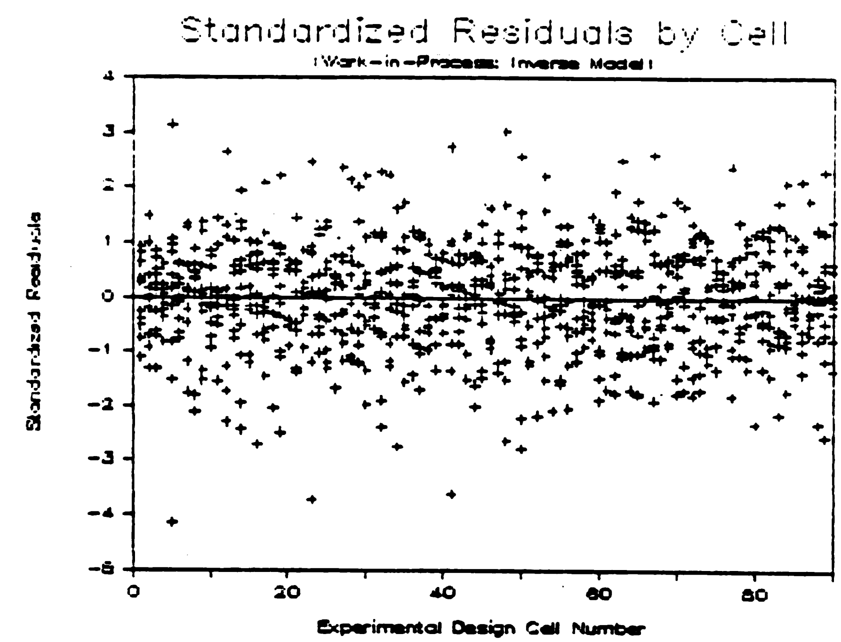
R-SQUARED = .77703
ADJUSTED R-SQUARED = .74975

\- -



SKEWNESS = -0.214   KURTOSIS = 1.043

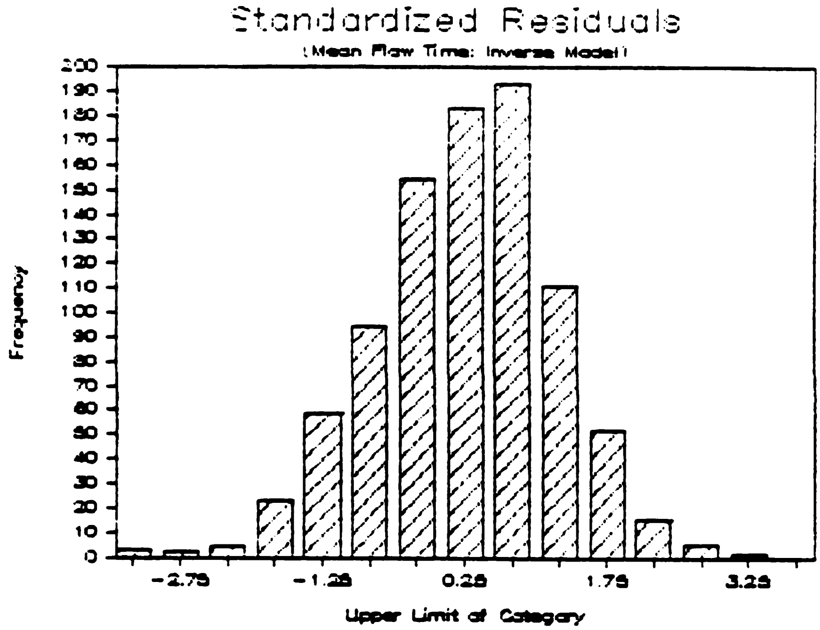
CHI-SQUARED = 32.759   D.F. = 14   SIGNIF. = .001



COCHRAN'S C = 0.041
CRITICAL VALUE (a = .01) = 0.047

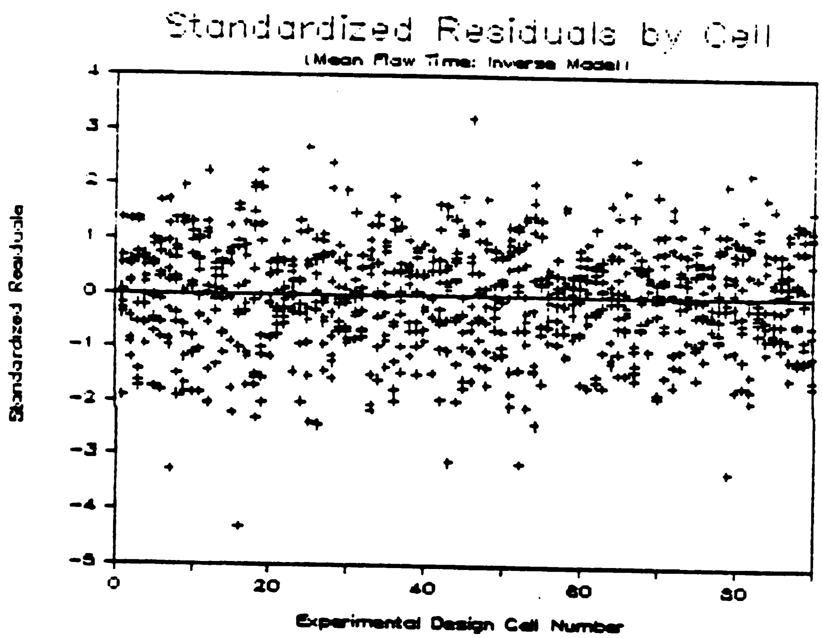
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(WORK-IN-PROCESS: INVERSE MODEL)

FIGURE 5-12



SKEWNESS = -0.322   KURTOSIS = 0.537

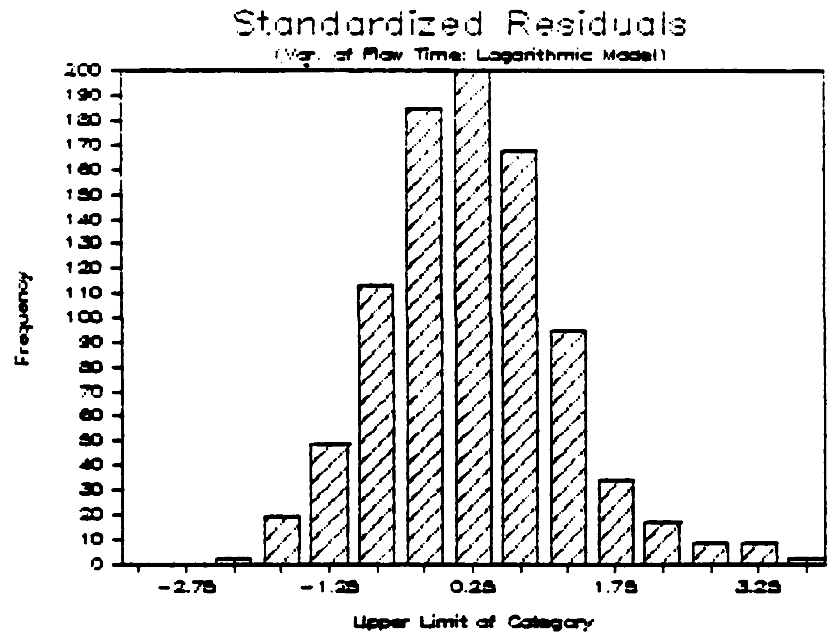
CHI-SQUARED = 23.903   D.F. = 14   SIGNIF. = .025



COCHRAN'S C = 0.034
CRITICAL VALUE (a = .01) = 0.047

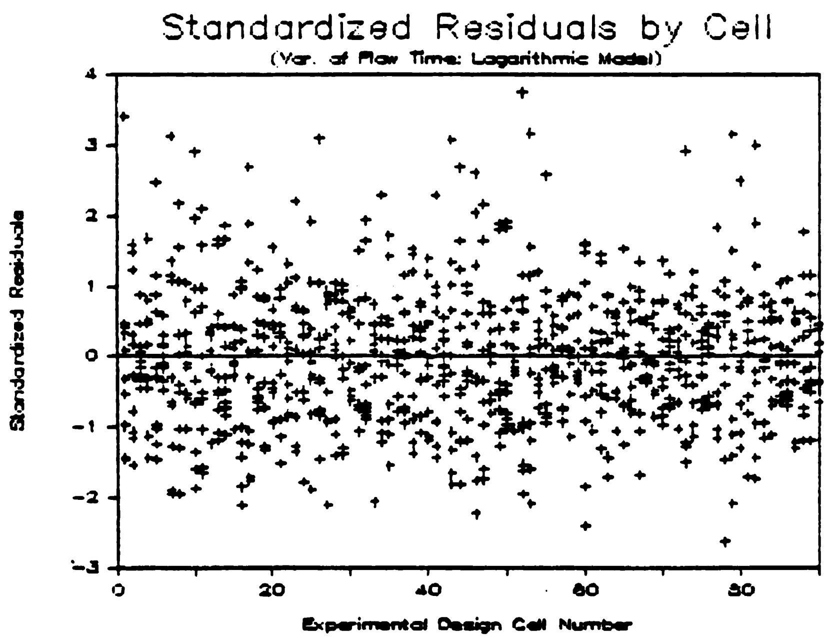
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(MEAN FLOW TIME IN THE SHOP: INVERSE MODEL)

FIGURE 5-13



SKEWNESS = 0.605 KURTOSIS = 1.571

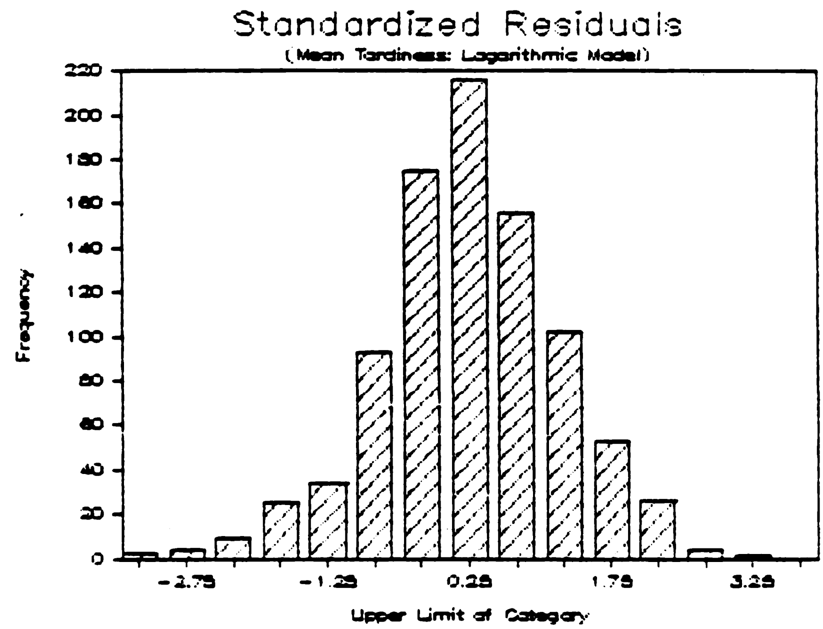
CHI-SQUARED = 53.217 D.F. = 14 SIGNIF. = .000



COCHRAN'S C = 0.046
CRITICAL VALUE (a = .01) = 0.047

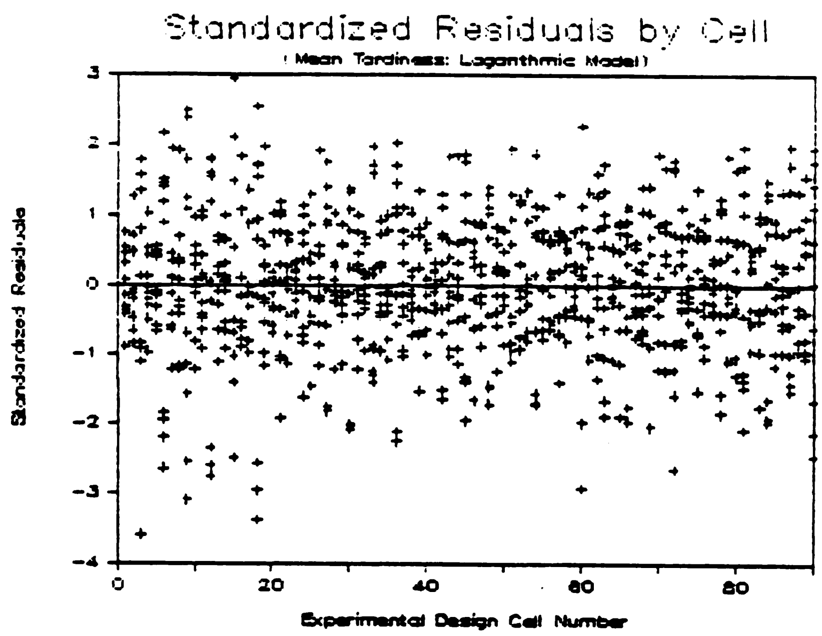
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(VARIANCE OF FLOW TIME IN THE SHOP : LOGARITHMIC MODEL)

FIGURE 5-14



SKEWNESS = -0.257 KURTOSIS = 0.584

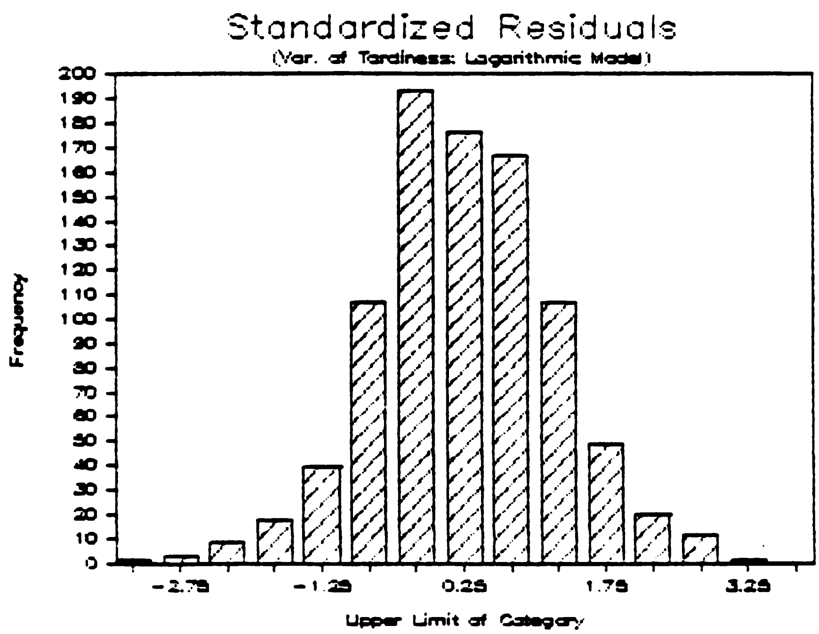
CHI-SQUARED = 30.849 D.F. = 14 SIGNIF. = .005



COCHRAN'S C = 0.050
CRITICAL VALUE (a = .01) = 0.047

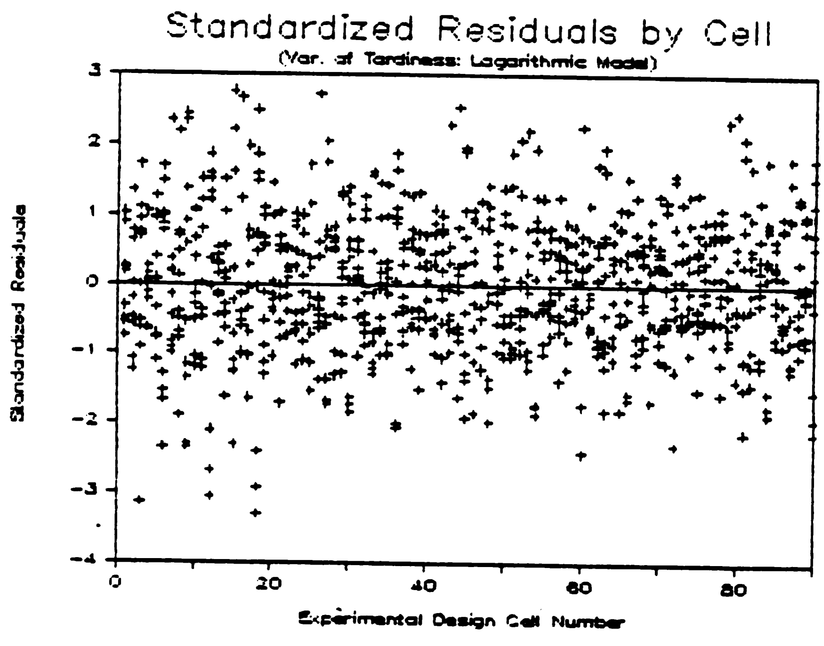
NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(MEAN TARDINESS: LOGARITHMIC MODEL)

FIGURE 5-15



SKEWNESS = -0.017 KURTOSIS = 0.313

CHI-SQUARED = 23.547 D.F. = 14 SIGNIF. = .050



COCHRAN'S C = 0.047
CRITICAL VALUE (a = .01) = 0.047

NORMALITY AND HOMOGENEITY OF VARIANCE TEST
(VARIANCE OF TARDINESS: LOGARITHMIC MODEL)

FIGURE 5-16

significantly reduced.

The results of Cochran's tests indicated that only the ANOVA model for mean tardiness violated the assumption of homoscedasticity. However, a visual examination of the plots of standardized residuals versus experimental design cell number suggested that the variabilities of errors were greatly reduced when compared to the original ones. The failure of assumptions may affect both the significance levels and the sensitivity of F tests. However, the slight violation of normality was negligible because the F test is relatively insensitive to departures from normality (Scheffe, 1959, pp. 350). This also applied to the situation of the slight violation of the homogeneity of variance assumption especially when the number of observations in each cell was same.

All statistical comparisons or confidence interval estimates were made on the transformed data for all system performance except the percent of jobs tardy. Appendix D shows summary tables of the transformed data for the five dependent variables.

The power of the F test of each ANOVA model for main effects is presented in Appendix E. It indicates the small probability of committing a Type II error for most main effects.

To reduce the error variability of the model the blocking variance reduction technique was used as discussed in 4.8. The efficiency of blocking factor for each of the six ANOVA models was calculated to provide an estimate of the increase in accuracy which results from the grouping into replicates (Neter and Wasserman, 1974, pp. 738-740). The estimates are calculated as follows:

$$E = [(n - 1)*MSB + n*(r - 1)* MSE] / [(n*r - 1)*MSE]$$

where: n = the number of observations per cell

r = the number of treatments

MSE = the error mean square

MSB = the mean square due to the blocking factor

Table 5-12 shows the efficiency of blocking factor for the six ANOVA models.

TABLE 5-12

THE EFFICIENCY OF THE BLOCKING FACTOR

ANOVA Model	Efficiency
Work-in-Process	1.15
Mean Flow Time in the Shop	1.14
Variance of Flow Time in the Shop	1.05
Mean Tardiness	1.09
Variance of Tardiness	1.08
Percent of Jobs Tardy	1.07

5.3 Experimental Results

5.3.1 General Overview

This section presents the results of the analysis of variance for this experiment. Specifically, this section describes significant main and interaction effects at the .05 level for each performance measurement. The results discussed in this section are summarized in Table 5-13.

Work-in-Process: All main effects were found to be significant at the .05 level. Also significant at the .05 level were four two-way interactions. These were: the interaction of order review/release mechanism and location; dispatching rule and location; dispatching rule and prevalence; and location and prevalence. A significant three-way interaction effect was also observed at the .05 level. This effect involved dispatching rule, location, and prevalence. No four-way interactions were significant.

Mean Flow Time in the Shop: The main effect of order review/release mechanism was significant, as were the other main effects at the .05 level. Two two-way interactions were also found to be significant. They were the interaction of order review/release mechanism and dispatching rule; and order review/release mechanism and location. None of the three-way and four-way interactions were significant at the .05 level.

Variance of Flow Time in the Shop: ANOVA results for this performance are also provided in Table 5-13. All main effects were found to be significant at the .05 level. Two two-way interactions involving (1) order review/release mechanism and dispatching rule and (2) order review/release mechanism and location were also significant. None of the three-way and four-way interactions were significant at the

TABLE 5-13

ANOVA RESULTS

Effects	Performance Criteria					
	WIP	MFT	VFT	MTA	VTA	PTA
Main						
ORR	*	*	*	*		*
DIS	*	*	*	*	*	*
LOC	*	*	*	*	*	*
PRE	*	*	*			*
2-Way						
ORR * DIS		*	*	*	*	*
ORR * LOC	*	*	*			*
ORR * PRE				*		*
DIS * LOC	*					
DIS * PRE	*				*	
LOC * PRE	*			*		
3-Way						
ORR * DIS * LOC						*
ORR * DIS * PRE						
ORR * LOC * PRE						
DIS * LOC * PRE	*					
4-Way						
ORR * DIS * LOC * PRE						

Where: WIP = Work-in-Process
MFT = Mean Flow Time in the Shop
VFT = Variance of Flow Time in the Shop
MTA = Mean Tardiness
VTA = Variance of Tardiness
PTA = Percent of Jobs Tardy

* indicates significant effect at the .05 level.

.05 level.

Mean Tardiness: All main effects except prevalence were found to be significant at the .05 level. Three two-way interactions were also significant. They were: (1) the interaction of order review/release mechanism and dispatching rule; (2) order review/release mechanism and prevalence; and, (3) location and prevalence. No three-way or four-way interactions were significant at the .05 level.

Variance of Tardiness: Main effects of dispatching rule and bottleneck location only were found to be significant. Two two-way interactions (order review/release mechanism and dispatching rule, and dispatching rule and prevalence) were also found to be significant. None of the three-way and four-way interactions were significant at the .05 level.

Percent of Jobs Tardy: All main effects were found to be significant at the .05 level. There were three two-way significant interactions: (1) order review/release mechanism and dispatching rule; (2) order review/release mechanism and location; and (3) order review/release mechanism and prevalence. There also existed a significant three-way interaction effect. This effect involved order review/release mechanism, dispatching rule, and bottleneck location.

5.3.2 Detailed Analysis

The ANOVA results for each of the six major performance measurements are analyzed in detail in this section. Duncan's multiple comparison method is used to test for significant differences between multiple pairs of experimental conditions and to provide further statistical insight into these differences.

One additional point must be made before proceeding to this detailed analysis. Since a significant interaction indicates that the relative effects of one factor change as we proceed from level to level of the other factor, it might be misleading to try to interpret significant main effects in the presence of a significant interaction effects. Under such conditions, it is generally more appropriate to examine the effects of one particular factor for each individual level of another factor and, similarly, to study another factor for each individual level of the particular factor. The detailed analysis in this study, therefore, does not interpret significant main or interaction effects in the presence of a higher significant interaction effect.

5.3.2.1 Work-in-Process

A subsequent post-hoc multiple comparison test for significant interaction effects relevant to the detailed discussion is provided in Appendix F. Duncan's procedure was used to test pairwise comparisons between means at the .05 protection level.

5.3.2.1.1 Dispatching Rule * Location * Prevalence

A significant three-way interaction effect was observed among dispatching rule, bottleneck location, and bottleneck prevalence. Table 5-14 presents the 3-way data. The nature of this interaction is shown in Figures 5-17 and 5-18. Figure 5-17 displays the interaction between dispatching rule and bottleneck location for the 100% prevalence while Figure 5-18 portrays the same interaction for the 50% prevalence.

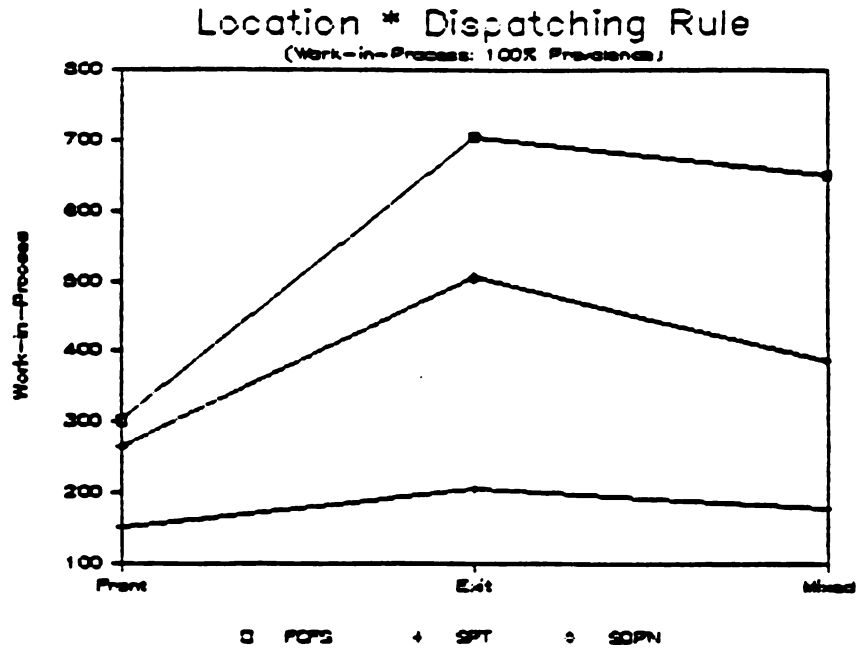
TABLE 5-14

THREE-WAY SUMMARY TABLE FOR WORK-IN-PROCESS (DISPATCHING RULE * LOCATION * PREVALENCE)

(Measured in Hours)		Dispatching Rule			
Prevalence	Location	FCFS	SPT	SOPN	Avg.
100%	Front	302.19	149.51	265.59	239.10
	Exit	705.72	205.77	506.18	472.55
	Mixed	652.27	178.89	388.37	406.51
	Avg.	553.39	178.06	386.71	372.72
50%	Front	321.63	142.64	264.05	242.77
	Exit	469.82	175.25	364.13	336.40
	Mixed	520.74	163.97	357.62	347.44
	Avg.	437.40	160.62	328.60	308.87
	Grand Avg.	495.39	169.34	357.66	340.80

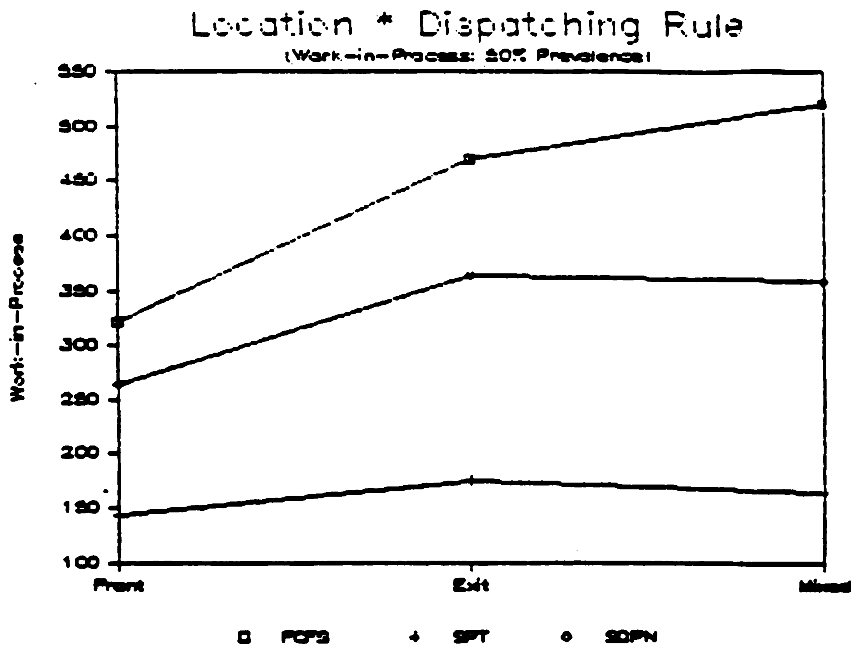
As illustrated in Figure 5-17 and 5-18, the SPT rule consistently performed the best in minimizing work-in-process, regardless of the level of location and prevalence. The SOPN rule performed the second best and the FCFS rule performed the worst for all levels of bottleneck location and prevalence. The results of Duncan's multiple comparison method (see Appendix F) supported these results.

