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Improving Job Shop Performance Through
Utilization of System Information In
Process Queue Management Under Transfer Batching

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Joel Arden Litchfield

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Improving Job Shop Performance Through Utilization of System Information in Process Queue Management Under Transfer Batching

By

Joel Ardon Litchfield

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ABSTRACT

Improving Job Shop Performance Through Utilization of System Information in Process Queue Management Under Transfer Batching

By

Joel Ardon Litchfield

Transfer batching is a shop floor in-process material flow practice that divides a release batch into an integer number of smaller batches for movement among processing stations. Previous research has shown that this approach, along with the Shortest Processing Time (SPT) queue management rule, dramatically reduces mean flow time. In this approach, the sequential processing of all transfer batches of the release batch at each processing station, or continuity of the release batch, is not specifically maintained. Disruption of continuity of a release batch requires additional setups at processing stations and increases the delay time between completion of the first and the last release batch of a transfer batch.

The question this dissertation investigated was whether any value or penalty is associated with protecting the continuity of the release batch, through a modification to

the SPT queue management rule, under a variety of job shop conditions. If a change in job shop performance is found, then the job shop environmental conditions that influence the performance change were to be identified. The study evaluated four job shop environmental factors for their impact on the value of protecting continuity of release batches.

To maintain continuity of release batches, the SPT queue management rule was modified in the following manner. Batches are selected for processing at a work station by first choosing a batch requiring the existing setup. If one is not available in the queue, all jobs in the queue that can be continuously supported throughout release batch processing by arrivals from the preceding station or by transfer batches already in the queue are identified. From that list of jobs, the job with the shortest processing time is selected. If the list is empty, the work station is left idle.

A simulation model composed of a ten-machine, ten-part closed job shop was used in this research. The performance measures evaluated were mean flow time, flow time variance, and mean lateness.

The analysis showed that, under the sets of conditions established for this study, the SPT modification improved the performance measures or, at worst, performed similarly to unmodified SPT. Conditions under which the SPT modification improved results included larger numbers of transfer batches, situations where the ratio of setup time to process time was small, and those where the variation in process times from station to station was large. Equally important, shop loading level was not a significant factor affecting the value of the modified SPT rule.

Issues not included in this study were the impact of supply uncertainty stemming from work station breakdowns or probabilistic processing times. Costs associated with the information system required to implement this approach also remain to be understood and explored.

DEDICATION

For my family; for my wife, Lori, who has delayed her own interests, provided love and support, and at times carried the burden of parenting virtually alone; for my children, Ben and Emily, who have been supportive and understanding to a point, and have made do with only parts of "Dad"; I dedicate this work.

ACKNOWLEDGMENTS

First and foremost, my family has made this work possible. My wife, Lori, and my children, Ben and Emily, have all made individual and group sacrifices of astounding magnitude in order to provide the time necessary to do this research and writing. Their encouragement, love, and support have made the work bearable, and success the only option.

My extended family has also been a source of strength and encouragement. Their prayers and consistent support have buoyed me in times of weariness and self doubt.

I would also like to extend my deepest appreciation for the support of my dissertation committee. The patience, many detailed reviews, and, most important, the mentoring I received from committee chair, Dr. Ram Narasimhan was particularly treasured. The reviews, improvement suggestions, and gentle guidance of Dr. Gary Ragatz, Dr. Souman Ghosh, and Dr. Shawnee Vickery were also highly prized and valued. The time that these individuals devoted to assisting in this effort was considerable, and deeply appreciated. The efforts of the committee as a whole made this dissertation much more than it otherwise could have been, and an created an invaluable learning experience.

I would also like to thank the rest of the Faculty and staff of the Management Department of the Eli Broad College of Business for their support and encouragement. Many times, allowances were made for my non-traditional student schedule and location that have allowed this work to progress to fruition.

The other students in the Management Department have also been instrumental in the successful completion of this work effort. At all times, I have been offered encouragement and understanding from others associated with this program, contemporaries and predecessors alike. The resulting atmosphere was very much like a team environment, with personal success augmenting the welfare of the group.

Several classmates deserve individual recognition. Dr. Vijay Kannon and Dr. Steve Lyman both provided consulting services in SIMAN language coding and processing, with Dr. Kannon also providing FORTRAN coding used, with modifications, in the processing and evaluation of the preliminary model runs. Dr. Paul Blossom helped tremendously with early program troubleshooting and later with continuing encouragement. Dr. Laura Birou was my unflagging cheerleader, continually reinforcing my knowledge of her expectation of my eventual success. Keah Choon Tan was an invaluable help in locating software and application support, and a continuing link to the internal life of the Department. To these and to many others with smaller, but no less appreciated roles, my deepest thanks.

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CHAPTER 1

INTRODUCTION

There are principally three types of part groupings within a job shop operation. The first is the release batch, which is the quantity of a particular part type that is released to the shop for production. The second is the operation batch, referred to as the "process batch" in Goldratt's (1981) work. An operation batch is a grouping of parts to be processed using a single setup at a given work station. The third type of part grouping of interest is the transfer batch. The transfer batch is the quantity of parts that are moved from work station to work station. In most previous works on job shop scheduling, the transfer batch has been the same size as the operation batch and the release batch. However, transfer batching in quantities less than operation batch size has been shown to significantly improve the mean flow time of jobs within a job shop. (Jacobs & Bragg, 1988, and Moily, 1986) The utilization of transfer batches in shop loading makes it possible to reap the flow time reduction benefits of small batch sizes without the usual requirement of setup time reduction. The reason for this is that transfer batching does not require a setup for each transfer batch.

The principal question to be addressed in this dissertation is to identify or characterize a set of conditions under which job shop performance could be further improved by maintaining release batch cohesiveness. Changing the queue management rules to prevent a transfer batch from capturing a processing station until the entire release batch can be processed, under certain conditions, can reduce setups and may be able to improve shop performance. Previous research on transfer batching in the job shop environment has not addressed queue management rules as a means of improving shop performance.

Maintaining release batch continuity is intuitively attractive in that it should help reduce non-productive setup time from the available machine time and thus (under certain circumstances) improve the performance of the shop. Also, since release batch continuity is designed to ensure that an entire release batch is processed contiguously (operation batch size equals the release batch size) at each operation, benefits, other than flow time reduction, might be possible. These organizationally specific benefits might include scrap minimization, release batch traceability, and job continuity. These additional benefits may indeed be of much greater interest to actual job shops than the potential for small improvements in flow time performance. The issues of release batch traceability and production continuity alone currently require some production processes to maintain the transfer batch equal to the release batch.

Under traditional queue management rules, because no mechanism exists to maintain release batch cohesiveness, some organizations may not avail themselves of the productivity gains provided by transfer batching. A queue management rule that provides for contiguous processing of a release batch while allowing the simultaneous processing of a release batch at successive stations (an important feature of transfer batching) would aenable these firms to use transfer batching.

CHAPTER 2

RESEARCH ISSUES

This chapter begins with a review of the literature relating to job shop performance improvement in general and the operations of job shops under transfer batching in particular. Next, some of the unexplored research issues suggested by the existing research are discussed, followed by a description of the specific research questions to be addressed in this dissertation. The chapter concludes with a description of the organization of the rest of the dissertation.

2.1 PREVIOUS RESEARCH

Improving job shop performance through improving dispatching or sequencing rules has received a lot of attention within the Operations Management literature. Most of the previous research assumes that release batches and transfer batches are the same size. Blackstone, Phillips, and Hogg (1982) restricted their discussion to only dispatching rules and found 34 different rules and modifications of rules to compare and contrast. In dividing these rules into categories based on decision criteria used, these researchers found that dispatching rules based solely on characteristics of processing time accounted for nearly half of the rules reviewed. When rules involving combinations of shop factors, all of which make use of processing time information, are included, nearly two-thirds (21 of 34) of the rules explored rely on processing time to some extent for the dispatching decision.

The reason for the research emphasis on processing time based rules is that the shortest processing time (SPT) dispatching rule has been shown to result in the smallest mean flow time under a broad set of conditions (Baker, 1984 Blackstone et al., 1982 , Conway & Maxwell, 1962). The application of SPT, however, produces mixed results compared to other dispatching rules such as due-date based rules, when other performance measures like mean lateness or percentage of late jobs are considered. Variance in flow times and job lateness, for instance, are shown to be significantly higher for the SPT rule compared to due-date based rules (Conway & Maxwell, 1962). Consequently, a significant amount of research exists that attempts to overcome the shortcomings of SPT in these areas and to create an overall "best" rule (Conway, 1965, Kannan and Ghosh, 1993).