Duncan's multiple comparison procedure in Appendix F also indicated that the front bottleneck location produced



LOCATION * DISPATCHING RULE INTERACTION
(WORK-IN-PROCESS: 100% PREVALENCE)

FIGURE 5-17



LOCATION * DISPATCHING RULE INTERACTION
(WORK-IN-PROCESS: 50% PREVALENCE)

FIGURE 5-18

significantly lower work-in-process than the exit and mixed location under all of the situations examined.

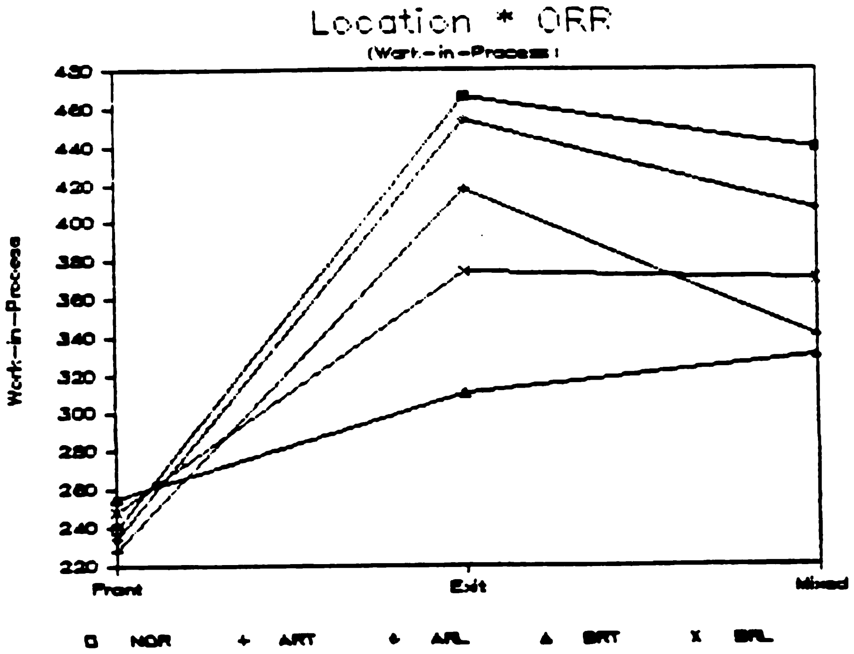
The mixed location performed better than the exit location for most situations considered. (see Table 5-14) However, there was no significant difference in work-in-process between locations when 50% prevalence was imposed on the shop. (see Appendix F) However, a significant difference between these two locations was observed for the 100% prevalence when the SPT or the SOPN rule was used.

It was apparent from Table 5-14 that for any type of dispatching rule and location the 100% prevalence had a higher work-in-process than the 50% prevalence. The only exception involved the front location and the FCFS rule. These results implied that the 100% prevalence produced relatively a higher work-in-process than the 50% prevalence.

5.3.2.1.2 Order Review/Release * Location

A significant interaction was observed between order review/release (ORR) mechanism and bottleneck location. Table 5-15 presents the two-way summary data and Figure 5-19 illustrates this interaction pictorially. When the bottleneck was located in the front or was mixed, the selection of order review/release mechanism did not affect significantly the resulting levels of work-in-process. (see Appendix F)

The benefit of using an order review/release mechanism was greatest when the bottleneck was at the exit. Under this location, however, the only order review/release mechanism



LOCATION * ORDER REVIEW/RELEASE INTERACTION (WORK-IN-PROCESS)

FIGURE 5-19

that did perform significantly better than the NOR mechanism was the BRT.

TABLE 5-15

TWO-WAY SUMMARY TABLE FOR WORK-IN-PROCESS
(ORDER REVIEW/RELEASE * LOCATION)

(Measured in Hours)	Order Review/Release Mechanism					
Location	NOR	ART	ARL	BRT	BRL	Avg.
Front	239.26	228.13	234.00	255.50	247.79	240.94
Exit	466.12	417.75	453.86	310.35	374.29	404.48
Mixed	438.90	340.07	406.34	329.67	369.90	376.98
Avg.	381.43	328.65	364.74	298.51	330.66	340.80

The front location yielded significantly lower work-in-process inventory level than the exit and the mixed location regardless of the type of order review/release mechanisms examined. However, there was no significant difference in performance between the exit and the mixed location for any of the order review/release mechanisms tested.

5.3.2.1.3 Discussion

It has been long known that the SPT rule performs well in minimizing work-in-process inventory level in the traditional job shop. (see Conway, Maxwell, and Miller 1967) The presence of the bottleneck operation did not affect the relative performance of the SPT rule as compared to the FCFS and the SOPN rule. These findings suggest that the SPT rule which excels in the non-bottleneck job shop is again appropriate for the bottleneck job shop with respect to the level of work-in-process.

The BRT mechanism's superiority, when the bottleneck was located at the exit, may be attributed to its effective control over the workload at the bottleneck work center. (see Table 5-16) These results provide two suggestions.

First, the BRT mechanism, when compared to the other order review/release mechanisms, can most effectively manage workload at the bottleneck work center. This in turn provides a significant reduction in work-in-process inventory in the shop. Second, as fewer jobs are released to the shop, less work-in-process is generated.

TABLE 5-16

AVERAGE WORKLOAD AT THE BOTTLENECK WORK CENTER
(ORDER REVIEW/RELEASE * LOCATION)

	Order Review/Release Mechanism					
Location	NOR	ART	ARL	BRT	BRL	Avg.
Front	141.60	92.02	128.38	56.38	94.50	102.57
Exit	112.43	104.24	112.88	57.46	82.85	93.97
Mixed	157.86	111.59	150.54	58.74	95.93	114.93
Avg.	137.30	102.62	130.60	57.52	91.09	103.83

The results of the superior performance of the front location over the exit and the mixed location under all situations tested can be explained by the following two reasons. First, higher work-in-process inventory occur as more operations are completed. That is, the level of inventory gets accumulated as orders gets close to completion. Second, the bottleneck work center is the place at which jobs spend their most time for waiting.

Higher work-in-process was produced when the shop operated at a 100% prevalence, in contrast to the 50%. As shown in Table 5-17, regardless of the type of dispatching rule and location, relatively fewer jobs were released into the shop for the 50% prevalence than for the 100% prevalence. This resulted in lower work-in-process inventory at the 50% prevalence level. The results suggest that bottlenecks created by routings tend to provide relatively higher work-in-process inventory than bottlenecks by long processing times. When a large number of jobs requires an operation of a certain work center having a fixed capacity in a given time period, bottlenecks are created by routings. On the other hand, bottlenecks are generated by long processing times in the situation in which relatively fewer jobs exist but each of which needs relatively long operation of the work center.

TABLE 5-17

AVERAGE JOB WAITING TIME IN THE BACKLOG FILE
(DISPATCHING RULE * LOCATION * PREVALENCE)

(Measured in Hours)		Dispatching Rule			
Prevalence	Location	FCFS	SPT	SOPN	Avg.
100%	Front	74.56	28.44	42.66	48.55
	Exit	39.44	25.36	53.70	39.50
	Mixed	47.25	33.47	52.40	44.37
	Avg.	53.75	29.09	49.59	44.14
50%	Front	83.37	58.57	76.09	72.68
	Exit	61.05	29.87	69.98	53.63
	Mixed	92.96	56.49	95.33	81.59
	Avg.	79.13	48.31	80.47	69.30
	Grand Avg.	66.44	38.70	65.03	56.72

5.3.2.1.4 Summary for Work-in-Process

The following conclusions can be drawn from the results of the detailed analysis with respect to work-in-process:

1. The selection of order review/release mechanism makes virtually no difference in performance when the bottleneck is at the front or mixed location.

2. In reducing the work-in-process inventory level, the BRT mechanism is the only order review/release mechanism which performs significantly better than the NOR

mechanism when the bottleneck is located at the exit.

3. When compared to other dispatching rules, the SPT rule produces the lowest level of work-in-process under all of the situations tested.

4. For all situations, significantly lower work-in-process inventory levels occur when the bottleneck is located at the front, when compared to the exit and mixed location.

5. Shop floor performance of the 100% prevalence is inferior to that of the 50% prevalence for the exit or mixed bottleneck location. Prevalence makes no difference when the bottleneck is at the front of the routings.

5.3.2.2 Mean Flow Time in the Shop

Duncan's multiple comparison test of significant interaction effects is provided in Appendix G to test pairwise comparisons between means at the .05 level.

5.3.2.2.1 Order Review/Release * Dispatching Rule

There existed a significant interaction between order review/release mechanism and dispatching rule. Table 5-18 and Figure 5-20 illustrate this interaction. The only significant interaction occurred primarily when tight release mechanisms were used. Figure 5-20 indicated that the benefits from using order review/release mechanisms were greatest when the FCFS rule was used. When used with either the SPT or the SOPN rule, the selection of order review/release mechanism did not make any significant difference in mean flow time in the shop. (see Appendix G)

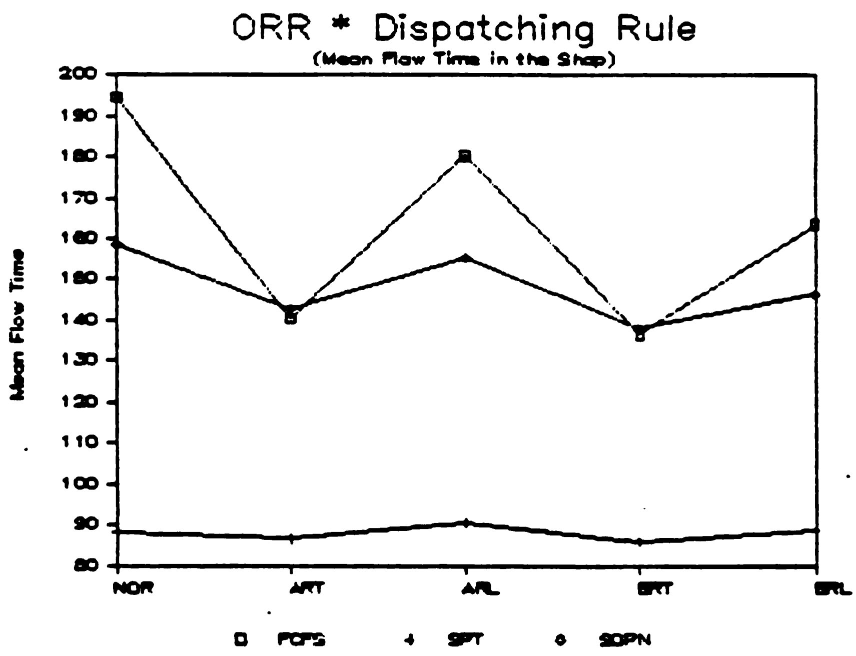
Both the BRT and the ART mechanism, when used with the FCFS rule, had significantly lower mean flow times than the other three order review/release mechanisms. The BRL mechanism also performed significantly better than both the

ARL and NOR mechanism.

TABLE 5-18

TWO-WAY SUMMARY TABLE FOR MEAN FLOW TIME IN THE SHOP
(ORDER REVIEW/RELEASE * DISPATCHING RULE)

(Measured in Hours)	Order Review/Release Mechanism					
Disp. Rule	NOR	ART	ARL	BRT	BRL	Avg.
FCFS	194.51	140.32	180.38	136.59	163.52	163.06
SPT	88.18	86.63	90.51	85.77	88.55	87.93
SOPN	158.80	142.85	155.45	138.01	146.34	148.29
Avg.	147.16	123.26	142.11	120.12	132.80	133.09



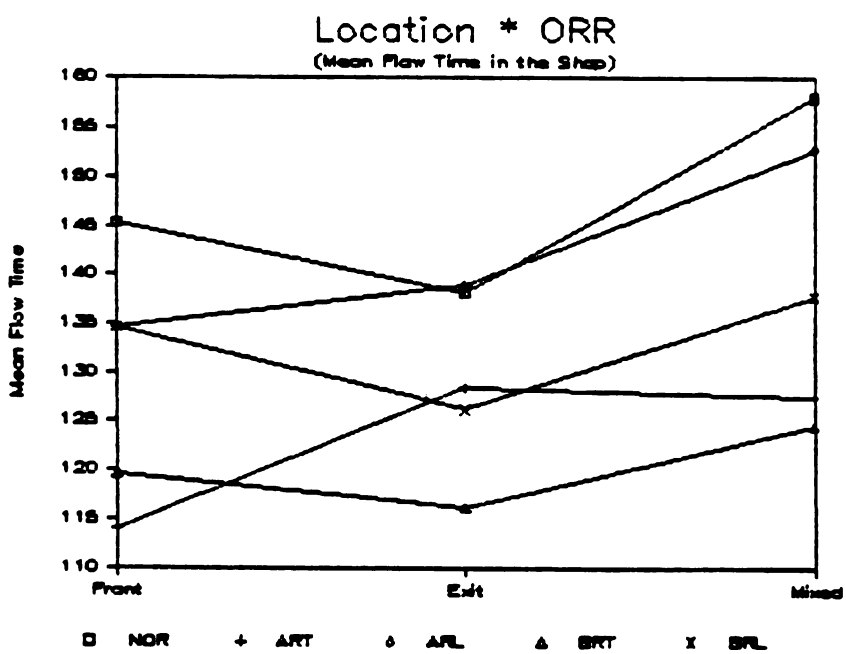
ORDER REVIEW/RELEASE * DISPATCHING RULE INTERACTION
(MEAN FLOW TIME IN THE SHOP)

FIGURE 5-20

As shown in Figure 5-20, the SPT rule produced the lowest mean flow time for all situations, performing significantly better than the SOPN and the FCFS rule with respect to mean flow time in the shop. (see Appendix G) It is interesting to note that the FCFS rule performed as well as the SOPN rule when the tight load limit level was imposed on the shop.

5.3.2.2.2 Order Review/Release * Location

A significant interaction was observed between order review/release mechanism and bottleneck location. Table 5-19 and Figure 5-21 illustrate this interaction. The only significant interaction occurred when the ART mechanism was used for the front bottleneck location. (see Appendix G) It



LOCATION * ORDER REVIEW/RELEASE INTERACTION (MEAN FLOW TIME IN THE SHOP)

FIGURE 5-21

was apparent that when compared to the NOR mechanism, employing the ART mechanism provided a significant improvement when the bottleneck was located in the front.

There was no significant difference in mean flow time in the shop among the remaining order review/release mechanisms for all types of bottleneck locations. Furthermore, under the order review/release mechanisms tested, the type of bottleneck location did not make any significant difference in performance.

TABLE 5-19

TWO-WAY SUMMARY TABLE FOR MEAN FLOW TIME IN THE SHOP
(ORDER REVIEW/RELEASE * LOCATION)

(Measured in Hours)	Order Review/Release Mechanism					
Location	NOR	ART	ARL	BRT	BRL	Avg.
Front	145.24	113.99	134.64	119.73	134.58	129.64
Exit	138.17	128.42	138.93	116.17	126.18	129.57
Mixed	158.07	123.26	142.11	120.12	132.80	140.07
Avg.	147.16	123.26	142.11	120.12	132.80	133.09

5.3.2.2.3 Prevalence

Mean flow time in the shop was significantly influenced by prevalence. Table 5-20 presents the performance of each level of prevalence. On average, orders found in the shop operating at the 50% prevalence experienced mean flow times which were lower by 8% when compared to those observed when the shop was at 100% prevalence. Since no higher interaction effects involving prevalence existed, this result can generally be applied to all situations.

TABLE 5-20

TABLE FOR MEAN FLOW TIME IN THE SHOP
(PREVALENCE)

	Prevalence	
(Measured in Hours)	100%	50%
	138.36	127.82

5.3.2.2.4. Discussion

In the traditional job shop, processing-time related dispatching rules such as the SPT were relatively effective in lowering mean flow times (Conway, Maxwell, and Miller 1967, pp. 186). The SPT rule, by giving top priority to a job with shortest imminent processing time, accelerates the progress of jobs on the whole. Under the bottleneck job shop, the SPT rule was again shown to be desirable in obtaining low flow times in the shop.

The performance of the FCFS rule was significantly affected by tight release mechanisms. The results suggest that when jobs are tightly controlled for release, due-date-oriented rules do not provide a significant reduction in lead times when compared to such simple dispatching rules as FCFS. This observation partially supports previous work that suggested that simple dispatching rules would be used effectively in the situation in which jobs were tightly released (see Nicholson and Pullen 1972). The SPT rule, however, demonstrated better performance over the FCFS in terms of mean flow time.

The result that there is no significant difference in performance among order review/release mechanisms examined when the SPT rule is used strongly suggest the following. The selection of dispatching rule is more important than the selection of order review/release mechanism in minimizing lead time.

As shown in Table 5-21, when the bottleneck was located in the front, the ART mechanism reduced average job waiting time in the shop by 31.23 hours when compared to the NOR mechanism. For the ART mechanism, this led to a significant reduction in mean flow time. The use of order review/release mechanisms, when compared to the NOR mechanism, tended to shorten average job waiting time in the shop in some

TABLE 5-21

AVERAGE JOB WAITING TIME IN THE SHOP
(ORDER REVIEW/RELEASE * LOCATION)

(Measured in Hours)	Order Review/Release Mechanism					
Location	NOR	ART	ARL	BRT	BRL	Avg.
Front	119.31	88.08	108.72	93.82	108.65	103.71
Exit	112.25	102.52	113.02	90.26	100.29	103.67
Mixed	132.17	101.48	126.84	98.55	111.74	114.15
Avg.	121.24	97.36	116.19	94.21	106.89	107.18

situations in the bottleneck job shop.

The 100% prevalence produced a significantly higher mean flow time in the shop than the 50% prevalence. Although a bottleneck job's average waiting time at the bottleneck work center for the 50% prevalence was longer than for the 100% prevalence, a job for the 100% prevalence, in total, spent more time in waiting in the shop than for the 50% prevalence by 9.7 hours. (see Table 5-22)

TABLE 5-22

AVERAGE JOB WAITING TIME AT THE BOTTLENECK WORK CENTER, IN THE SHOP, AND IN THE BACKLOG FILE (PREVALENCE)

(Measured in Hours)

Waiting Time	Prevalence 100%	50%
Bottleneck WC	50.85	80.44
Shop	112.44	101.92
Backlog File	44.14	69.30

Another reason for the inferior performance of the 100% prevalence was that the average job waiting time in the backlog file for the 100% prevalence was on average 25.1 hours shorter than for the 50% prevalence. (see also Table 5-22) This is due primarily to relatively long processing time of bottleneck jobs for the 50% prevalence. This subsequently led to release fewer jobs into the shop floor when compared to the 100% prevalence. This implies that with respect to lead time, bottlenecks created by routings tend to create more problems than bottlenecks by long processing times. Bottlenecks are created by routings when many jobs require a common operation in relatively short time period. For example, a single inspection stage may be a bottleneck created by routings.

5.3.2.2.5 Summary for Mean Flow Time in the Shop

The previous discussion of significant main and interaction effects involving the mean flow time in the shop suggests the following:

1. The use of the ART mechanism provides a significant improvement in reducing mean flow time in the shop over immediate release mechanism when the bottleneck is located in the front.

2. The SPT rule, as compared to other dispatching rules, exhibits superior performance in minimizing lead time.

3. When fewer jobs are released into the shop, simple dispatching rules such as the FCFS rule can provide performance equivalent to due-date-oriented rules such as the SOPN rule when major performance objective is the minimization of lead time in the shop.

4. The effectiveness of dispatching rules appears to be greater than that of order review/release mechanism in managing lead time.

5. Longer lead times are expected when bottlenecks are caused by routings rather than long operation times. This is due primarily to the tendency of release mechanisms to release more jobs to the shop as compared to the 50% prevalence.

5.3.2.3 Variance of Flow Time in the Shop

Duncan's multiple comparison test of significant interaction effects is provided in Appendix H to identify significant differences between means at the .05 level.

5.3.2.3.1 Order Review/Release * Dispatching Rule

There existed a significant interaction between order review/release mechanism and dispatching rule. Table 5-23 summarizes this two-way data and Figure 5-22 represents it in a graphic form. When the FCFS rule was used, the BRT, the ART, and the BRL mechanism yielded a significantly lower variance of flow time than the NOR mechanism. The only release mechanism that did not significantly do better than the NOR mechanism was the ARL mechanism.

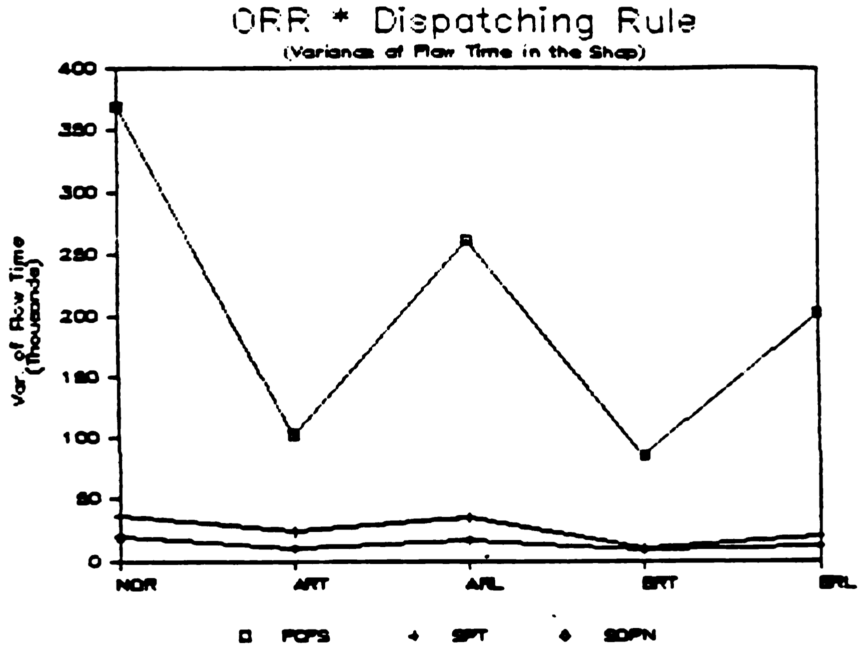
TABLE 5-23

TWO-WAY SUMMARY TABLE FOR VARIANCE OF FLOW TIME IN THE SHOP (ORDER REVIEW/RELEASE * DISPATCHING RULE)

	Order Review/Release Mechanism					
Disp. Rule	NOR	ART	ARL	BRT	BRL	Avg.
FCFS	368922	102778	260117	85183	201708	203742
SPT	36072	23633	35405	10232	19350	24939
SOPN	18796	10344	16137	8344	11486	13021
Avg.	141264	45585	103887	34587	77515	80568

When the SPT rule was used, the BRT mechanism performed significantly better than the other release mechanisms. There was no significant difference in variance of flow time among the remaining release mechanisms with respect to variance of flow time. (see Appendix H)

Under the SOPN rule, the BRT produced a significantly lower variance of flow time than the other release mechanisms. Both the ART and the BRL mechanism yielded a significantly lower variance than the NOR mechanism.



ORDER REVIEW/RELEASE * DISPATCHING RULE INTERACTION
(VARIANCE OF FLOW TIME IN THE SHOP)

FIGURE 5-22

Figure 5-22 indicated that the FCFS rule was the worst performer under any order review/release mechanism tested. The results of Duncan's tests supported this finding. The disadvantage of using the FCFS rule, however, was smallest when jobs are tightly released.

The performance of the SPT rule, when the BRT mechanism was used, provided equivalent performance to the SOPN rule. The performance of the SOPN rule was superior to that of using the SPT rule in most cases and about the same in some cases.