The review of dispatching rule research is interesting not merely for the emphasis on processing time based decision rules, but also for the timing of the developments. Initially, research focused on identifying the shortest processing time rule as the best, or at least a "good", dispatching rule. One of the earliest studies of this type was that of Conway and Maxwell (1962) who verified the superiority of the shortest processing time rule. They also questioned the sensitivity of this rule to inaccuracies in process time estimation. Subsequently, researchers have looked for conditions under which the shortest processing time rule would result in the "best" shop performance (relative to flow time or to due date measures) (Conway, 1965). Other researchers have focused on methods by which the straight application of shortest processing time rule could be modified to alleviate its shortcomings. Notable examples of these efforts include Baker's work (1984) in comparing several different performance measures when using several different sequencing rules. The performance measures used fell into the general classification of flow time performance (mean flow time) and due-date performance (mean late, percent late, and conditional mean late). Baker also looked at methods of modifying the traditional sequencing rules to improve performance. More recently, Kannan and Ghosh (1993) looked at methods by which to modify the straight application of the shortest processing time rule through truncation, to further improve the job shop's performance. Their results show that some of the shortcomings of SPT as a sequencing rule may be avoided by utilizing other available information (in this case, the number of times a job is not selected) in order to improve the performance of the rule.

The concept of a transfer batch size smaller than the release batch (the release batch usually being an integer multiple of transfer batch) is presented and defended in the work of Goldratt (1981), both in his publications and in the OPT (production scheduling software) packages sold through his consulting firm. Goldratt's methods and claims were explored and illuminated by Jacobs, (1984) and then quantified and evaluated by Jacobs and Bragg (1988), who verified the claims of reduced flow time for transfer batching.

Now that transfer batching, or repetitive lots, as some have defined it, has been shown to improve flow time, the focus has shifted, as it had in earlier job shop research, to factors that impact the performance of the transfer batching technique. Karmarkar, Kekre, and Kekre (1985) looked at the impact of lot size, using queuing theory to develop a least-cost approach to setting batch sizes. Kropp and Smunt (1990) developed optimal and heuristic methods for defining the lot split. They also test the usefulness of lot splitting in various environments, concluding that shops with large setup to processing time ratios benefit less from lot splitting. Wagner and Ragatz (1992) looked at the effect of setup times and due date assignment on flow time and lateness in an open job shop environment. They found that lot splitting improved flow times and due date performance under a variety of dispatching rules. D'Itri and Ghosh (1991) looked at the effect of capacity utilization and sequencing rules on the same performance measures. They concluded that all sequencing rules tested by them provided flow time improvements under transfer batching. They also found that the benefits of transfer batching are reduced at higher levels of capacity utilization.

In the context of transfer batching, it is necessary to explore methods by which SPT, the generally recognized "best" method of sequencing jobs to minimize flow time, can be modified to further improve the rule's ability to reduce setups. Jacobs and Bragg noted that future research into improving sequencing logic to minimize setup time could prove valuable (Jacobs & Bragg, 1988).

2.2 RESEARCH ISSUES

One common thread through the literature on transfer batching and repetitive lots is that the system appears to realize the benefits of small batches from an overall flow perspective while at the same time avoiding excessive setups through large operation batches. This ability to avoid setups through utilization of current setup assumes that at least one transfer batch requiring the same setup is in the process queue upon completion of processing the current batch. This may not always be the case.