5.3.2.3.2 Order Review/Release * Location

A significant interaction was observed between the order review/release mechanism and bottleneck location. Table 5-24 and Figure 5-23 provide this interaction effect. Referring to Figure 5-23, the tight release mechanisms produced a significantly lower variance than both the loose mechanisms and the NOR mechanism when the bottleneck was located in the front. The results of Duncan's tests supported these results. (see Appendix H)

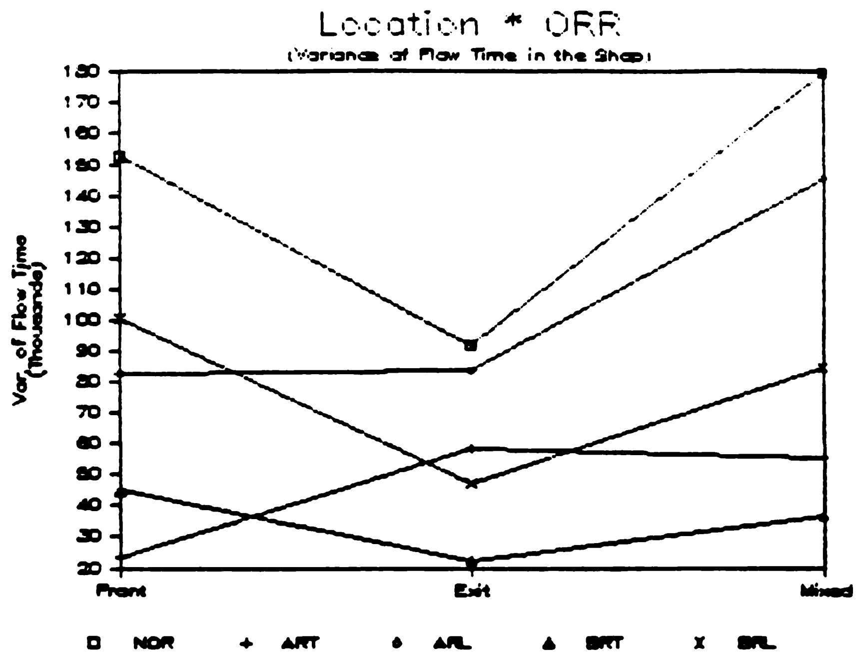
TABLE 5-24

TWO-WAY SUMMARY TABLE FOR VARIANCE OF FLOW TIME IN THE SHOP (ORDER REVIEW/RELEASE * LOCATION)

	Order Review/Release Mechanism					
Location	NOR	ART	ARL	BRT	BRL	Avg.
Front	152568	23478	82549	45009	100828	80887
Exit	91691	58264	83776	22223	47057	60603
Mixed	179531	55013	145334	36526	84659	100213
Avg.	141264	45585	103887	34587	77515	80568

When the bottleneck was located at the exit, the BRT mechanism was the only release mechanism that performed significantly better than the NOR mechanism. For the mixed location, the tight release mechanisms yielded a significantly lower variance than the NOR mechanism.

Within any type of order review/release mechanism tested, there was no significant difference in variance of



LOCATION * ORDER REVIEW/RELEASE INTERACTION
(VARIANCE OF FLOW TIME IN THE SHOP)

FIGURE 5-23

flow time among bottleneck locations, with the exception of the ART mechanism. (see Appendix H) When the ART mechanism was used, the front location had a significantly lower variance than the exit and mixed location.

5.3.2.3.3 Prevalence

Variance of flow time in the shop was also influenced by bottleneck prevalence. There was no higher interaction involving prevalence with respect to variance of flow time in the shop. Table 5-25 presents this main effect. The 50% prevalence provided a 14% reduction in performance over the 100% prevalence.

TABLE 5-25

TABLE FOR VARIANCE OF FLOW TIME IN THE SHOP
(PREVALENCE)

Prevalence	
100%	50%
86761	74374

5.3.2.3.4 Discussion

It was apparent from the results that the use of the BRT mechanism led to a considerable reduction in the variance of flow times in the shop regardless of the type of dispatching rules used at the work centers. The ART and the BRL mechanism also provided an improvement in performance over the NOR mechanism when either the FCFS or the SOPN rule was used. These results suggest that the use of an order review/release mechanism performs better than the immediate release mechanism in minimizing the variance of flow times in the shop. The results also suggest that tight control of job release tends to provide further improvement in lowering lead time variance.

The SOPN rule performs relatively well in minimizing variance of tardiness in the traditional job shops. (see Conway, Maxwell, Miller, 1967, pp. 226) The relative performance of the SOPN rule, as compared to the SPT and the FCFS rule, did not change in the bottleneck job shop. These results suggest that due-date oriented dispatching rules that excel in the traditional job shop again provide considerable improvement in minimizing variance of flow time in the bottleneck job shop.

Within any of the order review/release mechanisms tested, in general, there was no significant difference in variance of flow time among bottleneck locations. The sole exception was the ART mechanism. (see Appendix H) These results suggest that the type of bottleneck location does not appear to significantly affect the performance of each release mechanism with respect to variance of flow time, with the exception of the ART mechanism.

The superior performance of the 50% prevalence to that of the 100% prevalence can be explained by the nature of the order review/release mechanisms. These mechanisms tend to release fewer jobs when the 50% prevalence is imposed to the shop. (See the discussion of bottleneck prevalence for mean flow time in the shop.)

<u>5.3.2.3.5 Summary for Variance of Flow Time in the Shop</u>

The following conclusions may be drawn from the analysis of experimental results in terms of variance of flow time in the shop.

1. Employing order review/release mechanism other than the NOR mechanism tends to reduce the variance of flow time in the shop. The BRT mechanism, as compared to other release mechanisms, consistently performs significantly better than the NOR mechanism regardless of the type of dispatching rules and locations examined.

2. The SOPN rule performs the best under virtually all conditions tested in this experiment with respect to variance of flow time in the shop.

3. Within a given order review/release mechanism, there is no significant difference in variance of flow time among

locations, with the exception of the ART mechanism and the front location.

4. Larger variance of flow time in the shop are expected when bottlenecks are created by routings rather than long processing times.

5.3.2.4 Mean Tardiness

Mean tardiness under this study represents aggregate mean tardiness rather than conditional mean tardiness. For aggregate mean tardiness, jobs completed early are assigned tardiness of zero and included in the average. Results of the ANOVA were presented in Table 5-13. Duncan's multiple comparison test of significant interaction effects is provided in Appendix I.

5.3.2.4.1 Order Review/Release * Dispatching Rule

There existed a significant interaction effect between the order review/release mechanism and the dispatching rule. Table 5-26 summarizes the data and Figure 5-24 portrays it.

TABLE 5-26

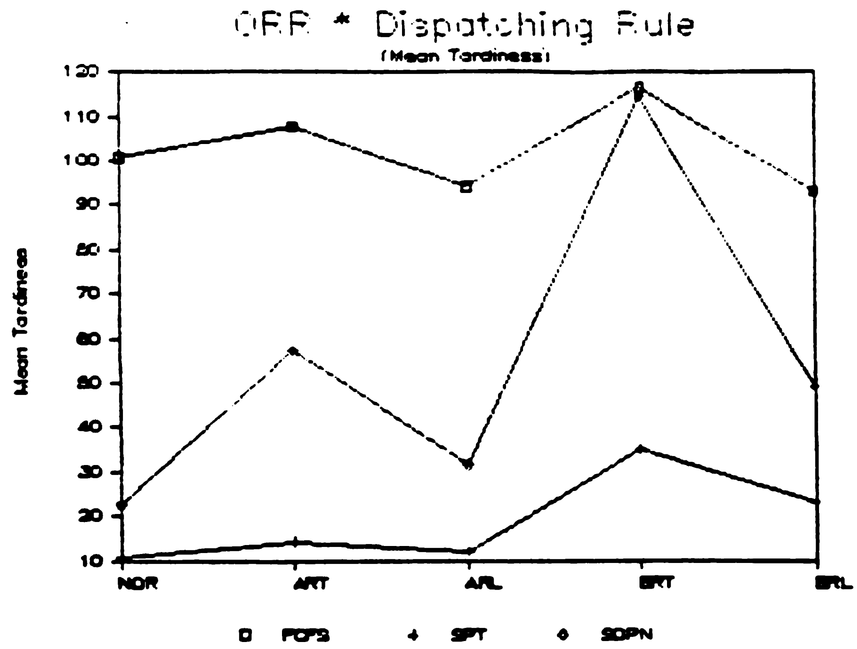
TWO-WAY SUMMARY TABLE FOR MEAN TARDINESS
(ORDER REVIEW/RELEASE * DISPATCHING RULE)

(Measured in Hours)	Order Review/Release Mechanism					
Disp. Rule	NOR	ART	ARL	BRT	BRL	Avg.
FCFS	100.75	107.75	94.38	116.53	93.24	102.53
SPT	10.51	14.35	12.09	34.95	23.15	19.01
SOPN	22.51	57.42	31.47	114.55	49.31	55.05
Avg.	44.59	59.84	45.98	88.68	55.23	58.86

Overall, the SPT rule performed best and the FCFS rule was the worst under all of the order review/release mechanisms considered.

It is interesting to note the rapidly deteriorating performance of the SOPN rule when it was used with tight order review/release mechanisms. Specifically, the performance of the SOPN rule significantly deteriorated when used with the BRT mechanism.

When jobs were not released tightly, there was no significant difference in mean tardiness between the SPT rule and the SOPN rule. (see Appendix I) When the FCFS rule was used, all order review/release mechanisms performed similarly regardless of the type of order review/release mechanisms examined.



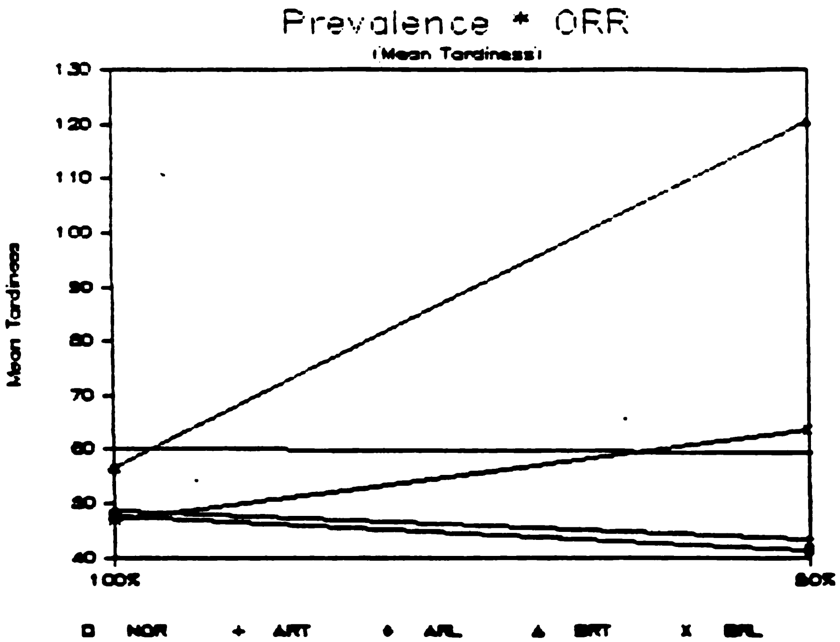
ORDER REVIEW/RELEASE * DISPATCHING RULE INTERACTION
(MEAN TARDINESS)

FIGURE 5-24

For both the SPT and the SOPN rule, however, the performance of mean tardiness was influenced by the specific order review/release mechanism in place.

5.3.2.4.2 Order Review/Release * Prevalence

The interaction between order review/release mechanism and bottleneck prevalence was significant. Table 5-27 and Figure 5-25 illustrate this interaction. The BRT mechanism was the major source of this significant interaction. Figure 5-25 indicated that the use of the BRT mechanism improved shop performance when the prevalence was 100%. This behavior was contrary to the general trend of other release mechanisms in which no difference in mean tardiness was obtained for the 50% prevalence. (see Appendix I)



PREVALENCE * ORDER REVIEW/RELEASE INTERACTION (MEAN TARDINESS)

FIGURE 5-25

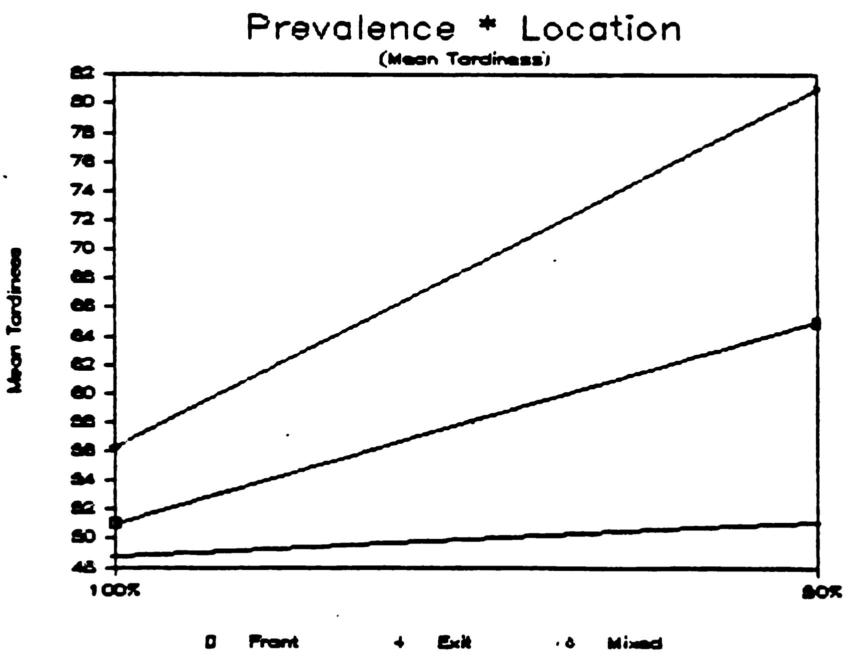
TABLE 5-27

TWO-WAY SUMMARY TABLE FOR MEAN TARDINESS
(ORDER REVIEW/RELEASE * PREVALENCE)

(Measured in Hours)	Order Review/Release Mechanism					
Prevalence	NOR	ART	ARL	BRT	BRL	Avg.
100%	47.76	60.16	48.60	56.65	46.85	52.00
50%	41.42	59.52	43.36	120.71	63.61	65.72
Avg.	44.59	59.84	45.98	88.68	55.23	58.86

5.3.2.4.3 Location * Prevalence

A significant interaction was also observed between bottleneck location and extent of bottleneck prevalence. Table 5-28 presents two-way summary data and Figure 5-26



PREVALENCE * LOCATION INTERACTION
(MEAN TARDINESS)

FIGURE 5-26

illustrates it in graphic form. For 100% prevalence, there was no significant difference in mean tardiness among locations tested. (see Appendix I) For the 50% prevalence, however, the exit location produced a significantly lower mean tardiness than the front and mixed location.

TABLE 5-28

TWO-WAY SUMMARY TABLE FOR MEAN TARDINESS (LOCATION * PREVALENCE)

(Measured in Hours)	Location			
Prevalence	Front	Exit	Mixed	Avg.
100%	51.03	48.69	56.29	52.00
50%	64.95	51.17	81.04	65.72
Avg.	57.99	49.93	68.67	58.86

5.3.2.4.4 Discussion

The relatively poor performance of the BRT mechanism was in part attributable to the relatively long mean flow times of orders in the system. (see Table 5-29) It is interesting to note the relationship between average waiting time in the backlog file and average flow time in the system for each order review/release mechanism. (see Table 5-29 and 5-30) Keeping an order off the floor did not lower its total time in the system. These results indicate that the use of an order review/release mechanism deteriorated mean tardiness due to its relatively long flow time in the system, although it appeared to improve flow times in the shop. These results also support the findings reported by Baker (1984) that the use of release mechanisms tended to increase mean tardiness due to its restriction of the set of jobs available for scheduling.

TABLE 5-29

MEAN FLOW TIME IN THE SYSTEM
(ORDER REVIEW/RELEASE * DISPATCHING RULE)

(Measured in Hours)	Order Review/Release Mechanism				
Dispatching	NOR	ART	ARL	BRT	BRL
FCFS	194.51	249.89	210.15	269.65	223.33
SPT	88.18	122.65	111.15	169.40	141.72
SOPN	158.80	220.63	184.81	292.05	210.28

TABLE 5-30

AVERAGE JOB WAITING TIME IN THE BACKLOG FILE
(ORDER REVIEW/RELEASE * DISPATCHING RULE)

(Measured in Hours)	Order Review/Release Mechanism				
Dispatching	NOR	ART	ARL	BRT	BRL
FCFS	0.00	109.57	29.76	133.06	59.82
SPT	0.00	36.01	20.65	83.65	53.18
SOPN	0.00	77.79	29.36	154.04	63.95

Specifically, the performance of the shop was worst when the BRT mechanism was used with the SOPN rule. The BRT mechanism, in contrast to the other order review/release mechanisms, tended to release relatively fewer jobs into the shop. (see Table 5-30) This may be attributable to the operating mechanics of the SOPN rule. That is, the SOPN rule does not perform well when the objective is to minimize work-in-process inventory or lead times of orders. Therefore, the SOPN rule created more workload in the shop which subsequently delays job releasing. These results suggest that in the bottleneck job shop, the SPT rule appears to be more effective than the SOPN rule in managing mean tardiness.

For loose release mechanisms, no significant difference was observed between the SPT and the SOPN rule with respect to mean tardiness. Table 5-30 also indicated that there was relatively a little difference in average job waiting time in the backlog file between the SPT and the SOPN rule for loose order review/release mechanisms, when compared to tight release mechanisms.

The BRT mechanism was the main cause for the significant interaction between order review/release mechanisms and bottleneck prevalence. The BRT mechanism released jobs according to the bottleneck work center processing time. Under the 50% prevalence, therefore, the BRT mechanism tended to release a considerably smaller number of jobs, as compared to other release mechanisms. (see Table 5-31) This subsequently increased the total flow time in the system which in turn increased mean tardiness. This result suggests that the BRT mechanism does not appear to be desirable in lowering mean tardiness when prevalence in the shop is 50%.

TABLE 5-31

AVERAGE JOB WAITING TIME IN THE BACKLOG FILE
(ORDER REVIEW/RELEASE * PREVALENCE)

(Measured in Hours)	Order Review/Release Mechanism				
Prevalence	NOR	ART	ARL	BRT	BRL
100%	0.00	73.40	25.75	82.31	39.25
50%	0.00	75.51	27.43	164.86	78.71

Although there was no significant difference between prevalence for all locations (see Appendix I), there was a considerable improvement in mean tardiness when the shop operated at 100% prevalence. This behavior may be caused by the relatively long job waiting time at the bottleneck work center rather than at the non-bottleneck work centers under the 50% prevalence due to the long processing time of bottleneck jobs. (see Table 5-32) These results suggest that

TABLE 5-32

AVERAGE JOB WAITING TIME AT THE BOTTLENECK
AND NON-BOTTLENECK WORK CENTER
(LOCATION * PREVALENCE)

(Measured in Hours)		Bottleneck Location		
	Prev	Front	Exit	Mixed
Bottleneck WC	100%	46.86	53.10	52.59
	50%	78.86	68.62	93.85
Non-Bottleneck WC	100%	24.28	23.87	25.66
	50%	20.66	20.74	21.21

mean tardiness tends to increase when the cause of bottlenecks are the long operation time of bottleneck jobs.

5.3.2.4.5 Summary for Mean Tardiness

Several conclusions with respect to mean tardiness may be summarized as follows:

1. The use of order release mechanisms tends to deteriorate mean tardiness.

2. The SPT and the SOPN rule perform similarly when the loose order review/release mechanisms or the NOR mechanism are used. However, the SPT rule performs significantly better than both the SOPN and the FCFS rule with respect to mean tardiness when used with the tight release mechanisms.

3. The performance of the FCFS rule is not affected by the selection of order review/release mechanism with respect to mean tardiness.

4. Shop performance, when the BRT and the ART mechanisms are used with the SOPN rule, rapidly deteriorates.

5. The performance of the BR mechanism, when compared to other release mechanisms, rapidly deteriorates as the prevalence shifts from 100% to 50%.

6. There is no significant difference among locations when 100% prevalence is imposed on the shop. As prevalence changes from 100% to 50%, however, the exit location produces a significantly lower mean tardiness than both the mixed and front location.

7. As prevalence shifts from 100% to 50%, mean tardiness tends to increase for all bottleneck locations examined.

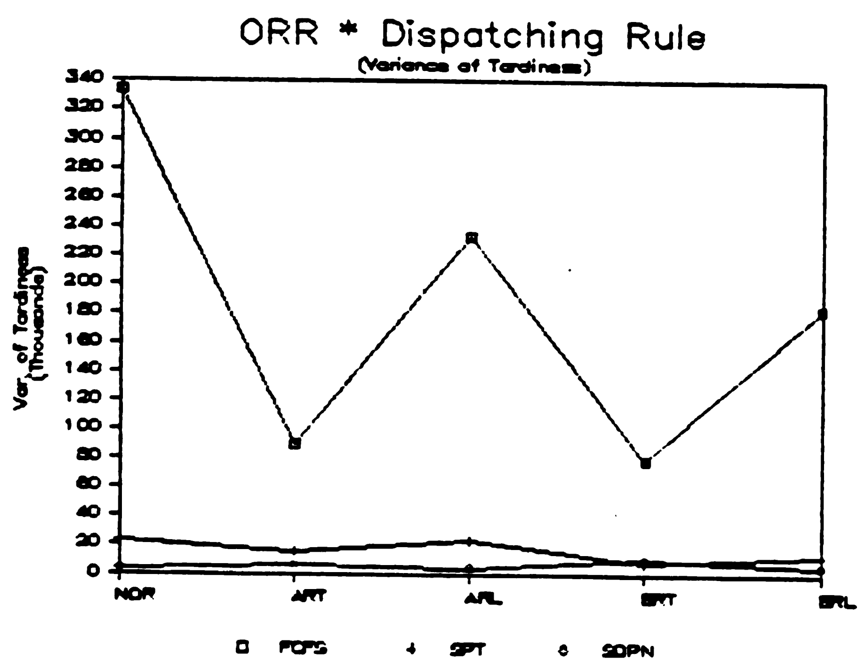
5.3.2.5. Variance of Tardiness

Table 5-11 presents the ANOVA results with respect to the variance of tardiness. The results of Duncan's multiple comparison test of significant interaction effects is provided in Appendix J to identify the significant difference between means at the .05 level.

5.3.2.5.1 Order Review/Release * Dispatching Rule

There existed a significant interaction effect between order review/release mechanism and dispatching rule. Table 5-33 and Figure 5-27 summarize this data. The performance of order review/release mechanisms was considerably affected by the specific type of dispatching rules. (see Appendix J) When the SPT rule was used, there was no significant difference in the variance of tardiness among order review/release mechanisms tested.

When the FCFS rule was used, however, the performance of the shop under tight release mechanisms was significantly better than those of the ARL, the BRL, and the NOR mechanisms.



ORDER REVIEW/RELEASE * DISPATCHING RULE INTERACTION
(VARIANCE OF TARDINESS)

FIGURE 5-27

TABLE 5-33

TWO-WAY SUMMARY TABLE FOR VARIANCE OF TARDINESS
(ORDER REVIEW/RELEASE * DISPATCHING RULE)

	Order Review/Release Mechanism					
Disp. Rule	NOR	ART	ARL	BRT	BRL	Avg.
FCFS	333805	89499	233707	78878	183635	183905
SPT	22875	15037	23032	7587	12986	16303
SOPN	3182	5833	3954	10097	5258	5665
Avg.	119954	36790	86898	32187	67923	68625

Under the SOPN rule, the NOR mechanism outperformed other release mechanisms. The BRT mechanism performed the worst.

The SOPN rule, as expected from prior results with this rule, performed impressively for all order review/release mechanisms tested. The FCFS rule performed the worst in all situations. The performance of the SPT rule, when used with the BR mechanism, approached to that of the SOPN rule.

5.3.2.5.2 Dispatching Rule * Prevalence

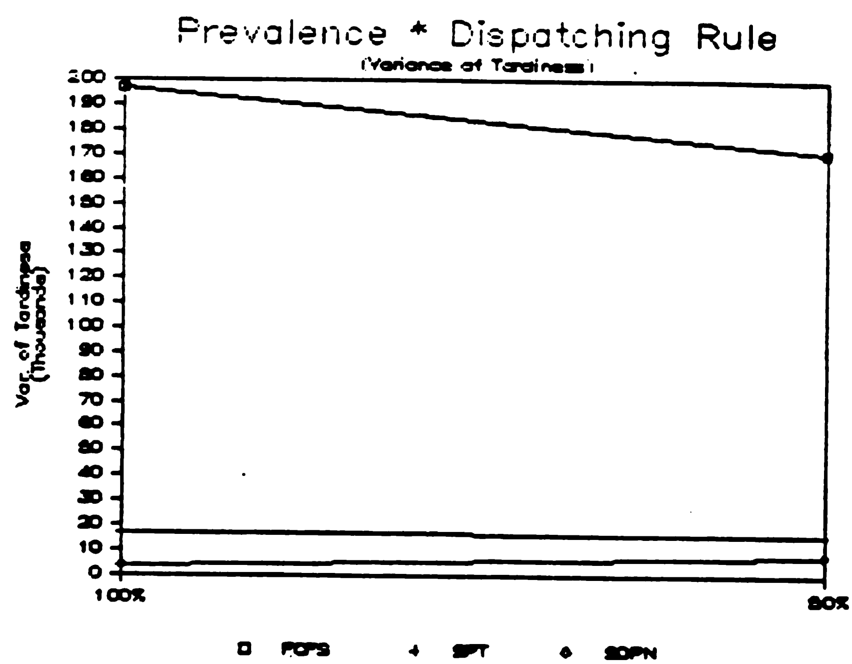
A significant interaction effect was also observed between dispatching rule and bottleneck prevalence. Table 5-34 and Figure 5-28 illustrate this interaction effect. In general, the FCFS rule was the worst performer and the SOPN the best for any type of prevalence. The results of Duncan's multiple comparison method supported these rankings of significant difference among dispatching rules examined for all levels of prevalence. (see Appendix J)

TABLE 5-34

TWO-WAY SUMMARY TABLE FOR VARIANCE OF TARDINESS
(DISPATCHING RULE * PREVALENCE)

	Dispatching Rule			
Prevalence	FCFS	SPT	SOPN	Avg.
100%	197278	16786	3559	72541
50%	170533	15822	7772	64709
Avg.	183905	16304	5665	68625

Regardless of the type of dispatching rules considered, there was no significant difference in the level of variance of tardiness between the 100% and the 50% prevalence levels. (see Appendix J)



PREVALENCE * DISPATCHING RULE INTERACTION
(VARIANCE OF TARDINESS)

FIGURE 5-28

5.3.2.5.3 Location

Table 5-35 shows a comparison of shop performance for each bottleneck location. On average, the largest variance of tardiness occurred when the bottleneck was located at the mixed and the smallest variance of tardiness occurred when it was at the exit.