It can be hypothesized that under transfer batching, there are times when the initial transfer batch of a large release batch will require a setup at the next processing station. Under this circumstance, the processing station will not be able to sustain the setup with successive transfer batches. If this condition occurs, the operation batch (previously defined as the number of units processed using the same setup) will no longer equal the release batch. This interruption of processing continuity may occur at the end of processing any transfer batch (with the exception of the last one). When this condition occurs, the completion of the release batch will require at least one additional setup which will generate additional cost. This condition may occur when the preceding process requires significantly more time than the succeeding process. It could also occur when the processing time difference is small, but the release batch is very large relative to the transfer batches, requiring many transfer batches. In either case, the inability to retain the current setup at the processing station through the end of the release batch will necessitate at least one additional setup. Under conditions of relatively high capacity utilization or large setup time requirements, this could have a significant effect on job shop productivity. The generation of unnecessary setups under high utilization would result in the reduction of available productive time at the station, potentially causing large queues to develop. The same could occur if setup times were relatively large, where one unnecessary setup would consume significant amounts of otherwise available processing time.

A potentially effective way to prevent unnecessary setups from occurring would be to modify the SPT dispatching rule in the transfer batching context. The rule should still select any transfer batch of the same release batch, which would use the same setup. Should a job of the same release batch not be available, then any job requiring the same setup at the current station should be selected if the preceding station can keep it supplied through completion. If none are available, select the job with the shortest processing time at the current station if the preceding station can keep it supplied through completion. The ability of the preceding station to supply the current station exists if processing information from the preceding station in the routing indicates that all transfer batches of the release batch would complete processing before the next-to-last transfer batch finished processing at the current station. Mathematically, this could be stated as the following:

$$((P_{(i-1)k})(N-Bmax_{ijk})) < ((P_{ik})(N-Bmin_{ijk}))+S_{ik}$$

where

$P_{i,k}$ = in-station transfer batch processing time
N = number of transfer batches in release batch
$B_{i,j}$ = serialized transfer batch number
Bmax = the largest serial number (i,j,k)
Bmin = the smallest serial number (i,j,k)
$S_{i,k}$ = setup time

with

i = sequentially assigned routing step number
j = release batch number
k = part type

If no jobs meet this criterion, then no job would be selected. The decision to not select a job to process if no job can meet this criterion assures that each station will experience a maximum of one setup per release batch. If two release batches should be in the queue at the same time, and the second release batch can be supplied by the previous station when the first batch is complete, then setups will be less than one per release batch per station. The "non-selection" decision also will insure that all transfer batches of a release batch will stay together throughout all processes, arriving at the shipping point sequentially from the last station. This condition is defined as release batch *cohesiveness*.

2.3 Problem Statement

The focus of this dissertation is to investigate appropriate modifications to the SPT rule to minimize flow time by reducing required setups. Specifically, in the context of transfer batching, no job is allowed to capture a facility unless successive jobs can support that setup through the full release batch.

It is hypothesized that under certain conditions, additional setup reduction through SPT rule modification under transfer batching will improve job shop productivity as measured by average flow time and flow time variance. Also, since reduction in flow time and smaller flow time variance should produce improvements in performance to schedule, an improvement in mean lateness and lateness variance is also hypothesized given the same conditions. Further, it is hypothesized that the factors forming the shop environment will have varying impact on the value of the SPT rule modification, either singly or interactively. The factors expected to have some impact on the performance of the Modified SPT rule are shop loading level, the ratio of setup time to processing time, number of transfer batches, and station-to-station processing time variance.

2.4 Problem Significance

The results of this investigation will provide additional insights into the mechanisms at work within a transfer batching environment, identifying the relative importance of reducing setups versus the simultaneous processing at successive stations provided through transfer batching, identified and tested in previous research. This research will also provide additional insight into factor levels at which there is a change in importance from simultaneous processing of parts in a release batch to setup minimization, if one exists. This information will result from identification of the point at which setup reduction enhances the performance measure improvements gained from simultaneous processing (transfer batching) alone.

From an application perspective, this research carries the potential for improving the actual performance under a specific set of conditions within job shops, over and above those available from less involved sequencing rules. This would be the result of smaller flow times and lower lateness values.

Additionally, even if the modified SPT queue management rule fails to provide the anticipated improvements in average flow time and due date performance, this rule is expected to have distinct advantages within some job shop environments so long as it does not negatively impact these measures. First, the time difference between the completion of the first piece and last piece of a release batch at its final processing station should be smaller. This is a consequence of the operation batch being equal to the release batch, or release batch cohesiveness as defined in Section 2.2. The operational advantage of this outcome is that, if a release batch is required to be shipped as a group and shipping storage space is at a premium (a common condition), batch cohesiveness reduces shipping costs and smoothes the shipping process. Other queue management rules allow or even create different completion times for a release batch, thus incurring additional storage costs.