TABLE 5-35

TABLE FOR VARIANCE OF TARDINESS
(LOCATION)

	Bottleneck Location			
	Front	Exit	Mixed	Avg.
	70976	47269	87629	68625

5.3.2.5.4 Discussion

The performance of order review/release mechanisms considered in this study was significantly affected by the specific type of dispatching rules in place. It is interesting to examine the performance of the system under the BRT mechanism in use. When used with the SOPN rule, the BRT mechanism performed the worst. However, its best performance occurred when this mechanism was used with the FCFS rule. These results suggest that the selection of dispatching rules appears to significantly affect the relative performance, as indicated by rankings, of the order review/release mechanisms in place.

For all situations examined, the SOPN rule, when compared to either the SPT or the FCFS rule, performed better or at least equivalently. These results suggest that the SOPN rule, which excels in the traditional job shop on reducing the variance of tardiness, is again the most appropriate dispatching rule in the bottleneck job shop. The SPT rule, when compared to the SOPN rule does not perform well alone. Its impact, however, may be significantly enhanced if used with the BRT mechanism. The results also suggest that the selection of dispatching rules is more critical than the selection of order review/release mechanisms in lowering variance of tardiness.

The level of prevalence did not make any difference in the level of the variance of tardiness for any given dispatching rule considered. These results imply that each of the dispatching rule tested is insensitive to the level of prevalence with respect to variance of tardiness.

5.3.2.5.5 Summary for Variance of Tardiness

General conclusions for this section are summarized as follows:

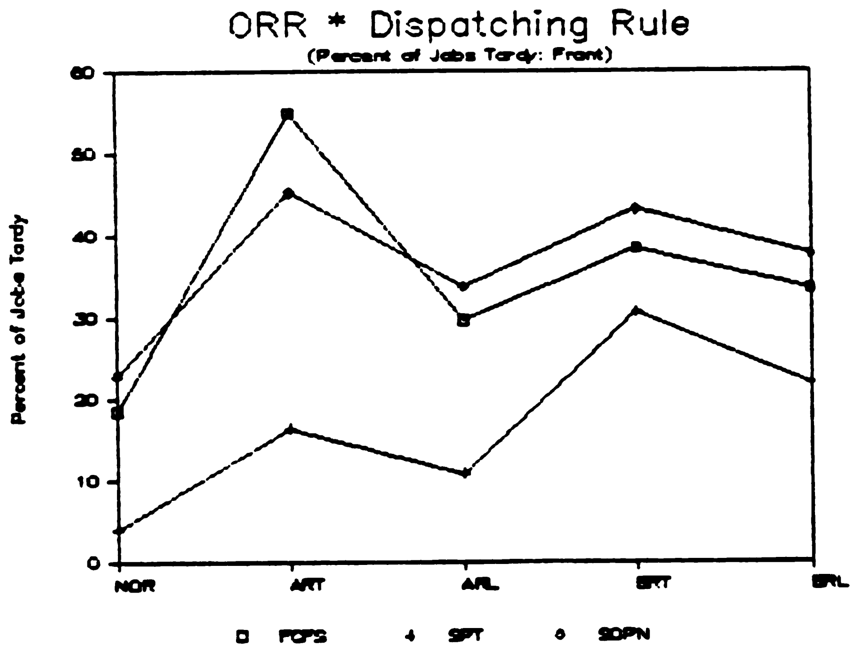
1. The SOPN rule, as compared to the SPT rule, exhibits consistently better or at least equal performance in terms of the variance of tardiness.
2. Variance of tardiness appears to be reduced when the location of the bottleneck in the routing is fixed.
3. The performance of the SPT rule is improved significantly when used with the BRT mechanism.
4. Each dispatching rule in this experiment is insensitive to the change in prevalence with respect to variance of tardiness.

5.3.2.6 Percent of Jobs Tardy

Results of the ANOVA are presented in Table 5-13. A post hoc Duncan's multiple comparison procedure for the significant interaction effects under discussion was conducted and provided in Appendix K.

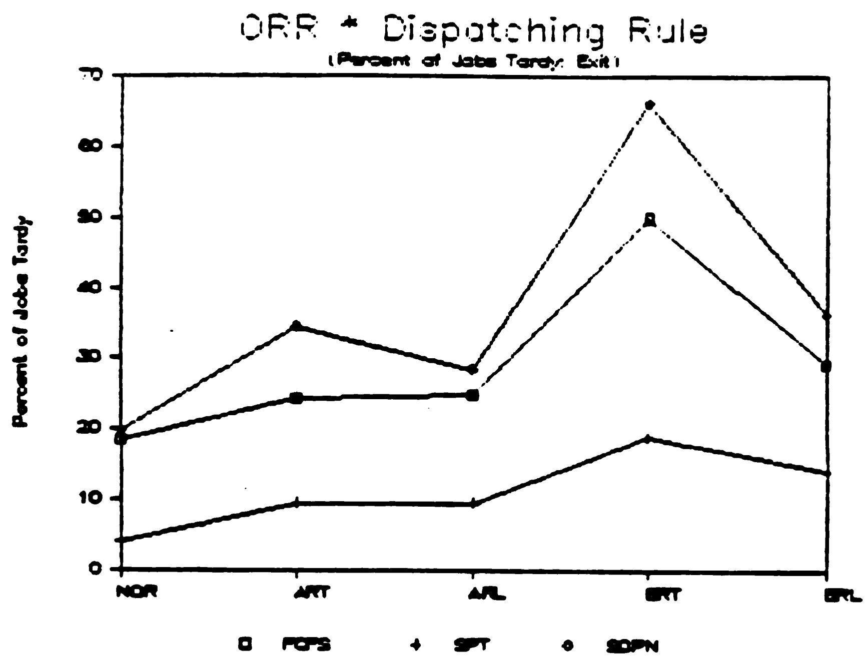
5.3.2.6.1 Order Review/Release * Dispatching Rule * Location

A significant three-way interaction effect was observed among order review/release mechanism, dispatching rule, and bottleneck location. Table 5-36 summarizes this result. The nature of this interaction is illustrated in Figures 5-29 through 5-31. Figures 5-29 through 5-31 show the interaction of order review/release mechanism and dispatching rule for each type of bottleneck location (i.e., the front, the exit, and the mixed, respectively).



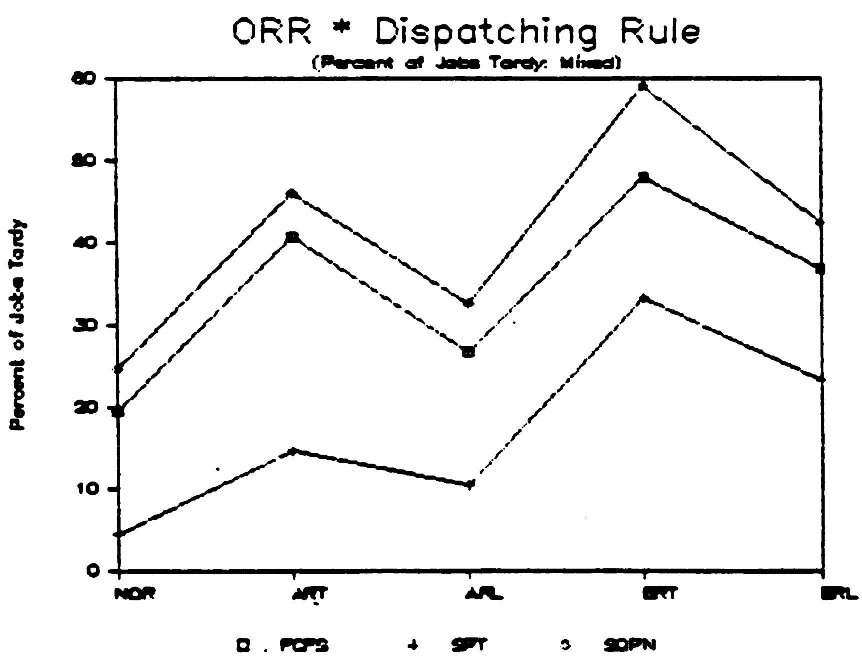
ORDER REVIEW/RELEASE * DISPATCHING RULE INTERACTION
(PERCENT OF JOBS TARDY: FRONT LOCATION)

FIGURE 5-29



ORDER REVIEW/RELEASE * DISPATCHING RULE INTERACTION
(PERCENT OF JOBS TARDY: EXIT LOCATION)

FIGURE 5-30



ORDER REVIEW/RELEASE * DISPATCHING RULE INTERACTION
(PERCENT OF JOBS TARDY: MIXED LOCATION)

FIGURE 5-31

TABLE 5-36

THREE-WAY SUMMARY TABLE FOR PERCENT OF JOBS TARDY
(ORDER REVIEW/RELEASE * DISPATCHING RULE * LOCATION)

(Measured in Percentage)		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	18.45	55.00	29.65	38.40	33.55	35.01
	SPT	3.95	16.35	10.75	30.65	21.90	16.72
	SOPN	22.90	45.30	33.70	43.20	37.60	36.54
	Avg.	15.10	38.88	24.70	37.42	31.02	29.42
Exit	FCFS	18.45	24.40	24.95	50.05	29.25	29.42
	SPT	3.90	9.50	9.50	18.90	14.10	11.38
	SOPN	19.65	34.55	28.60	66.35	36.30	37.09
	Avg.	14.00	22.82	21.02	45.10	26.55	25.96
Mixed	FCFS	19.55	40.80	26.65	47.90	36.70	34.32
	SPT	4.45	14.65	10.30	33.20	23.30	17.18
	SOPN	24.70	46.10	32.60	59.25	42.30	40.99
	Avg.	16.23	33.85	23.18	46.78	34.10	30.83
Grand Avg.		15.11	31.85	22.97	43.21	30.56	28.74

As shown in Figures 5-29 through 5-31, the performance of dispatching rules was significantly affected by the specific type of order review/release mechanism in place and the location of the bottleneck. In general, the performance of the SPT rule was superior to that of the other dispatching rules. Its performance was sensitive to the presence of the BRT mechanism. The BRT mechanism had an adverse impact on the operation of the SPT rule.

There was no significant difference in percent of jobs tardy among three dispatching rules when the bottleneck was located in the front and the BRT mechanism was used. (see Appendix K)

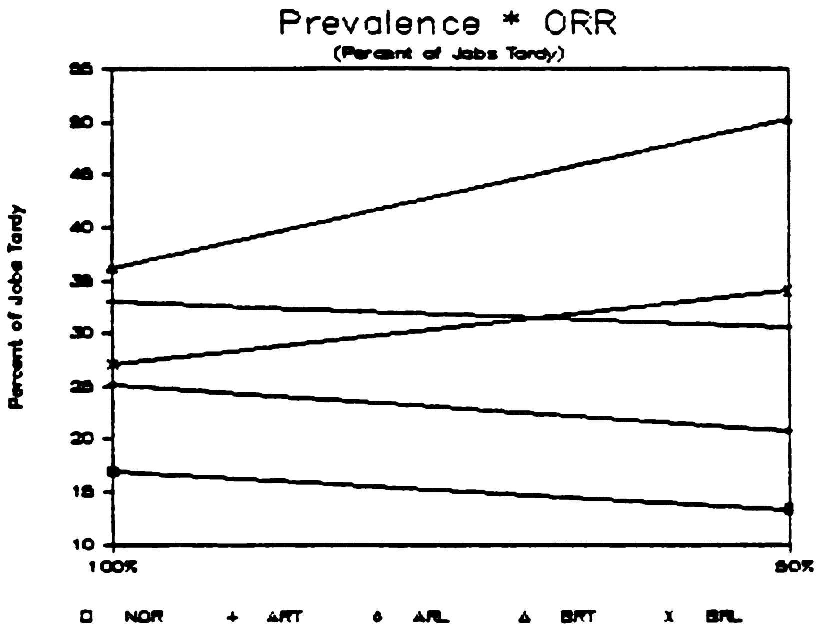
Furthermore, Duncan's multiple comparison tests in

Appendix K indicated that when the BRT or the BRL mechanism was used, there was no significant difference in percent of jobs tardy between the SPT and the FCFS rule both for the front and for the mixed location. When the bottleneck moved to the exit, however, the SPT rule produced the lowest number of jobs overdue. It performed significantly better than either the FCFS and the SOPN rule for all order review/release mechanisms tested.

The performance of order review/release mechanisms was also significantly influenced by the specific type of dispatching rule and location. The NOR mechanism yielded the lowest percent of jobs tardy in all situations examined.

5.3.2.6.2 Order Review/Release * Prevalence

A significant interaction was observed between order review/release mechanism and bottleneck prevalence. Table 5-37 presents two-way summary of the data while Figure 5-32 illustrates it graphically. The BR mechanism appeared to be the main cause of this significant interaction. It is apparent from Figure 5-32 that the BR mechanism, unlike NOR and the AR mechanisms, performs better under 100% prevalence than under 50%. As indicated in Appendix K, there was no significant difference in percent of jobs tardy between the 100% and the 50% prevalence for the NOR, the ART and the ARL mechanism. For the BRT and BRL mechanism, however, the 100% produced significantly lower percent of jobs tardy under the 50% prevalence.



PREVALENCE * ORDER REVIEW/RELEASE INTERACTION (PERCENT OF JOBS TARDY)

FIGURE 5-32

TABLE 5-37

TWO-WAY SUMMARY TABLE FOR PERCENT OF JOBS TARDY (ORDER REVIEW/RELEASE * PREVALENCE)

(Measured in percentage)	Order Review/Release Mechanism					
Prevalence	NOR	ART	ARL	BRT	BRL	Avg.
100%	16.88	33.11	25.12	36.13	27.11	27.67
50%	13.34	30.59	20.81	50.29	34.00	29.81
Avg.	15.11	31.85	22.97	43.21	30.56	28.74

Regardless of the level of prevalence, the NOR mechanism performed significantly better than the other order review/release mechanisms. (see Appendix K) For the

100% prevalence, the BRT and the ART performed similarly. For the 50% prevalence, however, the ART mechanism provided a significant improvement in performance over the BRT mechanism. These findings again suggest that the BRT mechanism is not desirable when the shop floor performance is to minimize the number of jobs tardy.

5.3.2.6.3 Discussion

When jobs in the backlog file were released according to the workload for the bottleneck work center, the number of jobs tardy was increased. This result occurred regardless of the type of dispatching rules and bottleneck locations in place. These findings suggest that when an interest is in reducing the number of jobs tardy, then the BR mechanism deteriorates the effectiveness of the dispatching rules.

Although the use of order review/release mechanism reduced mean flow time in the shop, it actually prolonged the overall average flow time in the system. This result was due primarily to the relatively long waiting time experienced in the backlog file. This subsequently led to an increase in both the aggregate mean tardiness and the number of jobs overdue. These findings suggest that for jobs to have a good chance of meeting their due dates, they should be released immediately.

It has long been recognized that in traditional job shops operating at moderate levels of shop capacity utilization, due-date-oriented dispatching rules are effective in lowering the percentage of jobs tardy (Conway, Maxwell, and Miller, 1967, pp. 233). For the bottleneck job shop, however, the SOPN rule produced an even higher percent of jobs tardy than the FCFS. These findings suggest that for the bottleneck job shop, due-date based rules do not appear to be desirable in minimizing proportion of jobs tardy even at moderate shop capacity utilization.

Referring to Figure 5-30, when the bottleneck was at the end, the ART mechanism performed as well the ARL. The performance of the BRT mechanism, on the other hand, deteriorated rapidly when the bottleneck shifted from the front to the exit. As shown in Table 5-38, when the bottleneck moved from the front to the exit, the BRT mechanism, when compared to the BRL mechanism, provided

TABLE 5-38

AVERAGE JOB WAITING TIME IN THE BACKLOG FILE
(ORDER REVIEW/RELEASE * DISPATCHING RULE * LOCATION)

(Measured in Hours)		Order Review/Release Mechanism				
Loca.	Disp.	NOR	ART	ARL	BRT	BRL
Front	FCFS	0.00	197.11	44.10	93.51	60.11
	SPT	0.00	42.30	20.73	94.59	59.91
	SOPN	0.00	102.55	39.09	95.29	59.96
Exit	FCFS	0.00	34.90	20.03	150.26	46.06
	SPT	0.00	23.59	19.96	59.01	35.53
	SOPN	0.00	40.22	20.10	196.29	52.29
Mixed	FCFS	0.00	96.69	25.16	155.42	73.27
	SPT	0.00	42.16	21.25	97.35	64.11
	SOPN	0.00	90.60	28.88	170.56	79.30

relatively longer average job waiting time in the backlog file. This resulted in lower workload in the shop but longer flow time in the system (as indicated in Table 5-39). This in turn adversely affected the performance of percent of jobs tardy.

TABLE 5-39
MEAN FLOW TIME IN THE SYSTEM
(ORDER REVIEW/RELEASE * DISPATCHING RULE * LOCATION)

(Measured in Hours)		Order Review/Release Mechanism				
Loca.	Disp.	NOR	ART	ARL	BRT	BRL
Front	FCFS	189.79	318.28	205.94	233.51	227.35
	SPT	86.41	128.40	111.16	181.00	148.72
	SOPN	159.52	237.26	190.75	228.45	207.61
Exit	FCFS	181.88	188.25	197.87	279.36	199.55
	SPT	86.01	109.58	108.09	142.60	122.02
	SOPN	146.61	186.14	170.94	332.13	191.16
Mixed	FCFS	211.87	243.14	226.64	296.49	243.09
	SPT	92.12	129.96	114.22	184.61	154.42
	SOPN	170.26	238.50	192.74	315.57	232.09

As shown in Table 5-40, the average job queue time at the bottleneck work center at the 50% prevalence is longer than at the 100% prevalence. This caused a higher percent of jobs tardy. The causes creating bottlenecks again made a significant difference in performance between the BR mechanism and the other mechanisms. These findings suggest that the BR mechanism is not worthwhile with respect to percent of jobs tardy when the 50% prevalence shop is operating under.

TABLE 5-40

AVERAGE JOB WAITING TIME AT THE BOTTLENECK WORK CENTER
(ORDER REVIEW/RELEASE * PREVALENCE)

(Measured in Hours)		Order Review/Release Mechanism				
		NOR	ART	ARL	BRT	BRL
Prevalence	100%	64.82	45.49	60.63	32.90	50.39
	50%	117.09	74.02	105.77	38.40	66.93

5.3.2.6.3 Summary for Percent of Jobs Tardy

Several conclusions can be reached after analyzing the performance of percent of jobs tardy.

1. As compared to the immediate release mechanism, employing the AR and BR mechanism tends to increase the number of jobs tardy. It also appears that relative differences between order review/release mechanisms tend to be heightened as fewer and fewer jobs are released into the shop floor.

2. Specifically, the performance of the BRT with respect to percent of jobs tardy is not encouraging in any of the situations examined.

3. The performance of the SPT rule consistently outperforms the SOPN rule and the FCFS rule for the bottleneck job shop. However, the performance of the SPT rule, when used with the BRT mechanism, rapidly deteriorates. As a result, there is no significant difference in performance among dispatching rules examined for the front location.

4. Surprisingly, the FCFS rule, as compared the SOPN rule, performs better or at least equally well in minimizing percent of jobs tardy.

5. The performance of both the BRT and the BRL mechanism deteriorates as prevalence shifts from 100% to 50%.

5.4 Bottleneck Jobs vs. Non-Bottleneck Jobs

We have so far examined the experimental results in light of aggregate performances of jobs. Jobs can, however, be split into two types: bottleneck jobs and non-bottleneck jobs. In this section, the emphasis is focused on the impact of the presence of the bottleneck on the performance of both bottleneck jobs and non-bottleneck jobs.

Statistics on both types of jobs were separately collected. ANOVA results for both types of jobs were also compared. In these analysis, the main factor of prevalence was ignored. The results for the 100% prevalence were not used to make comparisons under the same environment, Since at this level, all jobs are bottleneck jobs.

Appendix L and Appendix M present the ANOVA results for bottleneck jobs and non-bottleneck jobs, respectively, on six major performance criteria.

5.4.1 Work-in-Process

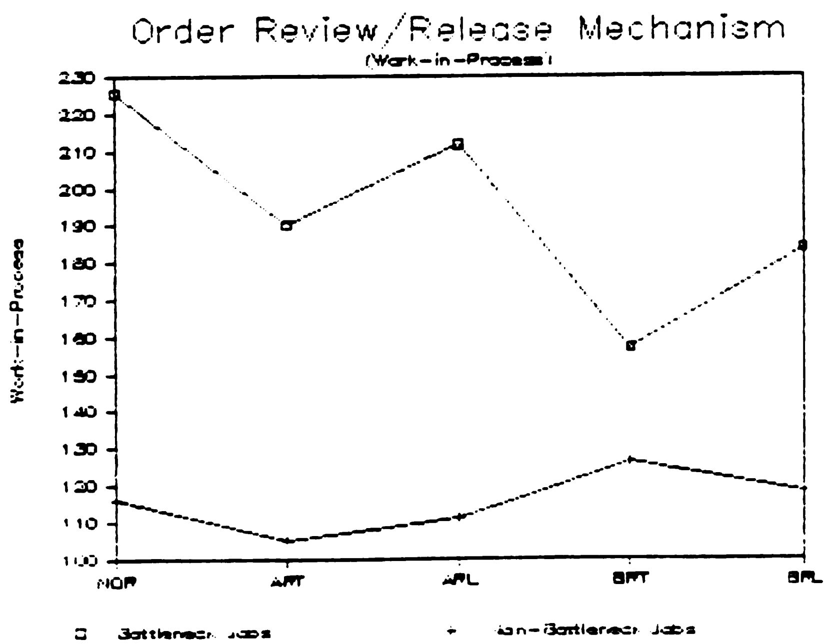
As shown in Table L-1 and M-1, all main effects were significant at the .05 level for both types of jobs. However, more extensive and diverse higher interaction effects were present among the factors for bottleneck jobs. The behavior of both types of jobs under each main factor is compared and examined below.

Figure 5-33 shows average work-in-process for bottleneck and non-bottleneck jobs for each type of order review/release mechanisms. It is interesting to note the performance of the AR mechanism and the BR mechanism and to compare these two mechanisms to the NOR mechanism.

The BR mechanism was effective in dealing with bottleneck jobs at the slight expense of the performance of non-bottleneck jobs. The AR mechanism, on the other hand, exhibited relatively consistent performance in controlling both bottleneck jobs and non-bottleneck jobs.

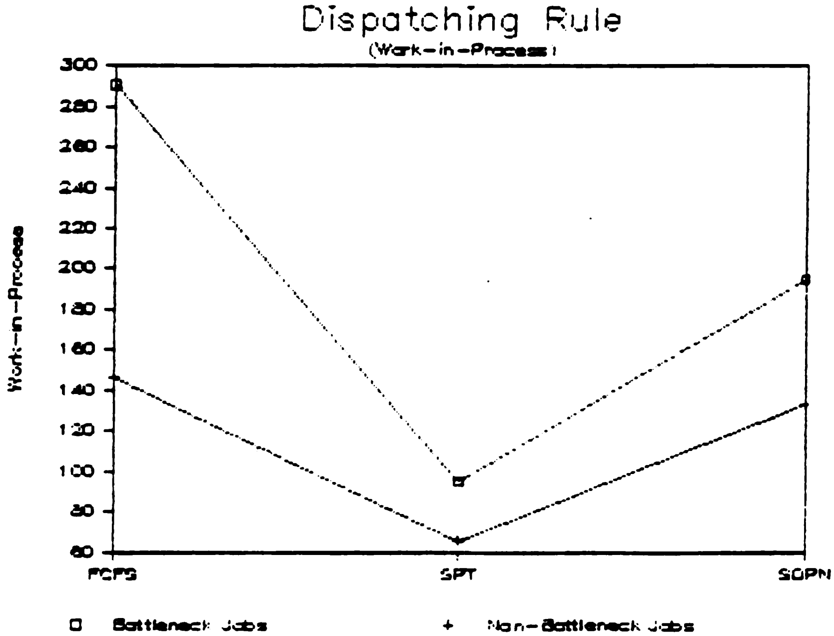
The SPT rule demonstrated strong performance for both types of jobs relative to the other dispatching rules. (see Figure 5-34) There was a significant difference between the effect of the FCFS rule on the performance of bottleneck jobs as compared to non-bottleneck jobs.

For both bottleneck and non-bottleneck jobs, there was a significant difference in performance among bottleneck



ORDER REVIEW/RELEASE MAIN EFFECT
(WORK-IN-PROCESS: BN VS. NBN)

FIGURE 5-33



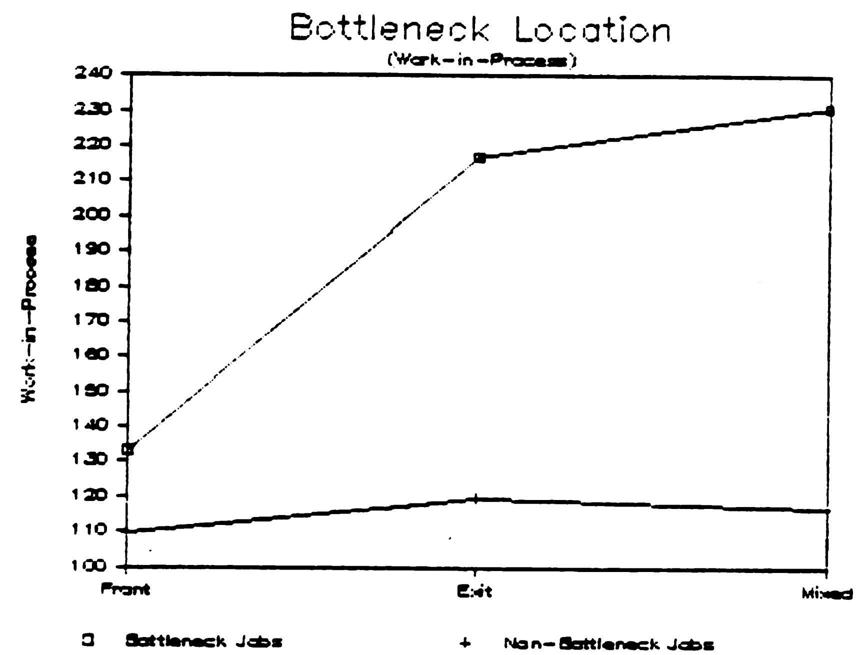
DISPATCHING RULE MAIN EFFECT
(WORK-IN-PROCESS: BN VS. NBN)

FIGURE 5-34

locations. For both types of jobs, the lowest level of work-in-process was produced when the bottleneck was located in the front. (see Figure 5-36) These results indicate that the front bottleneck produce the lowest level of work-in-process regardless of the type of jobs in the bottleneck job shop.

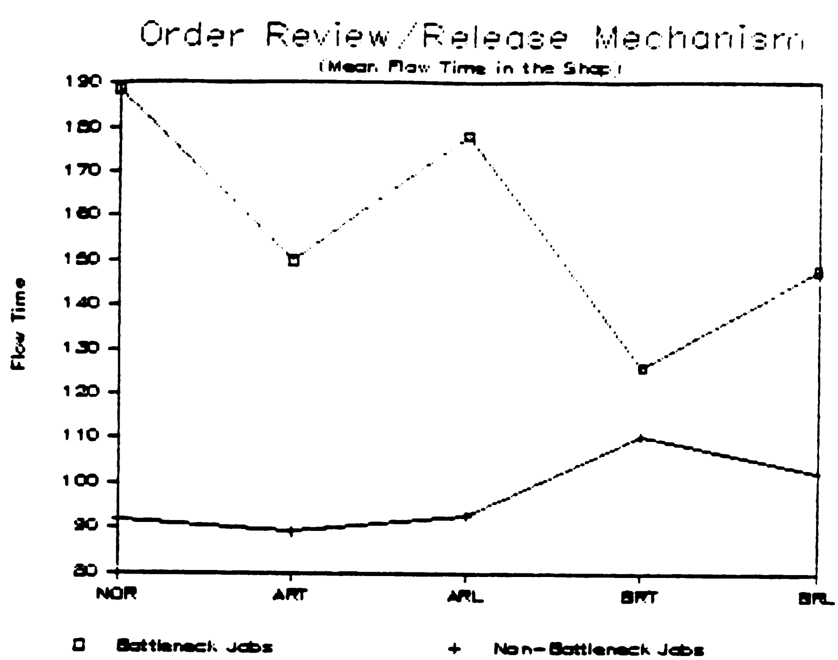
5.4.2 Mean Flow Time in the Shop

Mean flow time of bottleneck jobs was considerably reduced by means of the BR mechanism whereas that of non-bottleneck jobs was slightly increased. (see Figure 5-36) This result is consistent with the performance of work-in-process, indicating that the BR mechanism provided relatively good performance in lowering lead time and



BOTTLENECK LOCATION MAIN EFFECT
(WORK-IN-PROCESS: BN VS. NBN)

FIGURE 5-35



ORDER REVIEW/RELEASE MAIN EFFECT
(MEAN FLOW TIME IN THE SHOP: BN VS. NBN)

FIGURE 5-36

work-in-process for bottleneck jobs. This improvement, however, was accompanied by the deterioration of the performance of non-bottleneck jobs.

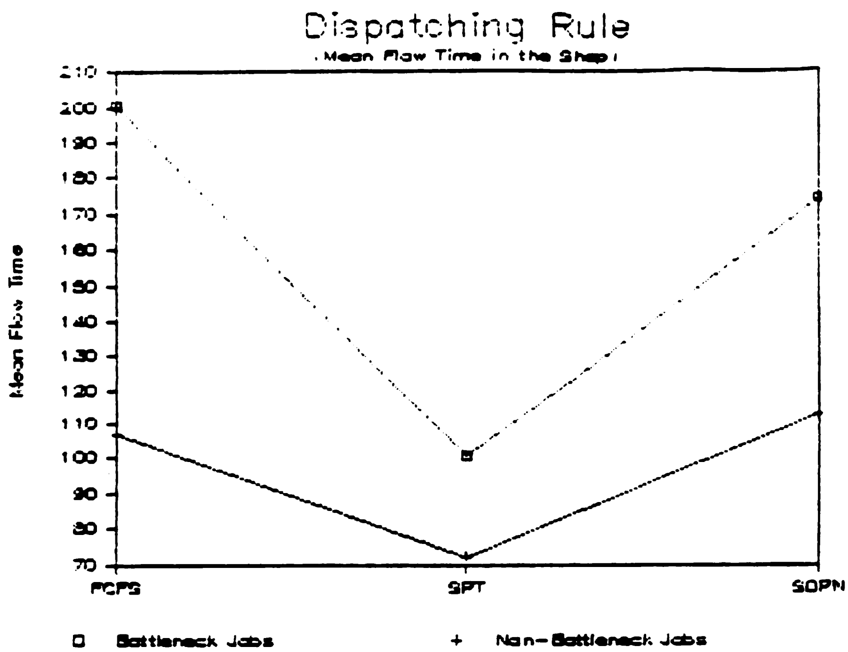
It was apparent from Figure 5-37 that the SPT rule demonstrated relatively good performance in managing both bottleneck and non-bottleneck jobs. The FCFS rule, on the other hand, was ineffective in managing either type of job.

Bottleneck jobs had the highest mean flow time when the bottleneck was located at the mixed whereas non-bottleneck jobs had the highest when faced by the exit bottleneck location. (see Figure 5-38) These results indicated that the performance of each type of jobs in the bottleneck job shop was significantly affected by the type of the bottleneck locations.

As contrasted to the performance of work-in-process, the behavior of non-bottleneck jobs, rather than bottleneck jobs, was considerably influenced by the presence of the bottleneck work center. (see Table L-2 and M-2) The more higher significant interactions present for the performance of mean flow time in the shop, when compared to that for work-in-process indicated this behavior for the non-bottleneck jobs.

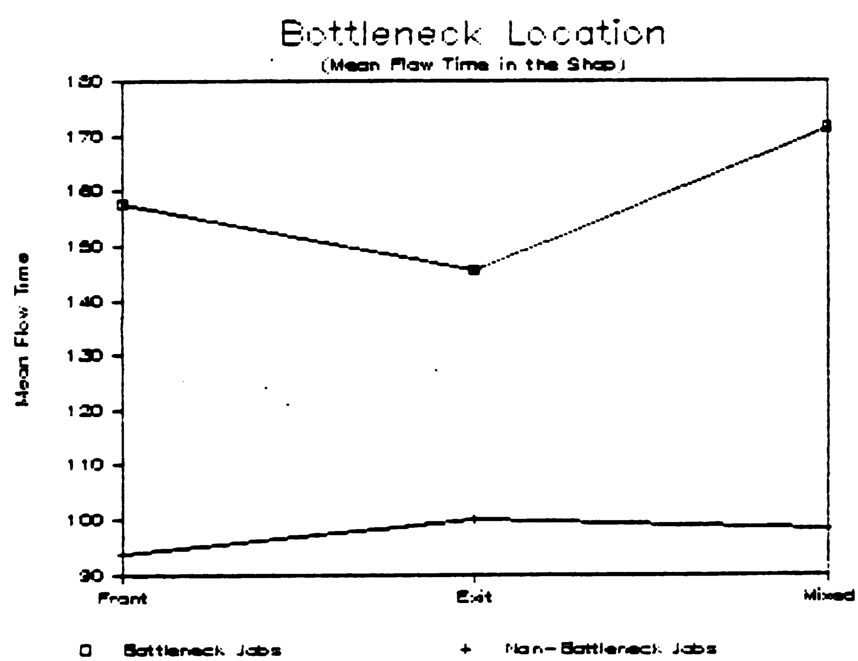
5.4.3 Variance of Flow Time in the Shop

The main effect due to bottleneck location was not significant when bottleneck jobs were examined only. (see Table K-3) However, it was found to be significant under non-bottleneck jobs, indicating that the performance of only



DISPATCHING RULE MAIN EFFECT
(MEAN FLOW TIME IN THE SHOP: BN VS. NBN)

FIGURE 5-37



BOTTLENECK LOCATION MAIN EFFECT
(MEAN FLOW TIME IN THE SHOP: BN VS. NBN)

FIGURE 5-38

non-bottleneck jobs was influenced by the type of bottleneck location. (see Table M-3)

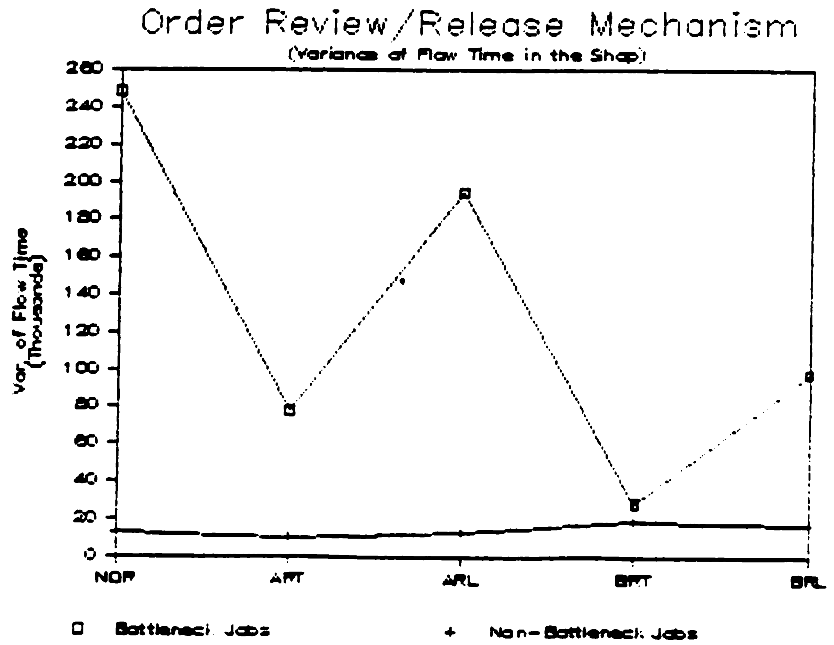
Figure 5-39 showed that the BRT mechanism reduced the variance of flow time for bottleneck jobs to a level close to that of non-bottleneck jobs. The BRT mechanism significantly improved the performance of bottleneck jobs with respect to both the mean flow time and the variance of flow time as well.

The bottleneck work center appeared to impose severe problems on the performance of the FCFS rule in controlling bottleneck jobs. (see Figure 5-40) This result indicates that random selection of jobs for process next tends to considerably increase variance of flow time under the bottleneck job shop.

5.4.4 Mean Tardiness

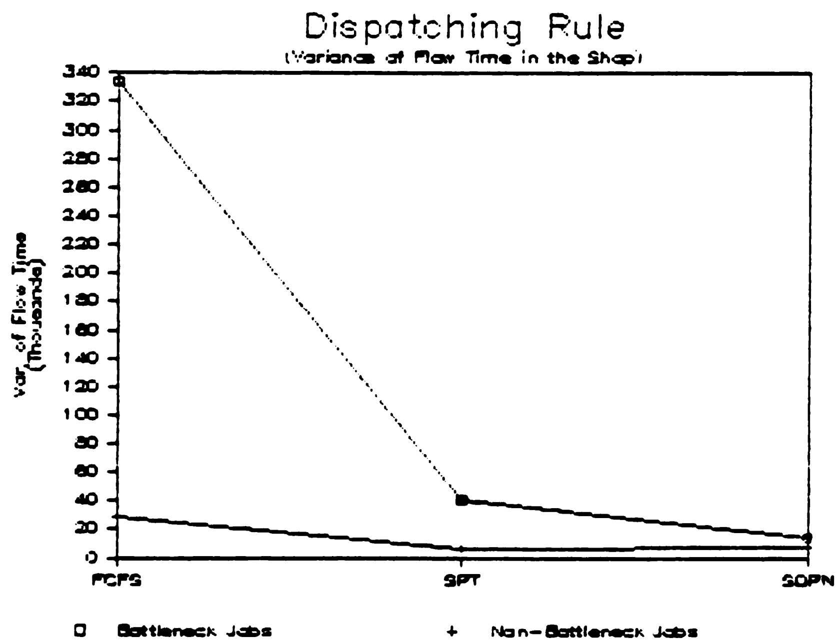
The use of the BRT mechanism caused mean tardiness to deteriorate for both bottleneck jobs and non-bottleneck jobs. (see Figure 5-41) Specifically, rapidly deteriorating performance of the non-bottleneck jobs largely contributed to the overall poor performance of the BRT mechanism. The ART mechanism, by contrast, provided almost equivalent performance as the NOR mechanism for bottleneck jobs. However, the mean tardiness of non-bottleneck jobs, when compared to the NOR mechanism, significantly increased.

The performance of both bottleneck jobs and non-bottleneck jobs was equally influenced by the type of the bottleneck location. (see Figure 5-42) The exit location



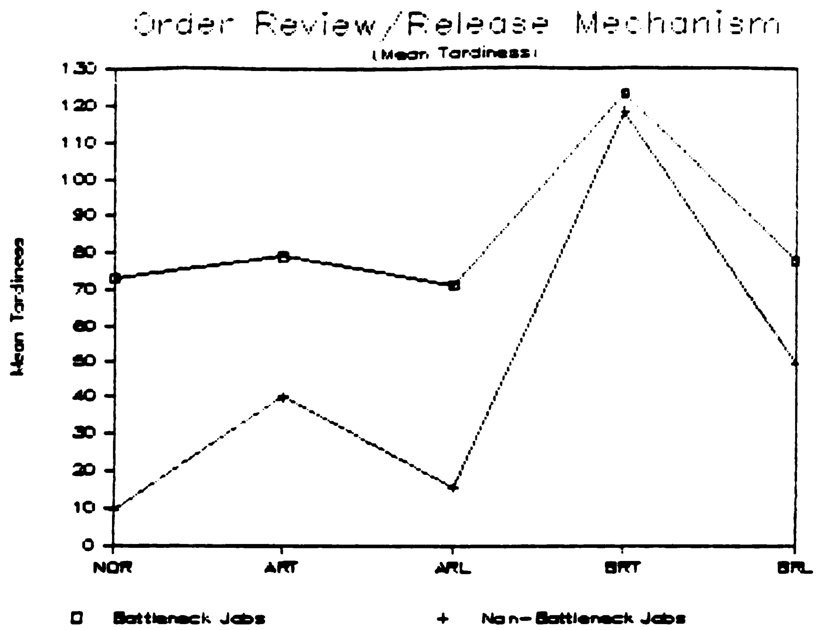
ORDER REVIEW/RELEASE MAIN EFFECT
(VARIANCE OF FLOW TIME IN THE SHOP: BN VS. NBN)

FIGURE 5-39



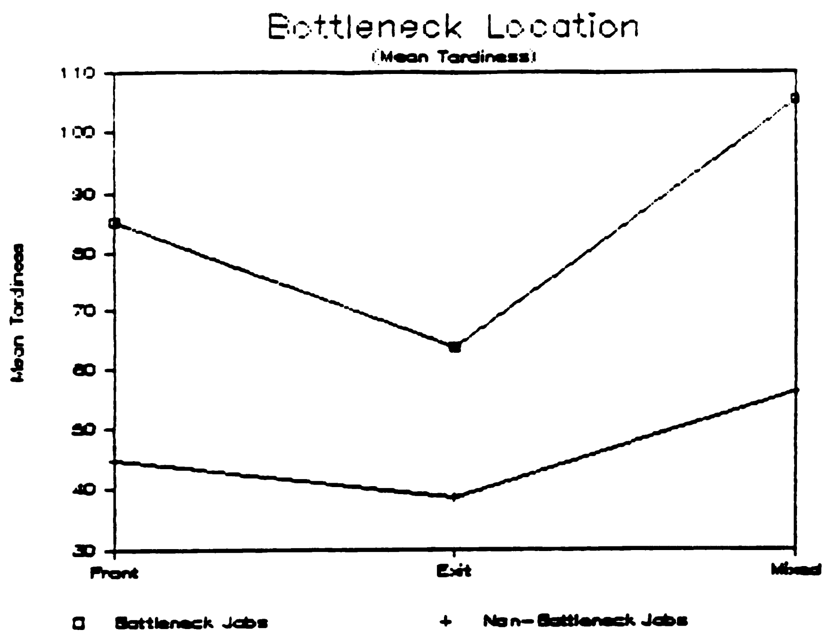
DISPATCHING RULE MAIN EFFECT
(VARIANCE OF FLOW TIME IN THE SHOP: BN VS. NBN)

FIGURE 5-40



ORDER REVIEW/RELEASE MAIN EFFECT
(MEAN TARDINESS: BN VS. NBN)

FIGURE 5-41



BOTTLENECK LOCATION MAIN EFFECT
(MEAN TARDINESS: BN VS. NBN)

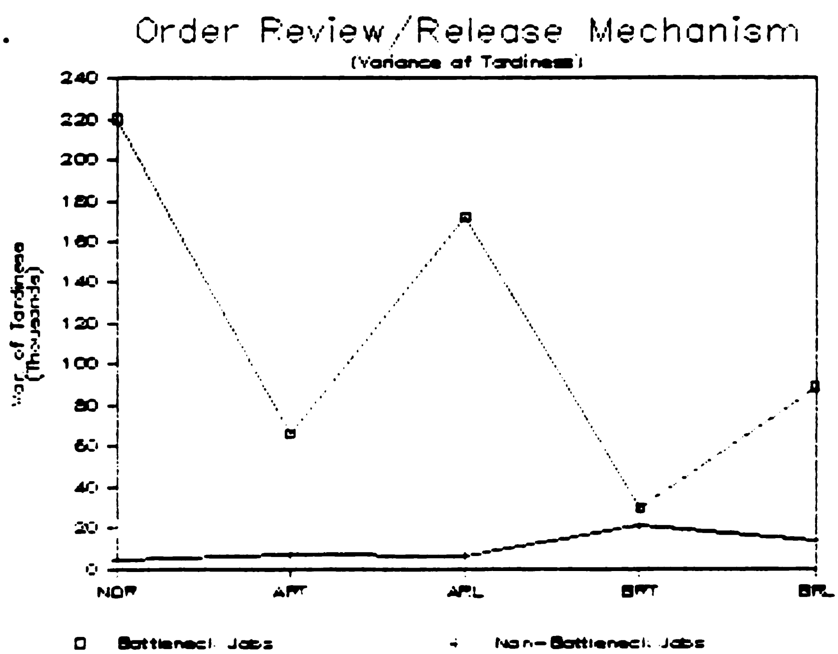
FIGURE 5-42

produced the lowest mean tardiness and the mixed location produced the highest under both types of jobs.

5.4.5 Variance of Tardiness

Like the performance of variance of flow time in the shop, the variance of tardiness for bottleneck jobs was not influenced by the type of bottleneck location. (see Table L-5) These results imply that the type of bottleneck location makes virtually no impact on the performance of bottleneck jobs for variance-related performance measures. The type of bottleneck location, however, did significantly affect the performance of non-bottleneck jobs. (see Table M-5)

Although mean tardiness deteriorated considerably under the BRT mechanism, associated variance was greatly reduced. (see Figure 5-43) This result indicated that the BRT



ORDER REVIEW/RELEASE MAIN EFFECT
(VARIANCE OF TARDINESS: BN VS. NBN)

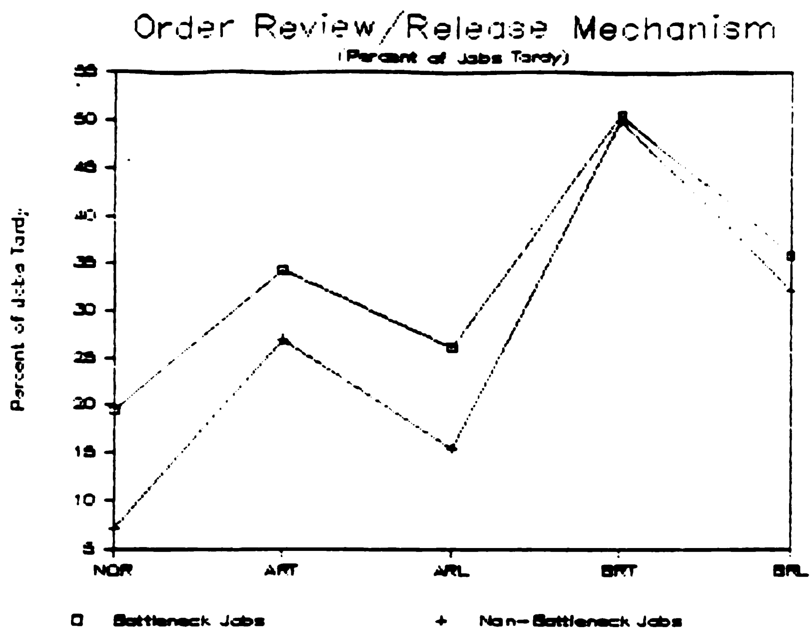
FIGURE 5-43

mechanism was relatively effective in lowering variance-related performance measures.

5.4.6 Percent of Jobs Tardy

There were no significant interaction effects for bottleneck jobs as compared to non-bottleneck jobs. (see Table K-6 and L-6)

A similar result was observed between mean tardiness and the percent of jobs tardy under bottleneck jobs. (see Figure 5-44) From both Figure 5-41 and 5-44, the BRT mechanism did really deteriorate the performance of both non-bottleneck jobs and bottleneck jobs. These results also suggest that focusing scheduling on bottleneck work center status greatly deteriorates the performance of both non-bottleneck jobs and bottleneck jobs in terms of mean



ORDER REVIEW/RELEASE MAIN EFFECT
(PERCENT OF JOBS TARDY: BN VS. NBN)

FIGURE 5-44

tardiness and percent of jobs tardy.

The SOPN rule had a lower percentage of jobs tardy than the FCFS rule for non-bottleneck jobs whereas it had higher percentage tardy for bottleneck jobs. The overall poor performance of the SOPN rule, when compared to the FCFS rule, involved primarily bottleneck jobs.

5.5 Summary

In this chapter, the appropriateness of the ANOVA model assumptions was examined mainly through a Chi-square and Cochran's test. Based on the original data for percentage of jobs tardy and transformed data for the other dependent variables, the experimental results of the study were analyzed using ANOVA. Then, the experimental results were examined according to bottleneck and non-bottleneck jobs.

In the next chapter, the major findings of the results will be summarized and managerial implications of the results discussed. Suggestions of additional future research areas relevant to this and other related studies will also be addressed.

CHAPTER 6

SUMMARY, MANAGERIAL IMPLICATIONS, AND FUTURE RESEARCH

6.1 Introduction

This research study was concerned with the management of a bottleneck job shop characterized by location and prevalence of the bottleneck. In this study, two fundamental control procedures (order review/release mechanisms and dispatching rules) were examined as methods of controlling high workload for the bottleneck work center. This chapter begins by summarizing major findings of the experiment in section 2. The results of this study are summarized by answering the research questions posed in Chapter one. Section 3 identifies and addresses several important managerial implications discovered in the study. Finally, in section 4, further research areas relevant to this study are outlined.

6.2 Summary of the Major Findings

The following are the major research questions addressed by this study:

1. What are the major characteristics of a bottleneck which should be considered when studying its impact on the operation of the shop floor?

2. Which control procedures (dispatching rules or order review/release mechanisms) have the greater impact on bottleneck work centers (and under what conditions)?

3. Can usage of information only about workload for bottleneck work centers improve significantly shop performance?

4. In a bottleneck job shop, where there is a mixture of bottleneck and non-bottleneck jobs, how does the presence of a bottleneck work center influence these two types of jobs?

5. How do such bottleneck characteristics as prevalence and the location of the bottleneck affect shop floor operations and the performance of dispatching rules and order review/release mechanisms?

6. Can we identify any general guidelines which can be used when dealing with a bottleneck job shop?

The focus of the summary of the major findings of this research study will be placed on these six major research questions.

6.2.1 Research Question One

The first research question intended to identify major factors involved when managers and researchers are studying the problems created by a bottleneck work center. This question was raised because of the lack of detailed knowledge surrounding the bottlenecks combined with their potential importance. A framework for a bottleneck job shop was first constructed. This framework was based partly on a review of the literature concerning bottlenecks and partly on the elaborate investigation of a bottleneck job shop, as summarized in Chapter two.

These efforts resulted in four major factors which must be considered when studying bottlenecks.

The first factor was the cause of a bottleneck: systematic or random. This was a very important distinction for scheduling control purposes. The focus of this study was on the systematic bottleneck because it is the systematic bottleneck which persistently exists and limits the total output of the system over the long run.

The second factor was the status of a bottleneck: stationary or floating. When the same work center consistently acts as the bottleneck, it is a stationary bottleneck. This study examined the impacts of one stationary bottleneck on shop performance.

The third factor was the location of a bottleneck work center in the job routing: front, exit and mixed. The results of this study indicated that the bottleneck location significantly affect the performance of the shop.

The final factor was the prevalence of a bottleneck: 100% and 50%. The experimental results of this study also indicated that the shop performance was significantly influenced by the level of prevalence.

The present research study was guided primarily by this framework. Specifically, the major focus of this study was on managing a job shop in which one systematic but stationary bottleneck work center was present with three bottleneck locations and two bottleneck prevalences.

6.2.2 Research Question Two

The second research question dealt with the evaluation of the relative effectiveness of the two control procedures in managing the bottleneck job shop. All system performance measures were found to be significantly affected by both types of control procedures. The experimental results of this study strongly suggest that the selection of dispatching rules has a greater impact than that of order review/release mechanisms under all situations considered.

Specifically, the performance of the SPT rule with respect to work-in-process, mean flow time in the shop, mean tardiness, and percent of jobs tardy is not very sensitive to changes of the order review/release mechanism. Neither is the performance of the SOPN rule with respect to the variance of flow time and tardiness.

The selection of order review/release mechanism therefore does not seem to provide significant difference in system performance when used with a particular dispatching rule. Rather, it appears to amplify the effect of that particular dispatching rule.

As compared to dispatching rule, the poor performance of order review/release mechanism in this research warrants more investigation. The type of job arrival distribution into the shop may partly contribute to this. In other words, the lack of a planning system, which releases jobs to the order review/release stage in a random fashion, tends to nullify the purpose of order review/release mechanism. This suggests that the use of order review/release mechanisms by itself can not make up for poorly planned (i.e., erratic) workload.