Second, because of the expected cohesiveness of the release batch, job flow monitoring and process documentation capabilities should be greatly improved. If customer requirements or internal quality control procedures require retention or detailed inspection of a unit from each setup, the setup avoidance afforded by this queue management rule is a significant advantage. This improvement alone may mean the difference between an actual job shop being able, from an operating requirement perspective, to employ transfer batching. These anticipated real world benefits are potentially important enough to include information about release batch cohesiveness in the statistics retained from the experimental runs.

Third, in actual practice, each time some particularly sensitive production processes are set up, one or two scrap units are generated as the setup is "tuned". Because of setup reduction under the proposed dispatching rule, a job shop could conceivably reduce the scrap costs associated with the introduction of transfer batching in these job shop environments.

2.5 Organization of the Dissertation

This dissertation began with an introduction to the topic of transfer batching and a discussion of the importance of the topic. Chapter 2 has been a discussion of the previous research, followed by a discussion of research issues suggested by the previous research. The specific questions to be addressed in this dissertation research, and their significance were then identified.

Chapter 3 discusses the experimental design utilized to pursue the research questions of interest. The performance measures are discussed in detail, including their relative importance. The research hypotheses are then formally stated.

The simulation model is presented in Chapter 4, including the model validation process. The results of the pilot runs, used to establish sample size requirements and to address autocorrelation and initialization issues are then reviewed. This chapter also presents details of tests carried out to assess model adequacy.

Chapter 5 is a discussion of the results of the data analysis, reviewing the significance of the main factor effects and factor interactions identified by the ANOVA. Included in this section is a discussion of the experimental factors investigated in this research.

Chapter 6 is an assessment of the results, with particular reference to the implications of the research for actual job shop operations. This chapter also discusses additional research opportunities afforded by the results of this dissertation.

CHAPTER 3

THE EXPERIMENT

This chapter discusses the framework under which the research questions will be approached and analyzed. The chapter begins with a review and detailed discussion of the experimental factors considered to be important to this work. The experimental design and the performance measures that will be used are discussed, followed by the formal statement of the research hypotheses.

3.1 Experimental Factors

The exploration of the research questions discussed in Section 2.3 will be approached in a manner similar to previous research (Jacobs & Bragg, 1988), i.e., through job shop modeling. A closed job shop model capable of producing results similar to the Jacobs and Bragg model was selected to ensure comparability and to help with validation of the new model.

The five factors discussed briefly in Section 2.2 that are to be investigated in this dissertation are:

queue management rule (SPT or Modified SPT)
shop loading level
the ratio of setup time to processing time
number of transfer batches
station-to-station processing time variance

Each of these factors are discussed more fully in what follows.

3.1.1 Queue Management Rule

The impact of queue management rule is the primary focus of this study. The initial question to be investigated is whether the proposed modification to the queue management rule has a positive impact on the performance of a job shop. The model was run with this factor set at two levels, one corresponding to SPT and the other corresponding to a Modified SPT.

3.1.2 Shop Loading

Shop floor loading, which D'Itri and Ghosh (1991) have shown does not greatly impact the benefits of transfer batching, may well impact the benefits of setup minimization under transfer batching. This may occur since setup minimization would in effect convert setup time into idle time, thereby favorably altering shop loading.

For comparability with the Jacobs and Bragg study, the "low" setting for shop floor loading was 90% for processing time plus setup time as calculated for standard processing techniques. The "high" level of this factor was set at 95%, to evaluate the impact of higher loadings.

The original work used decreasing release batch sizes to change shop floor loading as this effectively increased required setups, assuming one setup per release batch. For this study, the alteration of release batch size creates a significant problem. While Jacobs and Bragg used the transfer batch flow time as their performance measure, this study used release batch flow time, in order to identify release batch cohesiveness and due date performance. Changing release batch sizes will perforce change the mean flow time due to fewer units being processed.

The alternative method chosen to change shop loading was to change the demand for each part type. This change was accomplished in the model by increasing each randomly chosen weekly demand quantity by six units. The effect of this change was to increase the mean without changing σ, resulting in more frequent releases.