6.2.3 Research Question Three

The experiments performed in this research study examined a wide range of information used in the releasing mechanisms. This research question is particularly concerned with the relative performance of the BR mechanisms which utilize information only about workload for a bottleneck work center.

The BRT mechanism provided a significant improvement over the NOR mechanism when the bottleneck was located at the exit with respect to the level of work-in-process. For the mean flow time in the shop, the BRT mechanism performed significantly better than the NOR mechanism when used with the FCFS rule. The BRT mechanism, when compared to the ART and the NOR mechanism, performed better or at least similarly under all situations examined in terms of the variance of flow time in the shop.

For the performance measures of mean tardiness and the percent of jobs tardy, the BRT mechanism, as contrasted to the NOR and the AR mechanisms, did cause both measures to deteriorate significantly.

Relative to other release mechanisms, the BR mechanism tended to release fewer jobs at any one point into the shop. Furthermore, the BR mechanisms most effectively controlled the workload at the bottleneck work center. Although the use of the BRT mechanism led to a practical improvement in both the level of work-in-process and the lead time in the shop, the mean flow time in the system under the BR mechanism was the longest among order review/release mechanisms considered. This result adversely affected the performance in both mean tardiness and the number of jobs tardy.

These results strongly suggest that a tradeoff must be weighed when the BR mechanism is applied to the management of the bottleneck job shop. That is, the BRT mechanism provides a slight improvement in the level of work-in-process and mean and variance of lead time in the shop at the expense of considerable degradation in both mean tardiness and the number of jobs tardy.

6.2.4 Research Question Four

In this research study, jobs were divided into two groups: bottleneck jobs and non-bottleneck jobs. This research question therefore addresses the impact of the bottleneck operation on the performance of both types of jobs.

The results showed that work-in-process, mean flow time, and the variance of flow time and tardiness for bottleneck jobs can be controlled quite well by means of the BR mechanism. The BR mechanism, on the other hand, led to a significant degradation in mean tardiness and the percent of jobs tardy for both bottleneck and, particularly, non-bottleneck jobs.

The SPT rule exhibited relatively good performance for both bottleneck jobs and non-bottleneck jobs for all situations considered. The FCFS rule, however, exhibited rapidly deteriorating performance for bottleneck jobs.

The results suggest that the aggregate performance was largely determined by the performance of bottleneck jobs rather than non-bottleneck jobs due primarily to the difference in magnitude.

6.2.5 Research Question Five

We are concerned with the impact of descriptive characteristics of the bottleneck job shop on shop performance and the interaction between these characteristics and the two control procedures.

The result showed that shop performance was significantly influenced by location. In terms of the level of work-in-process, the highest level was observed for the exit location. The mixed location, however, performed the poorest for other performance measures. In general, performance can be expected to improve when the bottleneck location in the routing is fixed. That is, a bottleneck which appears consistently at the beginning of ending of job routings is easier to manage.

The result also indicates that better performance was obtained when the bottleneck was located at the end, rather than in the front. Under the front bottleneck, the input flow to the work centers following the bottleneck work center was restricted by the output rate of the bottleneck work center. This tended to delay the flow of jobs through the system slightly as compared to the shop in which the bottleneck was at the exit.

The experimental results indicate that neither mean tardiness nor the variance of tardiness was influenced by prevalence. Other performance measures, however, were slightly affected by prevalence. These results suggest that the impact of prevalence on shop performance is not as strong as location.

The results also indicate that the 100% prevalence created more problems than the 50% prevalence in terms of the level of work-in-process, mean flow time in the shop, the variance of flow time in the shop, and the variance of tardiness. Higher mean tardiness and the number of jobs tardy occurred when the shop operated at 50% prevalence. This can be attributable to the different causes of bottleneck: long operation time at the bottleneck work center (50% prevalence) and routing (100% prevalence).

There existed significant interaction effects between two control procedures and two bottleneck characteristics under some performance measures.

The performance of order review/release mechanisms was significantly influenced by these two characteristics of a bottleneck. For example, order review/release mechanisms made virtually no difference in minimizing work-in-process when the bottleneck was located in the front. Location also influenced the performance of dispatching rule in terms of mean flow time in the shop. When a front bottleneck was present, there was no significant difference between the SOPN and the FCFS rule. The selection rule used for the backlog file may contribute to these results. When the bottleneck located at the front, there was virtually little difference between the FCFS and the SOPN rule if the SLACK rule was used to select jobs in the backlog file.

It is also interesting to note that the performance of the BR mechanism greatly deteriorated when 50% prevalence was imposed on the shop. This was due to long processing times of bottleneck jobs at the bottleneck work center. This made the BR mechanism release relatively smaller numbers of jobs for the 50% prevalence than for the 100% prevalence. This suggests that the use of the BR mechanism under the 50% prevalence is not worthwhile when the minimization of mean tardiness and percent of jobs tardy are the major objectives.

6.2.6 Research Question Six

The SPT rule outperformed both the SOPN and the FCFS rule with respect to the level of work-in-process, mean flow time in the shop, mean tardiness, and the percent of jobs tardy. Surprisingly, the SPT rule also performed the best in minimizing mean tardiness and the number of jobs tardy in the bottleneck job shop in which the shop capacity utilization is operating at moderate.

The results suggest that the SPT rule is desirable in the bottleneck job shop even at moderate overall shop load when minimizing mean tardiness and the percent of jobs tardy as well.

As expected, the SOPN rule exhibits best performance in reducing the variance-related measures. It is interesting to note, however, that the FCFS rule performs as well as the SOPN rule when jobs are tightly released into the shop. This confirms the observations and findings reported by Nicholson and Pullen (1972).

6.3 Managerial Implications

While a great deal of research attention has been devoted to the balanced job shop, very little work has examined a job shop which is unbalanced. The focus of this research study was to manage this unbalanced shop by means of two control procedures. The results of this research study provide some managerial relevance.

First, shop performance is greatly influenced by both location and prevalence of the bottleneck. Managers must first identify these two environmental factors before implementing any control procedures. Furthermore, managers must also realize that the management of bottleneck job shop becomes further complicated due to the presence of interactions between control procedures and two characteristics of the bottleneck.

Second, the use of the SPT rule is highly recommended with respect to any performance measures in managing the bottleneck job shop. The SPT rule excels not only in minimizing lead time and work-in-process but also in reducing mean tardiness and the percent of jobs tardy.

Third, the use of the BR mechanism, which utilizes information about the bottleneck work center, must be carefully examined by weighing its advantages against its disadvantages. Specifically, the BRT mechanism provides an improvement under some situations in reducing lead time, work-in-process, and the variance of lead time and tardiness. The BRT mechanism, however, results in substantial degradation in mean tardiness and the number of jobs tardy.

Fourth, both researchers and practicing managers must be aware of the fact that the presence of the bottleneck can significantly affect not only bottleneck jobs but also non-bottleneck jobs. These results imply that the progress of not only bottleneck jobs but also non-bottleneck jobs should be monitored and controlled when managing bottlenecks.

Fifth, when a linkage between order review/release stage and planning stage is not in place, the use of an order review/release mechanism does not have as much impact on the shop as a dispatching rule does.

6.4 Future Research

The experimental results of this research study provide a basis for future research into the operation of bottleneck job shops. Several suggestions for future research on bottleneck job shop are provided below.

First, considering the relatively poor performance of order review/release mechanisms with respect to mean tardiness and the percent of jobs tardy in the bottleneck job shop, alternative order review/release mechanisms may be needed. Alternatives may employ different mechanics in terms of what to release and when to release. In this study, jobs in the backlog file were prioritized according to the dynamic SLACK rule every week. A mechanism more sensitive to the status of shop and bottleneck work center may improve the performance in delivery-related measurements.

One of alternatives is to develop a time-phased order review/release mechanism. This mechanism realizes the finite capacity of a bottleneck work center in a given time period. Therefore, this mechanism releases jobs in the backlog file in accordance with the available capacity of the bottleneck work center by segmenting the capacity of the bottleneck work center by time. This may provide a significant improvement over the order review/release mechanisms examined in this study.

Second, more research is needed to broaden this study to incorporate it with the planning system. That is, bottlenecks must be managed within the closed-loop system. Within the closed system, release of jobs from the planning system to the order review/release stage is controlled in response to the status of a bottleneck work center and a shop as well. Nothing has been done about managing the flow of orders from the planning system to the order review/release pool. This may provide significant impact on the performance of order review/release mechanism.

Third, additional research is needed to manage the bottleneck job shop under varying levels of capacity utilization. For example, this study examined a job shop operating under 82 percent capacity utilization. What happens to the general conclusions of this study as capacity utilizations increase or decrease is not known.

Finally, only a single fixed bottleneck was examined under this study. It is natural to expand this model to better represent reality in which multiple floating bottlenecks are present. The introduction of more complex models makes the bottleneck job shop research more rich and viable.

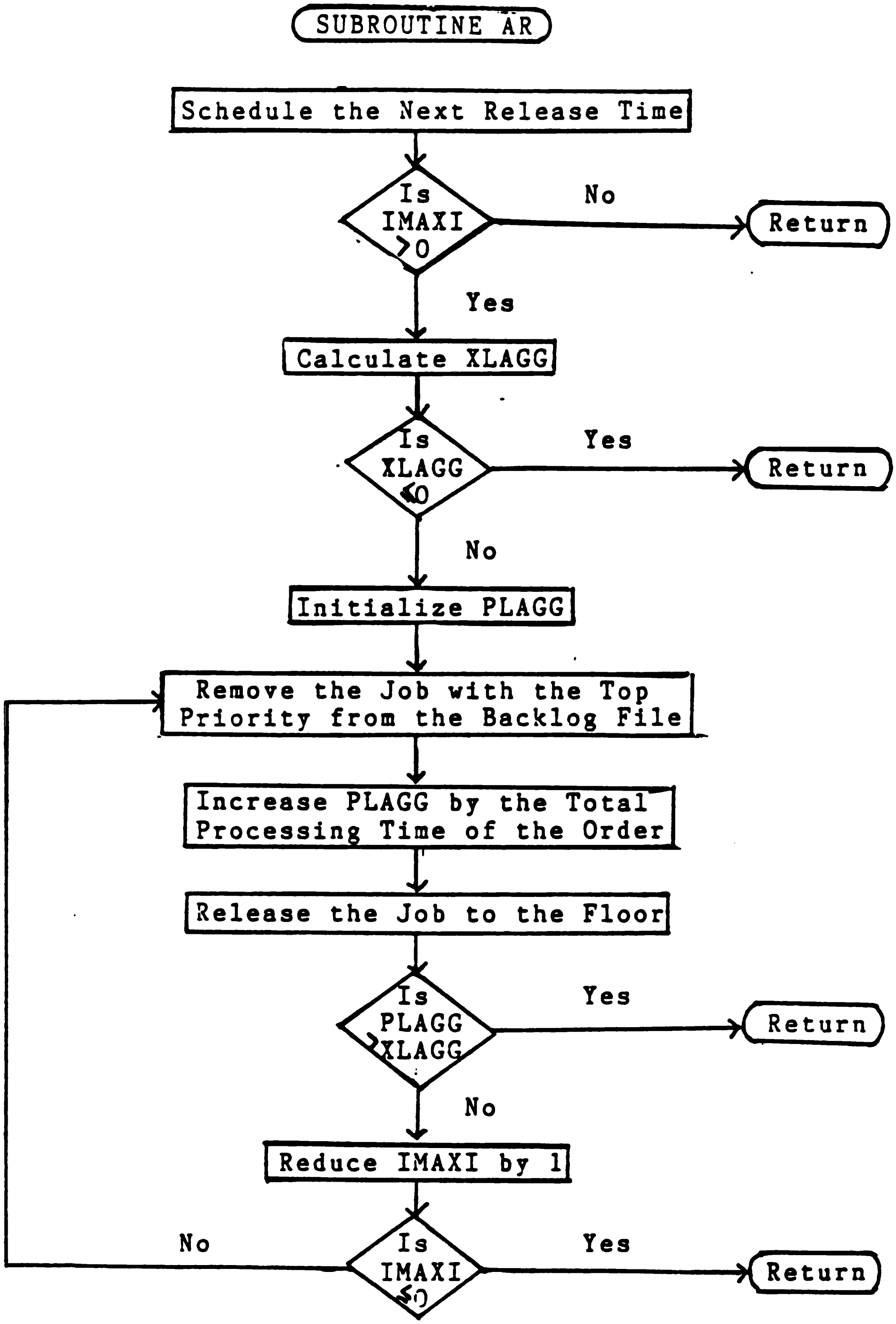
6.5 Summary

The major findings of the experimental results of this study were discussed. Based on these major findings, several important managerial implications of this study were also presented. More research areas relevant a bottleneck job shop were suggested for future work.

APPENDICES

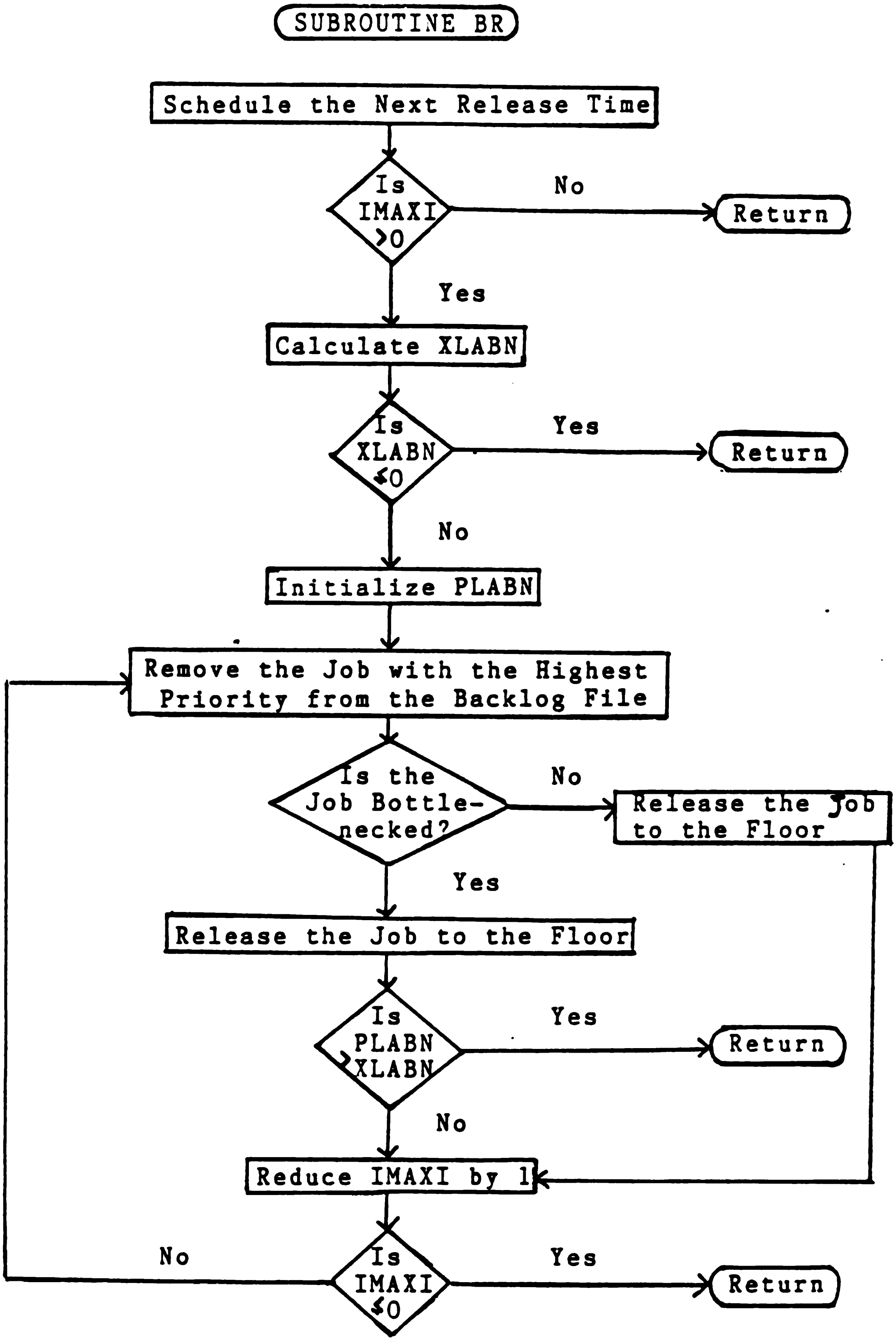
Appendix A and Appendix B presents the flowchart for the aggregate release mechanism and the bottleneck release mechanism, respectively. Variables used in Appendix A and Appendix B are described below.

Variable	Description
IMAXI	Number of jobs in the backlog file
XLAGG	Predetermined workload limit in the shop minus current workload in the shop
PLAGG	Predetermined workload limit in the shop minus planned workload in the shop
XLABN	Predetermined workload limit for the bottleneck work center minus existing workload for the bottleneck work center
PLABN	Predetermined workload limit for the bottleneck work center minus planned workload for the bottleneck work center



FLOWCHART OF THE AGGREGATE RELEASE MECHANISM

FIGURE A-1



FLOWCHART OF THE BOTTLENECK RELEASE MECHANISM

FIGURE B-1

TABLE C-1

ANALYSIS OF VARIANCE
(WORK-IN-PROCESS: ORIGINAL MODEL)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR WIP USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	9779267.51887	801	12208.82337		
JOBSET	4511994.32254	9	501332.70250	41.06315	0
DRR	767298.05237	4	191824.51309	15.71196	0
DISPATCH	16074910.45398	2	8037455.22699	658.33168	0
LOCATION	4600820.84808	2	2300410.42404	188.42196	0
PREVALEN	917233.98321	1	917233.98321	75.12878	0
DRR BY DISPATCH	409266.56509	8	51158.32064	4.19027	.00006
DRR BY LOCATION	733089.82602	8	91636.22825	7.50574	0
DRR BY PREVALEN	79968.38429	4	19992.09607	1.63751	.16281
DISPATCH BY LOCATION	2034550.45744	4	508637.61436	41.66148	0
DISPATCH BY PREVALEN	368009.29242	2	184004.64621	15.07145	3.75593E-007
LOCATION BY PREVALEN	735781.92782	2	367890.96391	30.13320	0
DRR BY DISPATCH BY LOCATION	334071.71811	16	20879.48238	1.71020	.03995
DRR BY DISPATCH BY PREVALEN	38677.18624	8	4834.64828	.39600	.92300
DRR BY LOCATION BY PREVALEN	51563.25318	8	6445.40665	.52793	.83598
DISPATCH BY LOCATION BY PREVALEN	370300.93144	4	92575.23286	7.58265	.00001
DRR BY DISPATCH BY LOCATION BY PREVALEN	37929.35989	16	2370.58499	.19417	.99978
(MODEL)	32065466.56212	98	327198.63839	26.80018	0
(TOTAL)	41844734.08099	899	46545.86661		

R-SQUARED = .76630
ADJUSTED R-SQUARED = .73770

- -

TABLE C-2

ANALYSIS OF VARIANCE
(MEAN FLOW TIME IN THE SHOP: ORIGINAL MODEL)

* A N A L Y S I S O F V A R I A N C E *

TESTS OF SIGNIFICANCE FOR MEANFLSP USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	644963.44883	801	805.19781		
JOBSET	441010.33823	9	49001.14869	60.85604	0
ORR	97961.89662	4	24490.47416	30.41548	0
DISPATCH	950761.94269	2	475380.97134	590.39029	0
LOCATION	21894.08042	2	10947.04021	13.59547	1.56160E-006
PREVALEN	25002.98859	1	25002.98859	31.05198	3.43244E-008
ORR BY DISPATCH	71341.64331	8	8917.70541	11.07517	0
ORR BY LOCATION	15176.56658	8	1897.07082	2.35603	.01655
ORR BY PREVALEN	4320.99884	4	1080.24971	1.34160	.25276
DISPATCH BY LOCATION	6859.24638	4	1714.81159	2.12968	.07536
DISPATCH BY PREVALEN	9084.23482	2	4542.11741	5.64100	.00369
LOCATION BY PREVALEN	1270.13802	2	635.06901	.78871	.45470
ORR BY DISPATCH BY LOCATION	12357.74029	16	772.35877	.95922	.50028
ORR BY DISPATCH BY PREVALEN	4127.12429	8	515.89054	.64070	.74377
ORR BY LOCATION BY PREVALEN	4723.57942	8	590.44743	.73329	.66215
DISPATCH BY LOCATION BY PREVALEN	1471.46491	4	367.86623	.45686	.76742
ORR BY DISPATCH BY LOCATION BY PREVALEN	2639.31864	16	164.95742	.20487	.99968
(MODEL)	1670803.30202	98	17040.85002	21.16356	0
(TOTAL)	2314966.75885	899	2575.04644		

R-SQUARED = .72139
ADJUSTED R-SQUARED = .68731

TABLE C-3

ANALYSIS OF VARIANCE
(VARIANCE OF FLOW TIME IN THE SHOP: ORIGINAL MODEL)

• A N A L Y S I S   O F   V A R I A N C E • • • • • • • • • • • • • • • • • •

TESTS OF SIGNIFICANCE FOR VARFLSH USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	3.[illegible]452[illegible]E+013	8[illegible]1	3.80184E+010		
J[illegible]T	2.6[illegible]76E+012	9	2.97862E+011	7.83467	0
GRP	1.36352E+012	4	3.4[illegible]881E+011	8.96621	4.37398E-007
DISPATCH	6.9[illegible]70E+012	2	3.4[illegible]435E+012	90.07085	0
LOCATION	2.3539[illegible]E+011	2	1.17698E+011	3.09581	.04578
PREVALEN	3.45[illegible]61E+010	1	3.45[illegible]61E+010	.90814	.34098
GRP BY DISPATCH	1.95291E+012	8	2.44113E+011	6.42092	4.13630E-008
GRP BY LOCATION	3.1[illegible]92E+011	8	3.92240E+010	1.03171	.41018
GRP BY PREVALEN	6.21[illegible]E+010	4	1.55490E+010	.40899	.80225
DISPATCH BY LOCATION	3.36[illegible]55E+011	4	8.42139E+010	2.21508	.06569
DISPATCH BY PREVALEN	[illegible]E+010	2	2.82519E+010	.74311	.47596
LOCATION BY PREVALEN	2.13431E+010	2	1.06716E+010	.28069	.75533
GRP BY DISPATCH BY LOCATION	4.93441E+011	16	3.08401E+010	.81119	.67370
GRP BY DISPATCH BY PREVALEN	5.6[illegible]E+010	8	1.[illegible]2923E+010	.32332	.95730
GRP BY LOCATION BY PREVALEN	1.2414[illegible]E+011	8	1.55165E+010	.40918	.91622
DISPATCH BY LOCATION BY PREVALEN	2.71722E+010	4	6.79304E+009	.17868	.94943
GRP BY DISPATCH BY LOCATION BY PREVALEN	2.12[illegible]E+011	16	1.33065E+010	.35006	.99163
(MODEL)	1.46625E+013	99	1.51658E+011	3.98907	0
(TOTAL)	4.53153E+013	[illegible]9	5.04063E+010		

R-SQUARED = .3[illegible]
ADJUSTED R-SQUARED = .24[illegible]

- -

TABLE C-4

ANALYSIS OF VARIANCE
(MEAN TARDINESS: ORIGINAL MODEL)

* A N A L Y S I S O F V A R I A N C E *

TESTS OF SIGNIFICANCE FOR MEANTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	2417364.26256	801	3017.93291		
JOBSET	1484622.34645	9	164958.03849	54.65928	0
ORR	229138.64062	4	57284.66016	18.98142	0
DISPATCH	1052884.87326	2	526442.43663	174.43808	0
LOCATION	53016.00020	2	26508.00010	8.78350	.00017
PREVALEN	42346.78028	1	42346.78028	14.03172	.00019
ORR BY DISPATCH	130078.32151	8	16259.79019	5.38772	1.27555E-006
ORR BY LOCATION	97175.91450	8	12146.98932	4.02494	.00011
ORR BY PREVALEN	157986.83244	4	39496.70811	13.08734	0
DISPATCH BY LOCATION	15499.06413	4	3874.76603	1.28391	.27465
DISPATCH BY PREVALEN	21559.43042	2	10779.71521	3.57189	.02855
LOCATION BY PREVALEN	18589.30442	2	9294.65221	3.07981	.04651
ORR BY DISPATCH BY LOCATION	98827.19109	16	6176.69944	2.04667	.00894
ORR BY DISPATCH BY PREVALEN	26258.52969	8	3282.31621	1.08760	.36945
ORR BY LOCATION BY PREVALEN	17224.55769	8	2153.06971	.71343	.67985
DISPATCH BY LOCATION BY PREVALEN	9823.08538	4	2455.77234	.81373	.51652
ORR BY DISPATCH BY LOCATION BY PREVALEN	25275.11918	16	1579.69495	.52344	.93592
(MODEL)	3480305.99535	98	35513.32648	11.76743	0
(TOTAL)	5897670.25791	899	6560.25613		

R-SQUARED = .59012
ADJUSTED R-SQUARED = .53997

- -

TABLE C-5

ANALYSIS OF VARIANCE
(VARIANCE OF TARDINESS: ORIGINAL MODEL)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR VARTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	2.88166E+013	801	3.59758E+010		
JOBSET	2.68040E+012	9	2.97822E+011	8.27842	0
ORR	9.56079E+011	4	2.39020E+011	6.64391	.00003
DISPATCH	5.99729E+012	2	2.99865E+012	83.35186	0
LOCATION	2.46826E+011	2	1.23413E+011	3.43045	.03285
PREVALEN	1.38005E+010	1	1.38005E+010	.38361	.53586
ORR BY DISPATCH	1.74990E+012	8	2.18737E+011	6.08013	1.28794E-007
ORR BY LOCATION	2.53597E+011	8	3.16996E+010	.88114	.53184
ORR BY PREVALEN	4.40907E+010	4	1.10227E+010	.30639	.87377
DISPATCH BY LOCATION	3.46305E+011	4	8.65763E+010	2.40652	.04812
DISPATCH BY PREVALEN	4.12465E+010	2	2.06233E+010	.57325	.56392
LOCATION BY PREVALEN	2.45557E+010	2	1.22778E+010	.34128	.71096
ORR BY DISPATCH BY LOCATION	4.55232E+011	16	2.84520E+010	.79087	.69713
ORR BY DISPATCH BY PREVALEN	9.39617E+010	8	1.17452E+010	.32648	.95684
ORR BY LOCATION BY PREVALEN	1.08589E+011	8	1.35736E+010	.37730	.93284
DISPATCH BY LOCATION BY PREVALEN	2.84190E+010	4	7.10474E+009	.19749	.93971
ORR BY DISPATCH BY LOCATION BY PREVALEN	2.04140E+011	16	1.27588E+010	.35465	.99099
(MODEL)	1.32444E+013	98	1.35147E+011	3.75662	0
(TOTAL)	4.20610E+013	899	4.67865E+010		