3.1.3 Setup Time Ratio

Intuitively, the amount of time each setup requires should significantly impact the value of setup minimization. There should also be an interaction between increasing the ratio of setup time to processing time and shop utilization level, since avoiding larger setup times would "free up" relatively more facility time. The Jacobs and Bragg work used a release batch setup-to-processing ratio of .25. This was chosen as the "low" factor setting in the present study. In the Kropp and Smunt (1990) work, as processing time became smaller relative to setup time, the value of lot splitting deteriorated. This conclusion would suggest that a setup to processing time ratio of <1 should be selected.

Therefore, a value of .75 was used as the high value for this factor.

3.1.4 Number Of Transfer Batches

It is reasonable to expect that the larger the number of transfer batches, the more often the conditions requiring additional setups may occur. As D'Itri and Ghosh (1991) have shown, the creation of additional transfer batches contributes diminishing marginal improvements in flow time. However, research has not shown that increasing transfer batches beyond a certain level ever leads to deterioration in performance (evaluated from a flow time perspective). The possibility exists, then, that transfer batches could be increased to the point where transfer batch size is a single unit, which is the ultimate goal of a small lot (kanban) system, and that average flow time would still be at the lowest value.

This factor was tested at two levels, covering a wide range of possibilities. Initially, values of 4 and 10 were used with a release batch size of 200 to replicate a portion of the Jacobs and Bragg work for validation. The "reasonableness" of these levels was checked and retained for the remainder of the study.

3.1.5 Station To Station Processing Time Variance

This factor was also hypothesized to produce a significant impact on the value of the modified SPT rule.

There should also be a significant interaction between this factor and the setup time ratio. These hypotheses are based on the expectation that, as the differences among the processing times at each station become larger for a product, the probability that the processing time plus setup time at a succeeding station will be less than the preceding station's processing time will increase. Thus, using SPT, when the transfer batch reaching the next station has a relatively short processing time, it also has a high probability of being selected as the next job for processing.

Due to a lack of existing research regarding this factor under transfer batching, the values used for this factor were set through preliminary experimental runs. The station to station processing time variance factor was eventually set at 1.0 for the "low" level and 6.4 for the "high". The 1.0 variance was selected because of ease of calculation it afforced. The 6.4 variance was arrived at through expansion of the distribution range of processing times. First, the smallest processing time was reduced to a small but significant value (0.8). All other values were then changed by a proportional amount to maintain the original mean.

3.2 Experimental Design

The experiment utilizes a 2^5 full factorial design with 32 combinations requiring multiple replications in each cell. Each of the five factors, discussed in Section 3.1, were set at two levels. Two levels for each factor is adequate to test for interactions, if interactions are present. Also, the statistical significance of factor effects is of interest in this research rather than the potential exploration of nonlinear effects afforded by additional factor levels.

3.3 Performance Measures

Data were collected for six performance measures. Of the six, the primary performance measure of interest is *flow time*. This was the measure of interest in the work of Jacobs and Bragg and is also of great interest to the operation of actual job shops.

The second most important measure is *lateness*. Its inclusion in the research was to investigate whether improvements (if any) in flow time performance would carry over to an improvement in the tardiness measure, one of the important performance measures in real world situations.

The third performance measure mentioned in the hypotheses and third in importance is *flow time variance*. The expectation associated with this measure was that, with the elimination of "separated" transfer batches, the variance of mean flow time would decrease. This measure is of lesser interest to management than mean flow time or mean lateness, however, because both mean flow time and mean lateness directly impact the total cost of operations of a real world production system. Flow time variance increases operating costs because of increased inventory uncertainty associated with delivery date and inability to adhere to promised delivery dates. Since these costs are hard to quantify, they tend to be of less interest to job shop management.

The fourth measure in order of importance is *cohesiveness*. This measure is merely the ratio of the theoretical minimum time between the completion of the first and last transfer batch and the actual measured time. The range of this measure is from zero to one. The cohesiveness of release batches was one of the expected and important benefits of the proposed modification to the SPT decision rule. As such, evaluation of this measure is important.

Fifth in importance is the *percent of jobs that are tardy*. This measure is similar to the lateness measure, but shows the percentage of jobs that actually miss the due date. It is not included in the formal hypotheses that follow in the next section because it is less responsive to small improvements in operations. This reduced sensitivity is because this measure uses the number of incidences of due dates missed in the calculation, ignoring the magnitude by which the date was exceeded. It also represents only the number of jobs falling within the right hand tail of the performance to due date distribution. It is included here because it is another reasonable indicator of how this rule may impact an actual job shop's performance from the customer perspective.

The sixth measure recorded but not included in hypotheses is lateness variance. This measure was included to indicate changes in variability of the lateness performance. This measure is interesting from a job shop customer's perspective. Improvements in this measure, *ceteris paribus*, would allow a job shop to more accurately set job lead times. This measure was not included in the following formal hypotheses, however, because it is actually a third level indicator of performance, driven by flow time and flow time variance through mean lateness.

3.4 Research Hypotheses

Formally, the first null hypothesis to be tested is:

1. H_0 = In a transfer batching context, a Modified SPT rule does not lead to a decrease in mean flow time.

It is anticipated that this first null hypothesis should be rejected for some combination of factors. In the presence of significant factor interactions, examination of the interactions is necessary to understand under what conditions the SPT rule modification improves performance, and will assist in identification of opportunities for real world application. The following hypotheses address the identification of any significant interactions:

2. H_0 = There is no difference in mean flow time under SPT modification as shop loading level increases.
3. H_0 = There is no difference in mean flow time under SPT modification as the ratio of setup time to processing time increases.
4. H_0 = There is no difference in mean flow time under SPT modification as the number of transfer batches increases.
5. H_0 = There is no difference in mean flow time under SPT modification as the station-to-station processing time variance increases.

It is also reasonable to expect that there may be significant higher level interactions among some of the factors. Specifically, an increase in shop loading level and an increase in setup time to processing time ratio together with the introduction of the Modified SPT rule could prove significant. To test for this specific three-way interaction, the following hypothesis is offered:

6. H_0 = There is no difference in mean flow time under SPT rule modification, increasing shop loading, and increasing setup time to processing time ratio.

The above six hypotheses pertain to the mean flow time performance measure because this measure has been shown to benefit from transfer batching in previous research (Jacobs and Bragg, 1986). The research questions of interest relate to tests of the same hypotheses on the other two performance measures, due date performance and flow time variance. As mentioned previously, no formal tests of hypotheses were carried out on the other three performance measures since they are deemed by practitioners to be less important in real world situations.

CHAPTER 4

THE MODEL

This chapter is devoted to the description of the model developed for this study, and the processes used to validate and "tune the model". The model environment is first described, along with the model building process. The methods used to validate the resulting model are then detailed. The pilot runs that were required to determine the data collection and management techniques are then described and the results detailed.

The analysis of the residuals from the experiment are included at the end of this chapter. The appropriateness of using ANOVA for the various performance measures is also examined in this chapter.

4.1 Simulation Model

To pursue the research questions of interest discussed in section 2.3, a job shop model with characteristics similar to the Jacobs and Bragg model was developed. For a detailed description of this model, see Appendix A. The model was created using SIMAN (version 3.5), a simulation modeling language, employing user-written exits to FORTRAN for decision rules and queue management. The complete code for the model is shown in Appendix B through D, with separate sections for the SIMAN code, the FORTRAN exits, and a reference dictionary of variable names and usages.

Briefly, this model is of a closed job shop producing ten products on ten machines. Routings were randomly developed, each machine selected without replacement with an equal probability of being the first, last, or next sequential machine. The model was patterned after the Jacobs and Bragg model because their work was seminal in the transfer batching literature, the original model is well documented, and it models an environment that has been shown to benefit from transfer batching. The output from some of factor level settings in this study were comparable to the Jacobs and Bragg results, and were used to help validate coding.

The Jacobs and Bragg model framework was enhanced to include the assignment of a due date to each release batch. The due date assignment method was a "total work" approach. This method was selected because the assignment process uses available endogenous system information (Cheng & Gupta, 1989) and has been shown to produce reasonable results (Wagner & Ragatz, 1992). The factor by which to multiply total work content was determined through pilot model runs, and was selected to produce a reasonable and consistent performance to due dates under transfer batching and straight SPT dispatching rule. It should be noted that the inclusion of a job due date does not change the model logic in any way. It merely allows for another type of performance measure.