R-SQUARED = .31489
ADJUSTED R-SQUARED = .23106

- -

TABLE C-6

ANALYSIS OF VARIANCE
(PERCENT OF JOBS TARDY : ORIGINAL MODEL)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR PERTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	192415.38334	801	240.21896		
JOBSET	138924.11667	9	15436.01296	64.25810	0
ORR	79462.68889	4	19865.67222	82.69819	0
DISPATCH	87988.14889	2	43994.07444	183.14156	0
LOCATION	3763.47556	2	1881.73778	7.83343	.00043
PREVALEN	1026.13444	1	1026.13444	4.27166	.03907
ORR BY DISPATCH	5024.65111	8	628.08139	2.61462	.00791
ORR BY LOCATION	9707.22444	8	1213.40306	5.05124	3.85114E-006
ORR BY PREVALEN	11810.93778	4	2952.73444	12.29185	0
DISPATCH BY LOCATION	1350.40444	4	337.60111	1.40539	.23032
DISPATCH BY PREVALEN	1042.10889	2	521.05444	2.16908	.11495
LOCATION BY PREVALEN	1211.20889	2	605.60444	2.52105	.08101
ORR BY DISPATCH BY LOCATION	8641.59556	16	540.09972	2.24836	.00348
ORR BY DISPATCH BY PREVALEN	976.60222	8	122.07528	.50818	.85072
ORR BY LOCATION BY PREVALEN	473.60222	8	59.20028	.24644	.98172
DISPATCH BY LOCATION BY PREVALEN	919.21778	4	229.80444	.95665	.43060
ORR BY DISPATCH BY LOCATION BY PREVALEN	1304.13778	16	81.50861	.33931	.99297
(MODEL)	353626.25555	98	3608.43118	15.02143	0
(TOTAL)	546041.63889	899	607.38781		

R-SQUARED = .64762
ADJUSTED R-SQUARED = .60450

\- -

TABLE D-1

SUMMARY TABLES FOR WORK-IN-PROCESS
(INVERSE MODEL: 10 OBSERVATIONS)

100% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	.0035	.0037	.0035	.0034	.0034	.0035
	SPT	.0068	.0069	.0068	.0066	.0068	.0068
	SOPN	.0038	.0040	.0039	.0038	.0038	.0039
Exit	FCFS	.0015	.0017	.0015	.0020	.0017	.0017
	SPT	.0051	.0051	.0050	.0056	.0052	.0052
	SOPN	.0019	.0021	.0021	.0031	.0023	.0022
Mixed	FCFS	.0014	.0018	.0015	.0019	.0017	.0017
	SPT	.0056	.0058	.0056	.0059	.0057	.0057
	SOPN	.0023	.0028	.0025	.0031	.0026	.0026
	Avg.	.0035	.0038	.0036	.0039	.0037	.0037

50% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	.0032	.0033	.0034	.0031	.0032	.0032
	SPT	.0073	.0075	.0074	.0066	.0069	.0071
	SOPN	.0041	.0040	.0042	.0035	.0038	.0039
Exit	FCFS	.0020	.0023	.0021	.0027	.0023	.0023
	SPT	.0057	.0059	.0057	.0063	.0060	.0059
	SOPN	.0026	.0028	.0027	.0035	.0032	.0030
Mixed	FCFS	.0018	.0023	.0019	.0025	.0020	.0021
	SPT	.0061	.0065	.0062	.0062	.0061	.0062
	SOPN	.0027	.0031	.0029	.0031	.0031	.0030
	Avg.	.0040	.0042	.0041	.0042	.0041	.0041

TABLE D-2

SUMMARY TABLES FOR MEAN FLOW TIME IN THE SHOP
(INVERSE MODEL: 10 OBSERVATIONS)

100% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	.0058	.0084	.0061	.0069	.0058	.0066
	SPT	.0118	.0114	.0110	.0116	.0112	.0114
	SOPN	.0068	.0077	.0068	.0077	.0067	.0071
Exit	FCFS	.0054	.0063	.0056	.0076	.0062	.0062
	SPT	.0116	.0115	.0113	.0120	.0115	.0116
	SOPN	.0068	.0069	.0067	.0077	.0072	.0071
Mixed	FCFS	.0051	.0067	.0051	.0067	.0057	.0058
	SPT	.0108	.0113	.0107	.0116	.0111	.0111
	SOPN	.0061	.0069	.0062	.0074	.0066	.0066
	Avg.	.0078	.0086	.0077	.0088	.0080	.0082

50% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	.0061	.0081	.0066	.0079	.0068	.0071
	SPT	.0119	.0121	.0116	.0118	.0116	.0118
	SOPN	.0073	.0078	.0074	.0079	.0077	.0076
Exit	FCFS	.0063	.0071	.0063	.0080	.0070	.0070
	SPT	.0122	.0121	.0119	.0121	.0120	.0121
	SOPN	.0081	.0080	.0079	.0073	.0080	.0079
Mixed	FCFS	.0056	.0071	.0057	.0077	.0066	.0066
	SPT	.0114	.0118	.0113	.0116	.0114	.0115
	SOPN	.0069	.0074	.0070	.0071	.0073	.0071
	Avg.	.0084	.0091	.0084	.0090	.0087	.0087

TABLE D-3

SUMMARY TABLES FOR VARIANCE OF FLOW TIME IN THE SHOP
(LOGARITHMIC MODEL: 10 OBSERVATIONS)

100% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	12.07	10.43	11.67	11.44	11.97	11.52
	SPT	9.72	9.42	9.71	9.01	9.56	9.48
	SOPN	9.76	8.88	9.52	9.18	9.60	9.39
Exit	FCFS	12.20	11.70	12.03	10.95	11.66	11.71
	SPT	9.78	9.75	9.80	9.13	9.65	9.62
	SOPN	9.70	9.38	9.72	8.52	9.26	9.32
Mixed	FCFS	12.34	11.51	12.31	11.54	12.09	11.96
	SPT	10.34	9.97	10.24	9.41	9.91	9.98
	SOPN	9.87	9.10	9.69	9.04	9.49	9.44
	Avg.	10.64	10.02	10.52	9.80	10.35	10.27

50% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	12.00	10.93	11.83	10.89	11.73	11.48
	SPT	9.91	9.56	9.85	8.95	9.41	9.54
	SOPN	9.63	9.03	9.45	9.02	9.17	9.26
Exit	FCFS	11.62	11.30	11.54	10.64	11.21	11.26
	SPT	9.50	9.46	9.52	8.96	9.29	9.35
	SOPN	9.52	9.33	9.56	8.84	9.09	9.27
Mixed	FCFS	12.23	11.62	12.19	10.90	11.73	11.73
	SPT	10.24	9.88	10.21	9.16	9.62	9.82
	SOPN	9.83	9.37	9.75	9.12	9.25	9.46
	Avg.	10.50	10.05	10.43	9.61	10.35	10.13

TABLE D-4

SUMMARY TABLES FOR MEAN TARDINESS
(LOGARITHMIC MODEL: 10 OBSERVATIONS)

100% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	4.44	4.75	4.37	4.17	4.44	4.44
	SPT	1.82	2.13	2.19	2.33	2.18	2.13
	SOPN	1.78	3.04	2.62	2.68	2.62	2.55
Exit	FCFS	4.52	4.28	4.50	4.25	4.35	4.38
	SPT	1.83	2.14	2.17	2.17	2.17	2.10
	SOPN	1.22	2.55	2.39	3.81	2.44	2.48
Mixed	FCFS	4.62	4.46	4.69	4.39	4.56	4.54
	SPT	2.40	2.46	2.53	2.84	2.61	2.57
	SOPN	2.03	3.22	2.73	3.38	2.81	2.83
	Avg.	2.74	3.23	3.13	3.34	3.13	3.11

50% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	4.33	4.46	4.27	4.39	4.44	4.38
	SPT	1.92	2.33	2.14	3.40	2.85	2.53
	SOPN	1.59	3.16	2.47	3.68	2.98	2.78
Exit	FCFS	4.18	4.05	4.25	4.68	4.14	4.26
	SPT	1.44	1.77	1.77	2.33	1.94	1.85
	SOPN	0.78	2.19	1.82	4.50	2.31	2.32
Mixed	FCFS	4.46	4.41	4.50	4.85	4.54	4.55
	SPT	2.14	2.41	2.31	3.39	2.94	2.64
	SOPN	1.84	3.06	2.57	4.44	3.26	3.04
	Avg.	2.52	3.09	2.90	3.96	3.27	3.15

TABLE D-5

SUMMARY TABLES FOR VARIANCE OF TARDINESS
(LOGARITHMIC MODEL: 10 OBSERVATIONS)

100% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	11.88	10.38	11.49	11.24	11.81	11.36
	SPT	8.48	8.30	8.59	7.84	8.46	8.33
	SOPN	5.90	7.22	6.81	6.89	6.81	6.72
Exit	FCFS	11.95	11.42	11.79	10.67	11.40	11.44
	SPT	8.36	8.50	8.54	7.71	8.36	8.29
	SOPN	4.83	6.24	6.13	7.93	6.24	6.27
Mixed	FCFS	12.09	11.33	12.09	11.32	11.89	11.75
	SPT	9.53	9.11	9.37	8.61	9.04	9.13
	SOPN	6.18	7.43	6.93	7.71	7.04	7.05
	Avg.	8.80	8.88	9.08	8.88	9.01	8.93

50% Prevalence		Order Review/Release Mechanism					
Loca.	Disp.	NOR	ART	ARL	BRT	BRL	Avg.
Front	FCFS	11.78	10.79	11.64	10.81	11.59	11.32
	SPT	8.73	8.51	8.74	8.55	8.56	8.62
	SOPN	5.83	7.40	6.80	8.21	7.31	7.11
Exit	FCFS	11.29	10.97	11.23	10.61	10.92	11.00
	SPT	7.69	7.88	7.88	7.61	7.67	7.75
	SOPN	4.63	6.30	5.93	8.70	6.30	6.37
Mixed	FCFS	11.98	11.42	11.99	10.93	11.58	11.58
	SPT	9.27	9.01	9.29	8.69	8.94	9.04
	SOPN	6.27	7.49	7.13	8.86	7.62	7.47
	Avg.	8.61	8.86	8.96	9.22	8.95	8.92

TABLE E-1

POWER OF THE F-TEST

Source of Variation	WIP	MFT	VFT	MTA	VTA	PTA
JOBSET	>.99	>.99	>.99	>.99	>.99	>.99
ORR	>.99	>.99	>.99	>.99	>.99	>.99
DISPATCHING	>.99	>.99	>.99	>.99	>.99	>.99
LOCATION	>.99	>.99	>.99	>.99	>.99	>.99
PREVALENCE	>.99	>.99	>.86	>.00	>.00	>.00

WHERE WIP : WORK-IN-PROCESS

MFT : MEAN FLOW TIME IN THE SHOP

VFT : VARIANCE OF FLOW TIME IN THE SHOP

MTA : MEAN TARDINESS

VTA : VARIANCE OF TARDINESS

PTA : PERCENT OF JOBS TARDY

Appendix F presents a multiple comparison test for the significant interaction effects for work-in-process using the Duncan procedure at the .05 protection level. Each group is compared schematically with other groups. Groups underlined by a common line do not differ from each other; groups not underlined by a common line do differ.

In addition, a probability associated with the F ratio and a homogeneity of variance test (Cochran's C) are also provided for each multiple comparison analysis.

Appendix G through K present the Duncan procedure for mean flow time in the shop, variance of flow time in the shop, mean tardiness, variance of tardiness, and percent of jobs tardy, respectively.

APPENDIX F: DUNCAN PROCEDURE FOR WORK-IN-PROCESS

I. Dispatching Rule * Location * Prevalence

a. Dispatching Rule for the Front Location and the 100% Prevalence
(F Prob. = .0000; Cochran's C = .4307, P = .126)

FCFS   SOPN   SPT

b. Dispatching Rule for the Exit Location and the 100% Prevalence
(F Prob. = .0000; Cochran's C = .6537, P = .000)

FCFS   SOPN   SPT

c. Dispatching Rule for the Mixed Location and the 100% Prevalence
(F Prob. = .0000; Cochran's C = .6506, P = .000)

FCFS   SOPN   SPT

d. Dispatching Rule for the Front Location and the 50% Prevalence
(F Prob. = .0000; Cochran's C = .4922, P = .008)

FCFS   SOPN   SPT

e. Dispatching Rule for the Exit Location and the 50% Prevalence
(F Prob. = .0000; Cochran's C = .5796, P = .000)

FCFS   SOPN   SPT

f. Dispatching Rule for the Mixed Location and the 50% Prevalence
(F Prob. = .0000; Cochran's C = .4998, P = .006)

FCFS   SOPN   SPT

g. Location for the FCFS Rule and the 100% Prevalence
(F Prob. = .0000; Cochran's C = .5218, P = .002)

Mixed   Exit   Front

h. Location for the SPT Rule and the 100% Prevalence
(F Prob. = .0000; Cochran's C = .5055, P = .004)

Exit   Mixed   Front

i. Location for the SOPN Rule and the 100% Prevalence
(F Prob. = .0000; Cochran's C = .4524, P = .054)

Exit Mixed Front

j. Location for the FCFS Rule and the 50% Prevalence
(F Prob. = .0000; Cochran's C = .3507, P = 1.000)

Mixed Exit Front

k. Location for the SPT Rule and the 50% Prevalence
(F Prob. = .0000; Cochran's C = .4041, P = .304)

Exit Mixed Front

l. Location for the SOPN Rule and the 50% Prevalence
(F Prob. = .0000; Cochran's C = .3498, P = 1.000)

Exit Mixed Front

II. Order Review/Release Mechanism * Location

a. Order Review/Release Mechanism for the Front Location
(F Prob. = .7110; Cochran's C = .2050, P = 1.000)

BRT BRL NOR ARL ART

b. Order Review/Release Mechanism for the Exit Location
(F Prob. = .0492; Cochran's C = .2511, P = .812)

NOR ARL ART BRL BRT

c. Order Review/Release Mechanism for the Mixed Location
(F Prob. = .6292; Cochran's C = .2189 P = 1.000)

NOR ARL BRL ART BRT

d. Location for the NOR Mechanism
(F Prob. = .0000; Cochran's C = .3682, P = .719)

Exit Mixed Front

e. Location for the ART Mechanism
(F Prob. = .0000; Cochran's C = .3526, P = 1.000)

Exit Mixed Front

f. Location for the ARL Mechanism
(F Prob. = .0000; Cochran's C = .3674, P = .732)

Exit Mixed Front

g. Location for the BRT Mechanism
(F Prob. = .0442; Cochran's C = .3562, P = .951)

Exit Mixed Front

h. Location for the BRL Mechanism
(F Prob. = .0004; Cochran's C = .3645, P = .788)

Exit Mixed Front

APPENDIX G: DUNCAN PROCEDURE FOR MEAN FLOW TIME IN THE SHOP

I. Order Review/Release Mechanism * Dispatching Rule

a. Order Review/Release Mechanism for the FCFS Rule
(F Prob. = .0000; Cochran's C = .3403, P = .000)

NOR ARL BRL ART BRT

b. Order Review/Release Mechanism for the SPT Rule
(F Prob. = .3649; Cochran's C = .2680, P = .125)

ARL BRL NOR ART BRT

c. Order Review/Release Mechanism for the SOPN Rule
(F Prob. = .3978; Cochran's C = .2807, P = .054)

NOR ARL BRL ART BRT

d. Dispatching Rule for the NOR Mechanism
(F Prob. = .0000; Cochran's C = .4374, P = .065)

FCFS SOPN SPT

e. Dispatching Rule for the ART Mechanism
(F Prob. = .0000; Cochran's C = .5039, P = .002)

FCFS SOPN SPT

f. Dispatching Rule for the ARL Mechanism
(F Prob. = .0000; Cochran's C = .4470, P = .042)

FCFS SOPN SPT

g. Dispatching Rule for the BRT Mechanism
(F Prob. = .0000; Cochran's C = .4196, P = .138)

FCFS SOPN SPT

h. Dispatching Rule for the BRL Mechanism
(F Prob. = .0000; Cochran's C = .4603, P = .022)

FCFS SOPN SPT

II. Order Review Release Mechanism * Location

a. Order Review/Release Mechanism for the Front Location
(F Prob. = .0479; Cochran's C = .2933, P = .022)

NOR ARL BRL BRT ART

b. Order Review/Release Mechanism for the Exit Location
(F Prob. = .5272; Cochran's C = .2508, P = .336)

ARL NOR BRL ART BRT

c. Order Review/Release Mechanism for the Mixed Location
(F Prob. = .1287; Cochran's C = .2556, P = .259)

NOR ARL BRL ART BRT

d. Location for the NOR Mechanism
(F Prob. = .3559; Cochran's C = .3429, P = 1.000)

Mixed Front Exit

e. Location for the ART Mechanism
(F Prob. = .0475; Cochran's C = .4183, P = .145)

Mixed Exit Front

f. Location for the ARL Mechanism
(F Prob. = .4137; Cochran's C = .3610, P = .855)

Mixed Front Exit

g. Location for the BRT Mechanism
(F Prob. = .5889; Cochran's C = .3510, P = 1.000)

Mixed Front Exit

h. Location for the BRL Mechanism
(F Prob. = .5397; Cochran's C = .3376, P = 1.000)

Mixed Front Exit

APPENDIX H: DUNCAN PROCEDURE FOR VARIANCE OF FLOW TIME IN THE SHOP

I. Order Review/Release Mechanism * Dispatching Rule

a. Order Review/Release Mechanism for the FCFS Rule
(F Prob. = .0000; Cochran's C = .3207, P = .002)

BRT ART BRL ARL NOR

b. Order Review/Release Mechanism for the SPT Rule
(F Prob. = .0000; Cochran's C = .2957, P = .018)

BRT BRL ART ARL NOR

c. Order Review/Release Mechanism for the SOPN Rule
(F Prob. = .0000; Cochran's C = .3153, P = .004)

BRT ART BRL ARL NOR

d. Dispatching Rule for the NOR Mechanism
(F Prob. = .0000; Cochran's C = .4848, P = .006)

SOPN SPT FCFS

e. Dispatching Rule for the ART Mechanism
(F Prob. = .0000; Cochran's C = .5395, P = .000)

SOPN SPT FCFS

f. Dispatching Rule for the ARL Mechanism
(F Prob. = .0000; Cochran's C = .4961, P = .003)

SOPN SPT FCFS

g. Dispatching Rule for the BRT Mechanism
(F Prob. = .0000; Cochran's C = .4724, P = .011)

SOPN SPT FCFS

h. Dispatching Rule for the BRL Mechanism
(F Prob. = .0000; Cochran's C = .5432, P = .000)

SOPN SPT FCFS

II. Order Review Release Mechanism * Location

a. Order Review/Release Mechanism for the Front Location
(F Prob. = .0005; Cochran's C = .2690, P = .117)

ART BRT BRL ARL NOR

b. Order Review/Release Mechanism for the Exit Location
(F Prob. = .0006; Cochran's C = .2491, P = .368)

BRT BRL ART ARL NOR

c. Order Review/Release Mechanism for the Mixed Location
(F Prob. = .0004; Cochran's C = .2491, P = .366)

ART ART BRL ARL NOR

d. Location for the NOR Mechanism
(F Prob. = .2534; Cochran's C = .3613, P = 1.000)

Exit Front Mixed

e. Location for the ART Mechanism
(F Prob. = .0187; Cochran's C = .4156, P = .161)

Front Exit Mixed

f. Location for the ARL Mechanism
(F Prob. = .2033; Cochran's C = .3865, P = .434)

Front Exit Mixed

g. Location for the BRT Mechanism
(F Prob. = .1944; Cochran's C = .3754, P = .597)

Exit Front Mixed

h. Location for the BRL Mechanism
(F Prob. = .3791; Cochran's C = .3726, P = .642)

Exit Front Mixed

APPENDIX I: DUNCAN PROCEDURE FOR MEAN TARDINESS

I. Order Review/Release Mechanism * Dispatching Rule

a. Order Review/Release Mechanism for the FCFS Rule
(F Prob. = .9911; Cochran's C = .2807, P = .054)

ART BRL NOR ARL BRT

b. Order Review/Release Mechanism for the SPT Rule
(F Prob. = .0003; Cochran's C = .2959, P = .018)

NOR ARL ART BRL BRT

c. Order Review/Release Mechanism for the SOPN Rule
(F Prob. = .0000; Cochran's C = .3054, P = .009)

NOR ARL BRL ART BRT

d. Dispatching Rule for the NOR Mechanism
(F Prob. = .0000; Cochran's C = .7877, P = .000)

SOPN SPT FCFS

e. Dispatching Rule for the ART Mechanism
(F Prob. = .0000; Cochran's C = .7130, P = .000)

SPT SOPN FCFS

f. Dispatching Rule for the ARL Mechanism
(F Prob. = .0000; Cochran's C = .7373, P = .000)

SPT SOPN FCFS

g. Dispatching Rule for the BRT Mechanism
(F Prob. = .0000; Cochran's C = .5742, P = .000)

SPT SOPN FCFS

h. Dispatching Rule for the BRL Mechanism
(F Prob. = .0000; Cochran's C = .6702, P = .000)

SPT SOPN FCFS

II. Order Review Release Mechanism * Prevalence

a. Order Review/Release Mechanism for the 100% Prevalence
(F Prob. = .0428; Cochran's C = .3184, P = .000)

NOR BRL ARL ART BRT

b. Order Review/Release Mechanism for the 50% Prevalence
(F Prob. = .0000; Cochran's C = .2884, P = .006)

NOR BRL ART BRL BRT

c. Prevalence for the NOR Mechanism
(F Prob. = .4446; Cochran's C = .5165, P = .757)

100% 50%

d. Prevalence for the ART Mechanism
(F Prob. = .5597; Cochran's C = .5563, P = .288)

100% 50%

e. Prevalence for the ARL Mechanism
(F Prob. = .2887; Cochran's C = .5365, P = .492)

100% 50%

f. Prevalence for the BRT Mechanism
(F Prob. = .0034; Cochran's C = .5448, P = .398)

100% 50%

g. Prevalence for the BRL Mechanism
(F Prob. = .5399; Cochran's C = .5680, P = .198)

100% 50%

III. Location * Prevalence

a. Location for the 100% Prevalence
(F Prob. = .1315; Cochran's C = .3828, P = .182)

Exit Front Mixed

b. Location for the 50% Prevalence
(F Prob. = .0072; Cochran's C = .3658, P = .455)

Exit Front Mixed

c. Prevalence for the Front Location
(F Prob. = .2879; Cochran's C = .5345, P = .400)

100% 50%

d. Prevalence for the Exit Location
(F Prob. = .3656; Cochran's C = .5426, P = .299)

100% 50%

e. Prevalence for the Mixed Location
(F Prob. = .6051; Cochran's C = .5856, P = .036)

100% 50%

APPENDIX J: DUNCAN PROCEDURE FOR VARIANCE OF TARDINESS

I. Order Review/Release Mechanism * Dispatching Rule

a. Order Review/Release Mechanism for the FCFS Rule
(F Prob. = .0000; Cochran's C = .3203, P = .002)

BRT ART BRL ARL NOR

b. Order Review/Release Mechanism for the SPT Rule
(F Prob. = .3949; Cochran's C = .2613, P = .187)

NOR ARL ART BRL BRT

c. Order Review/Release Mechanism for the SOPN Rule
(F Prob. = .0000; Cochran's C = .3235, P = .002)

NOR ARL BRL ART BRT

d. Dispatching Rule for the NOR Mechanism
(F Prob. = .0000; Cochran's C = .6244, P = .000)

SOPN SPT FCFS

e. Dispatching Rule for the ART Mechanism
(F Prob. = .0000; Cochran's C = .6016, P = .000)

SOPN SPT FCFS

f. Dispatching Rule for the ARL Mechanism
(F Prob. = .0000; Cochran's C = .4980, P = .002)

SOPN SPT FCFS

g. Dispatching Rule for the BRT Mechanism
(F Prob. = .0000; Cochran's C = .6223, P = .000)

SOPN SPT FCFS

h. Dispatching Rule for the BRL Mechanism
(F Prob. = .0000; Cochran's C = .5825, P = .000)

SOPN SPT FCFS

II. Dispatching Rule * Prevalence

a. Dispatching Rule for the 100% Prevalence
(F Prob. = .0000; Cochran's C = .5627, P = .000)

SOPN SPT FCFS

b. Dispatching Rule for the 50% Prevalence
(F Prob. = .0000; Cochran's C = .6338, P = .000)

SOPN SPT FCFS

c. Prevalence for the FCFS Rule
(F Prob. = .0807; Cochran's C = .5072, P = .861)

100% 50%

d. Prevalence for the SPT
(F Prob. = .5520; Cochran's C = .5227, P = .580)

100% 50%

e. Prevalence for the SOPN Rule
(F Prob. = .2898; Cochran's C = .5914, P = .025)

100% 50%

APPENDIX K: DUNCAN PROCEDURE FOR PERCENT OF JOBS TARDY

I. Order Review/Release Mechanism * Dispatching Rule * Location

a. Order Review/Release Mechanism for the FCFS Rule and the Front Location
(F Prob. = .0000; Cochran's C = .5299, P = .000)

NOR ARL BRL BRT ART

b. Order Review/Release Mechanism for the SPT Rule and the Front Location
(F Prob. = .0000; Cochran's C = .4830, P = .000)

NOR ARL ART BRL BRT

c. Order Review/Release Mechanism for the SOPN Rule and the Front Location
(F Prob. = .0427; Cochran's C = .2704, P = .582)

NOR ARL BRL BRT ART

d. Order Review/Release Mechanism for the FCFS Rule and the Exit Location
(F Prob. = .0000; Cochran's C = .8691, P = .000)

NOR ART ARL BRL BRT

e. Order Review/Release Mechanism for the SPT Rule and the Exit Location
(F Prob. = .0000; Cochran's C = .7399, P = .000)

NOR ART ARL BRL BRT

f. Order Review/Release Mechanism for the SOPN Rule and the Exit Location
(F Prob. = .0000; Cochran's C = .2450, P = 1.000)

NOR ARL ART BRL BRT

g. Order Review/Release Mechanism for the FCFS Rule and the Mixed Location
(F Prob. = .0000; Cochran's C = .4357, P = .001)

NOR ARL BRL ART BRT

h. Order Review/Release Mechanism for the SPT Rule and the Mixed Location
(F Prob. = .0000; Cochran's C = .5884, P = .000)

NOR ARL ART BRL BRT

i. Order Review/Release Mechanism for the SOPN Rule and the Mixed Location
(F Prob. = .0029; Cochran's C = .2870, P = .376)

NOR ARL BRL ART BRT

j. Dispatching Rule for the NOR Mechanism and the Front Location (F Prob. = .0001; Cochran's C = .9867, P = .000)

SPT FCFS SOPN

k. Dispatching Rule for the ART Mechanism and the Front Location (F Prob. = .0001; Cochran's C = .4686, P = .202)

SPT SOPN FCFS

l. Dispatching Rule for the ARL Mechanism and the Front Location (F Prob. = .0001; Cochran's C = .8542, P = .000)

SPT FCFS SOPN

m. Dispatching Rule for the BRT Mechanism and the Front Location (F Prob. = .2834; Cochran's C = .4244, P = .454)

SPT FCFS SOPN

n. Dispatching Rule for the BRL Mechanism and the Front Location (F Prob. = .0452; Cochran's C = .4943, P = .116)

SPT FCFS SOPN

o. Dispatching Rule for the NOR Mechanism and the Exit Location (F Prob. = .0005; Cochran's C = .9907, P = .000)

SPT FCFS SOPN

p. Dispatching Rule for the ART Mechanism and the Exit Location (F Prob. = .0000; Cochran's C = .9848, P = .000)

SPT FCFS SOPN

q. Dispatching Rule for the ARL Mechanism and the Exit Location (F Prob. = .0002; Cochran's C = .9910, P = .000)

SPT FCFS SOPN

s. Dispatching Rule for the BRT Mechanism and the Exit Location (F Prob. = .0000; Cochran's C = .4809, P = .156)

SPT FCFS SOPN

t. Dispatching Rule for the BRL Mechanism and the Exit Location (F Prob. = .0015; Cochran's C = .8326, P = .000)

SPT FCFS SOPN

u. Dispatching Rule for the NOR Mechanism and the Mixed Location (F Prob. = .0000; Cochran's C = .9846, P = .000)

SPT FCFS SOPN

v. Dispatching Rule for the ART Mechanism and the Mixed Location (F Prob. = .0002; Cochran's C = .6316, P = .002)

SPT FCFS SOPN

w. Dispatching Rule for the ARL Mechanism and the Mixed Location (F Prob. = .0000; Cochran's C = .9370, P = .000)

SPT FCFS SOPN

x. Dispatching Rule for the BRT Mechanism and the Mixed Location (F Prob. = .0190; Cochran's C = .4791, P = .162)

SPT FCFS SOPN

y. Dispatching Rule for the BRL Mechanism and the Mixed Location (F Prob. = .0259; Cochran's C = .5961, P = .007)

SPT FCFS SOPN

II. Order Review/Release Mechanism * Prevalence

a. Order review/Release Mechanism for the 100% Prevalence
(F Prob. = .0000; Cochran's C = .3200, P = .000)

NOR ARL BRL ART BRT

a. Order review/Release Mechanism for the 50% Prevalence
(F Prob. = .0000; Cochran's C = .3506, P = .000)

NOR ARL ART BRL BRT

c. Prevalence for the NOR Mechanism
(F Prob. = .1117; Cochran's C = .6554, P = .003)

100% 50%

d. Prevalence for the ART Mechanism
(F Prob. = .5342; Cochran's C = .5002, P = .997)

100% 50%

e. Prevalence for the ARL Mechanism
(F Prob. = .0920; Cochran's C = .5765, P = .148)

100% 50%

f. Prevalence for the BRT Mechanism
(F Prob. = .0009; Cochran's C = .6164, P = .026)

100% 50%

g. Prevalence for the BRL Mechanism
(F Prob. = .0413; Cochran's C = .5680, P = .198)

100% 50%

TABLE L-1

ANALYSIS OF VARIANCE
(WORK-IN-PROCESS: BOTTLENECK JOBS)

A N A L Y S I S   O F   V A R I A N C E

TESTS OF SIGNIFICANCE FOR BWIP USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	1838633.54692	396	4643.01401		
JOBSET	863095.26811	9	95899.47423	20.65457	0
ORR	252687.52956	4	63171.88239	13.60579	0
DISPATCH	2875873.68444	2	1437936.84222	309.69901	0
LOCATION	837786.54858	2	418893.27429	90.22012	0
ORR BY DISPATCH	173888.47911	8	21736.05989	4.68145	.00002
ORR BY LOCATION	235899.53768	8	29487.44221	6.35093	0.92064E-007
DISPATCH BY LOCATION	358169.15956	4	89542.28989	19.28538	0
ORR BY DISPATCH BY LOCATION	135657.56889	16	8478.59806	1.82610	.02616
(MODEL)	5733057.77588	53	108170.90143	23.29756	0
(TOTAL)	7571691.32280	449	16863.45506		

R-SQUARED = .75717
ADJUSTED R-SQUARED = .72467

TABLE L-2

ANALYSIS OF VARIANCE
(MEAN FLOW TIME IN THE SHOP: BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR BMFLSP USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	964161.86357	396	2434.75816		
JOBSET	507653.63744	9	56405.95972	23.16784	0
ORR	226247.66778	4	56561.91694	23.23110	0
DISPATCH	799919.81564	2	399959.90782	164.27144	0
LOCATION	51130.49924	2	25565.24962	10.50015	.00004
ORR BY DISPATCH	109863.99102	8	13732.99888	5.64041	0.58619E-007
ORR BY LOCATION	29175.17342	8	3646.89668	1.49785	.15599
DISPATCH BY LOCATION	20114.87022	4	5028.71756	2.06539	.08462
ORR BY DISPATCH BY LOCATION	15397.09778	16	962.31861	.39524	.98339
(MODEL)	1759502.75255	53	33198.16514	13.63514	0
(TOTAL)	2723663.81613	449	6066.06641		

R-SQUARED = .64601
ADJUSTED R-SQUARED = .59863

TABLE L-3

ANALYSIS OF VARIANCE
(VARIANCE OF FLOW TIME IN THE SHOP: BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * * * * *

TESTS OF SIGNIFICANCE FOR BVARFLSP USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	5.42556E+013	396	1.37009E+011		
JOBSET	4.46502E+012	9	4.96114E+011	3.62193	.00023
DRR	2.90712E+012	4	7.26780E+011	5.30461	.00036
DISPATCH	9.42630E+012	2	4.71315E+012	34.40027	0
LOCATION	7.30954E+011	2	3.65477E+011	2.66754	.07067
DRR BY DISPATCH	4.09798E+012	8	5.12249E+011	3.73879	.00031
DRR BY LOCATION	7.37308E+011	8	9.21635E+010	.67268	.71569
DISPATCH BY LOCATION	1.04532E+012	4	2.61330E+011	1.90739	.10840
DRR BY DISPATCH BY LOCATION	1.11402E+012	16	6.96260E+010	.50819	.94300
(MODEL)	2.45240E+013	53	4.62717E+011	3.37727	0
(TOTAL)	7.87796E+013	449	1.75456E+011		

R-SQUARED = .31130
ADJUSTED R-SQUARED = .21912

- -

TABLE L-4

ANALYSIS OF VARIANCE
(MEAN TARDINESS: BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR BMEANTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	1861986.68988	396	4701.98659		
JOBSET	1851444.13913	9	205716.01546	43.75097	0
ORR	169675.24147	4	42418.81037	9.02147	5.55530E-007
DISPATCH	949703.61880	2	474851.80940	100.98961	0
LOCATION	130188.91853	2	65094.45927	13.84403	1.54345E-006
ORR BY DISPATCH	124867.50653	8	15608.43832	3.31954	.00109
ORR BY LOCATION	49598.46680	8	6199.80835	1.31855	.23237
DISPATCH BY LOCATION	28829.14507	4	7207.28627	1.53282	.19193
ORR BY DISPATCH BY LOCATION	56305.74760	16	3519.10922	.74843	.74366
(MODEL)	3360612.78393	53	63407.78838	13.48532	0
(TOTAL)	5222599.47380	449	11631.62466		

R-SQUARED = .64349
ADJUSTED R-SQUARED = .59576

- -

TABLE L-5

ANALYSIS OF VARIANCE
(VARIANCE OF TARDINESS: BOTTLENECK JOBS)

* * * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * * * * *

TESTS OF SIGNIFICANCE FOR BVARTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	5.17419E+013	396	1.30661E+011		
JOBSET	4.45152E+012	9	4.94613E+011	3.78546	.00014
ORR	2.22169E+012	4	5.55422E+011	4.25085	.00222
DISPATCH	8.52362E+012	2	4.26181E+012	32.61723	0
LOCATION	7.43555E+011	2	3.71778E+011	2.84535	.05930
ORR BY DISPATCH	3.78155E+012	8	4.72694E+011	3.61770	.00045
ORR BY LOCATION	6.38229E+011	8	7.97787E+010	.61058	.76912
DISPATCH BY LOCATION	1.02774E+012	4	2.56935E+011	1.96642	.09866
ORR BY DISPATCH BY LOCATION	1.06378E+012	16	6.64864E+010	.50865	.94267
(MODEL)	2.24517E+013	53	4.23617E+011	3.24216	0
(TOTAL)	7.41936E+013	449	1.65242E+011		

R-SQUARED = .30261
ADJUSTED R-SQUARED = .20927

\- -

TABLE L-6

ANALYSIS OF VARIANCE
(PERCENT OF JOBS TARDY: BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * * * * *

TESTS OF SIGNIFICANCE FOR BPERTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	113143.12445	396	285.71496		
JOBSET	118877.17556	9	13208.57506	46.22990	0
ORR	49472.65333	4	12368.16333	43.28847	0
DISPATCH	56796.76000	2	28398.38000	99.39416	0
LOCATION	5688.28000	2	2844.14000	9.95447	.00006
ORR BY DISPATCH	1730.10667	8	216.26333	.75692	.64108
ORR BY LOCATION	3999.18667	8	499.89833	1.74964	.08551
DISPATCH BY LOCATION	1989.40000	4	497.35000	1.74072	.14019
ORR BY DISPATCH BY LOCATION	5694.93333	16	355.93333	1.24576	.22993
(MODEL)	244248.49556	53	4608.46218	16.12958	0
(TOTAL)	357391.62000	449	795.97243		

R-SQUARED = .68342
ADJUSTED R-SQUARED = .64105

TABLE M-1

ANALYSIS OF VARIANCE
(WORK-IN-PROCESS: NON-BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * * * * * * * * * *

TESTS OF SIGNIFICANCE FOR NWIP USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	144385.99014	396	364.61109		
JOBSET	158198.43487	9	17577.60387	48.20919	0
ORR	22722.20498	4	5680.55124	15.57975	0
DISPATCH	566169.94484	2	283084.97242	776.40254	0
LOCATION	7945.16124	2	3972.58062	10.89539	.00002
ORR BY DISPATCH	4227.81782	8	528.47723	1.44943	.17419
ORR BY LOCATION	4034.49809	8	504.31226	1.38315	.20194
DISPATCH BY LOCATION	24510.50969	4	6127.62742	16.80593	0
ORR BY DISPATCH BY LOCATION	5595.86031	16	349.74127	.95922	.50120
(MODEL)	793404.43184	53	14969.89494	41.05716	0
(TOTAL)	937790.42199	449	2088.62009		

R-SQUARED = .84604
ADJUSTED R-SQUARED = .82543

- -

TABLE M-2

ANALYSIS OF VARIANCE
(MEAN FLOW TIME IN THE SHOP: NON-BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR MMFLSP USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	68811.37214	396	173.76609		
JOBSET	62295.80687	9	6921.75632	39.83376	0
DDR	28854.95053	4	7213.73763	41.51497	0
DISPATCH	145827.71613	2	72913.85807	419.60924	0
LOCATION	3037.65373	2	1518.82687	8.74064	.00019
DDR BY DISPATCH	9688.52187	8	1211.06523	6.96951	1.31521E-008
DDR BY LOCATION	1810.14893	8	226.26862	1.30214	.24066
DISPATCH BY LOCATION	18797.92013	4	4699.48003	27.04486	0
DDR BY DISPATCH BY LOCATION	5921.06187	16	370.06637	2.12968	.00683
(MODEL)	276233.78007	53	5211.95811	29.99410	0
(TOTAL)	345045.15221	449	768.47473		

R-SQUARED = .83057
ADJUSTED R-SQUARED = .77398

\- -

TABLE M-3

ANALYSIS OF VARIANCE
(VARIANCE OF FLOW TIME IN THE SHOP: NON-BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR NVARFLSR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	1.86535E+010		39647104757.09819		
JOBSET	7.43778E+009		9826420211.4384	17.54430	0
ORR	3.83263E+009		4958156485.7599	20.34097	0
DISPATCH	4.44939E+010	2	2.22469E+010	472.29657	0
LOCATION	1.23123E+009		2615614547.1734	13.06905	3.18893E-006
ORR BY DISPATCH	1.61056E+009		8201320297.3959	4.27366	.00006
ORR BY LOCATION	648917733.45376		881114716.68172	1.72201	.09153
DISPATCH BY LOCATION	3.53422E+009		4883554642.1549	18.75723	0
ORR BY DISPATCH BY LOCATION	649508032.84244		1640594252.05265	.86179	.61421
(MODEL)	6.34387E+010	53	1.19696E+009	25.41054	0
(TOTAL)	8.20922E+010		449182833443.1356		

R-SQUARED = .77277
ADJUSTED R-SQUARED = .74236

* *

TABLE M-4

ANALYSIS OF VARIANCE
(MEAN TARDINESS: NON-BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR NMEANTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	1545027.75543	396	3901.58524		
JOBSET	200135.30358	9	88903.02262	22.78662	0
ORR	676231.84369	4	169057.96092	42.33058	0
DISPATCH	184393.00938	2	92196.50469	23.63052	0
LOCATION	24667.25551	2	12333.62776	3.16118	.04345
ORR BY DISPATCH	115673.89818	8	14459.23627	3.70599	.00034
ORR BY LOCATION	95907.47004	8	11988.43376	3.07271	.00227
DISPATCH BY LOCATION	10831.90756	4	2707.97689	.69407	.59640
ORR BY DISPATCH BY LOCATION	71053.21089	16	4440.82568	1.13821	.31707
(MODEL)	1978893.89882	53	37337.62058	9.56986	0
(TOTAL)	3523921.64625	449	7848.37783		

R-SQUARED = .56156
ADJUSTED R-SQUARED = .50288

- -

TABLE M-5

ANALYSIS OF VARIANCE
(VARIANCE OF TARDINESS: NON-BOTTLENECK JOBS)

* A N A L Y S I S O F V A R I A N C E *

TESTS OF SIGNIFICANCE FOR NVARTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	3.26250E+010		39682386459.57597		
ORSET	1.95818E+010	9	2.17575E+009	26.40910	0
IIR	1.67076E+010	4	4.17690E+009	50.69899	0
DISPATCH	3.17950E+010	2	1.58975E+010	192.96233	0
LOCATION	933546159.79915		2466773079.8996	5.66565	.00375
IRR BY DISPATCH	2.62030E+009		8327537577.5538	3.97552	.00015
IRR BY LOCATION	2.31550E+009		8289437105.3883	3.51316	.00061
DISPATCH BY LOCATION	1.37930E+009		4344924696.6482	4.18545	.00249
IRR BY DISPATCH BY LOCATION	1.30772E+009		1581732441.29095	.99206	.46444
(MODEL)	7.66407E+010	53	1.44605E+009	17.55205	0
(TOTAL)	1.09266E+011		449243353546.9210		

R-SQUARED = .70142
ADJUSTED R-SQUARED = .66145

\- -

TABLE M-6

ANALYSIS OF VARIANCE
(PERCENT OF JOBS TARDY: NON-BOTTLENECK JOBS)

* A N A L Y S I S   O F   V A R I A N C E *

TESTS OF SIGNIFICANCE FOR NPERTAR USING SEQUENTIAL SUMS OF SQUARES

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIG. OF F
RESIDUAL	97820.43556	396	247.02130		
JOBSET	77976.46444	9	8664.05160	35.07411	0
PR	97120.54222	4	24280.13556	98.29167	0
DISPATCH	23692.89333	2	11846.44667	47.95719	0
LOCATION	3698.17333	2	1849.08667	7.48554	.00064
PR BY DISPATCH	8765.81778	8	1095.72722	4.43576	.00004
PR BY LOCATION	6925.20444	8	865.65056	3.50436	.00063
DISPATCH BY LOCATION	1158.97333	4	289.74333	1.17295	.32219
PR BY DISPATCH BY LOCATION	6370.31556	16	398.14472	1.61179	.06274
(MODEL)	225708.39444	53	4258.64876	17.24001	0
(TOTAL)	323528.82000	449	720.55416		

R-SQUARED = .69765
ADJUSTED R-SQUARED = .65718

\- -

LIST OF REFERENCES

LIST OF REFERENCES

Aggarwal, S.C., "MRP, JIT, OPT, FMS?," Harvard Business Review, September-October, 1985, 8-16.

Ahn, Y.J., S.A. Melnyk, and G.R. Ragatz, "Managing the Bottleneck Job Shop Through the Use of Dispatching Rules," 1987 Midwest DSI Conference Proceedings, 99-101.

Anderson, V.L. and R.A. McLean, Design of Experiments: A Realistic Approach, Marcel Dekker, Inc., 1974.

Baker, C.T. and B.P. Dzielinski, "Simulation of a Simplified Job Shop," Management Science, Vol. 6, No. 3, 1960, 311-323.

Baker, K.R., Introduction To Sequencing and Scheduling, John Wiley & Sons., 1974.

Baker, K.R., "The Effects of Input Control In a Simple Scheduling Model," Journal of Operations Management, Vol. 4, No. 2, 1984, 99-112

Baker, K.R. and J.W.M. Bertrand, "A Comparison of Due Date Selection Rules," AIIE Transactions, Vol. 13, No. 2, 1981, 123-131.

Bechte, W., "Controlling Manufacturing Lead Time and Work-in-Process Inventory by Means of Load-Oriented Release," 1982 APICS Conference Proceedings, 67-72.

Bertrand, J.W.M., "The Use of Workload Information to Control Job Lateness in Controlled and Uncontrolled Release Production Systems," Journal of Operations Management, Vol. 3, No. 2, 1983, 79-92.

Billington, P.J., "Cost Implications of a Bottleneck in Multilevel Production Systems," 1985 AIDS Proceedings, 803-805.

Billington, P.J., J.O. McClain, and L.J. Thomas, "Heuristics For Multilevel Lot-Sizing With A Bottleneck," Management Science, Vol. 32, No. 8, 1986, 989-1006.

Blackstone, J.H., D.T. Phillips, and G.L. Hogg, "A State-of-the-Art Survey of Dispatching Rules for Manufacturing Job Shop Performance," International Journal of Production Research, Vol. 20, No. 1, 1982, 27-45.

Cochran W.G. and G.M. Cox, Experimental Design, Second Edition, John Wiley & Sons., 1957.

Conway, R.W., "Some Tactical Problems in Digital Simulation," Management Science, Vol. 10, No. 1, 1963, 47-61.

Conway, R.W., "Priority Dispatching and Work-In-Process Inventory in a Job Shop," Journal of Industrial Engineering, Vol. 16, No. 2, 1965, 123-130.

Conway, R.W.. and W.L. Maxwell, "Network Dispatching By The Shortest Operation Discipline," Operations Research, Vol. 10, No. 1, 1962, 51-73.

Conway, R.W., W.L. Maxwell, and L.W. Miller, Theory of Scheduling, Reading, Massachusetts: Addison-Wesley, 1967.

Davis, E.W., "Project Scheduling under Resource Constraints - Historical Review and Categorization of Procedures," AIIE Transactions, Vol. 5, No. 4, 1973, 297-312.

Deane, R.H. and C.L. Moodie, "A Dispatching Methodology for Balancing Workload Assignments in a Job Shop Production Facility," AIIE Transactions, Vol. 4, No. 4, 1972, 277-283.

Elvers, D.A., "Job Shop Dispatching Rules Using Various Delivery Setting Criteria," Production and Inventory Management, Vol. 14, No. 4, 1973, 62-69.

Elvers, D.A., "The Sensitivity of the Relative Effectiveness of Job Shop Dispatching Rules with Respect to Various Arrival Distribution," AIIE Transactions, Vol. 6, No. 1, 1974, 41-49.

Fishman, G.S., "Grouping Observations in Digital Simulation," Management Science, Vol. 24, No. 5, 1978, 510-521.

Fogarty, D.W. and T.R. Hoffmann, Production and Inventory Management, South-Western Publishing Co., 1983.

Fox, R.F., "MRP, Kanban, or OPT: What's Best?", Inventories and Production Magazine, July-August, 1982a.

Fox, R.F., "OPT An Answer for America: Part II," Inventories and Production Magazine, November-December, 1982b.

Goldratt, E.M. and J. Cox, The Goal: Excellence In Manufacturing, North River Press, Inc., 1984.

Harty, J.D., "Controlling Production Capacity," 1969 APICS Conference Proceedings, 60-64.

Huang, P.Y., L.P. Rees, and B.W. Taylor, "A Simulation Analysis of the Japanese Just-In-Time Technique (with Kanbans) for a Multiline, Multistage Production System," Decision Sciences, Vol. 14, No. 1, 1983, 326-344.

Irastorza, J.C. and R.H. Deane, "A Loading and Balancing Methodology for Job Shop Control," AIIE Transactions, Vol. 6, No. 4, 1974, 302-307.

Irastorza, J.C. and R.H. Deane, "Starve the Shop: Reduce Work-in-Process," Production and Inventory Management, Vol. 17, No. 2, 1976, 20-25.

Jacobs, F.R., "The OPT Scheduling System: A Review of a New Production Scheduling System," Production and Inventory Management, Vol. 24, No. 3, 1983, 47-51.

Kaczka, E.E., "Computer Simulation," Decision Sciences, Vol. 1, No. 1, 1970, 174-192.

Kempthorne O., The Design and Analysis of Experiments, John Wiley & Sons, Inc., 1966.

Kleijnen, J.P.C., Statistical Techniques in Simulation, New york: Marcel Dekker, 1974.

Lundrigan, R., "What Is This Thing Called OPT?", Production and Inventory Management, Vol. 27, No. 2, 1986, 2-12.

Meleton, M.P., "OPT-Fantasy or Breakthrough?," Production and Inventory Management, Vol. 27, No. 2, 1986, 13-21.

Melnyk, S.A. and P.L. Carter, The Principles and Practices of Shop Floor Control: The Second Stage Lessons From The "Leading Edge", A Report Submitted to The Educational and Research Foundation of The APICS, 1987.

Melnyk, S.A., P.L. Carter, D.M. Dilts, and D.K Lyth, Shop Floor Control, Homewood Illinois: Dow&Jones-Irwin, 1985.

Neter J. and W. Wasserman, Applied Linear Statistical Models, R.D. Irwin, Inc., 1974.

Nicholson T.A.J. and R.D. Pullen, "A Practical Control System for Optimizing Production Schedules," International Journal of Production Research, Vol. 9, No. 2, 1971, 219-227.

Ow, P.S., "Focused Scheduling in Proportionate Flowshops," Management Science, Vol. 31, No. 7, 1985, 852-869

Prather, K.L., "Seven Deadly Sins of Production Control", 1983 APICS Conference Proceedings, 218-220.

Pritsker, A.A.B., Introduction to Simulation and SLAMII, New York: Halsted Press Division of John Wiley and Sons, Inc., 1984.

Ragatz, G.L., An Evaluation of Order Release Mechanisms for Job Shops, Unpublished Dissertation, Indiana University, 1985.

Sandman, W.E. and J.P. Hayes, How To Win Productivity in Manufacturing, Yellow Book of Pennsylvania, 1980.

Shannon, R.E., Systems Simulation: The Art and Science, Prentice-Hall, Inc., 1975.

Scheffe, H., The Analysis of Variance, New York: John Wiley, 1959.

Schonberger, R.J., "Clearest-Road-Ahead Priorities For Shop Floor Control: Moderating Infinite-Capacity loading Uneveness," Production and Inventory Management, Vol. 20, No. 2, 1979, 17-27.

Solberg, J.J., "Capacity Planning with a Stochastic Workflow Model," AIIE Transactions, Vol. 12, No. 2, 1981, 116-122.

Vollmann, T.E., "OPT As An Enhancement To MRP II," Production and Inventory Management, Vol. 27, No. 2, 1986, 38-46.

Walker, H.M. and J. Lev, Statistical Inference, Henry Holt and Company, 1953.

Wallace, T.F., APICS dictionary, Fifth Edition, American Production and Inventory Control Society, Inc., 1984.

Wight, O.W., "Input/Output Control: A Real Handle on Lead Time," Production and Inventory Management, Vol. 11, No. 3, 1970, 9-31.

Wight, O.W., Production and Inventory Management in the Computer Age, Van Nosyrand Reinhold Company, 1974.

Winer, B.J., Statistical Principles In Experimental Design, McGraw-Hill Book Co., 1971.