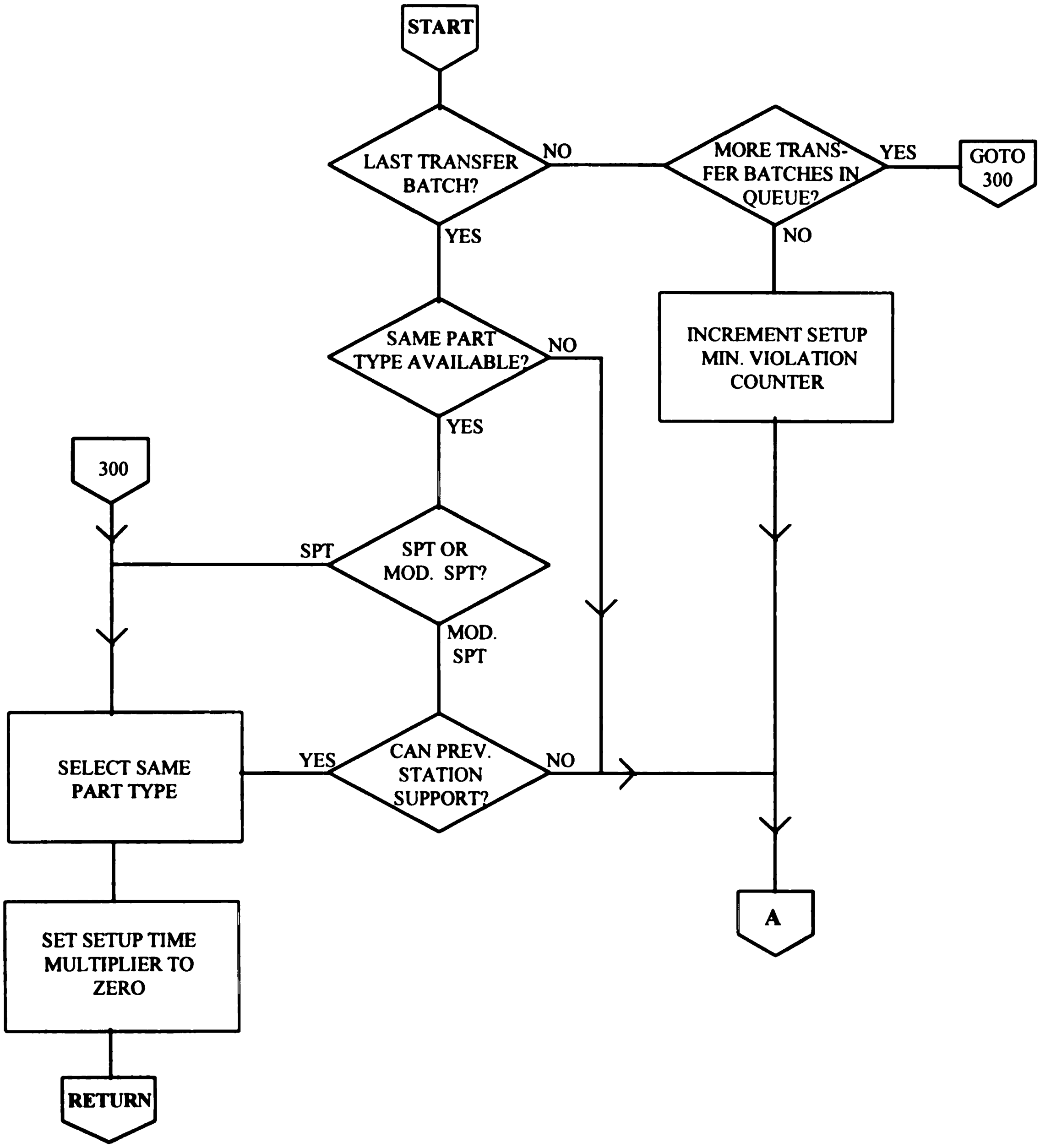

Figure 4-1
Queue Management Decision Logic Flow Chart

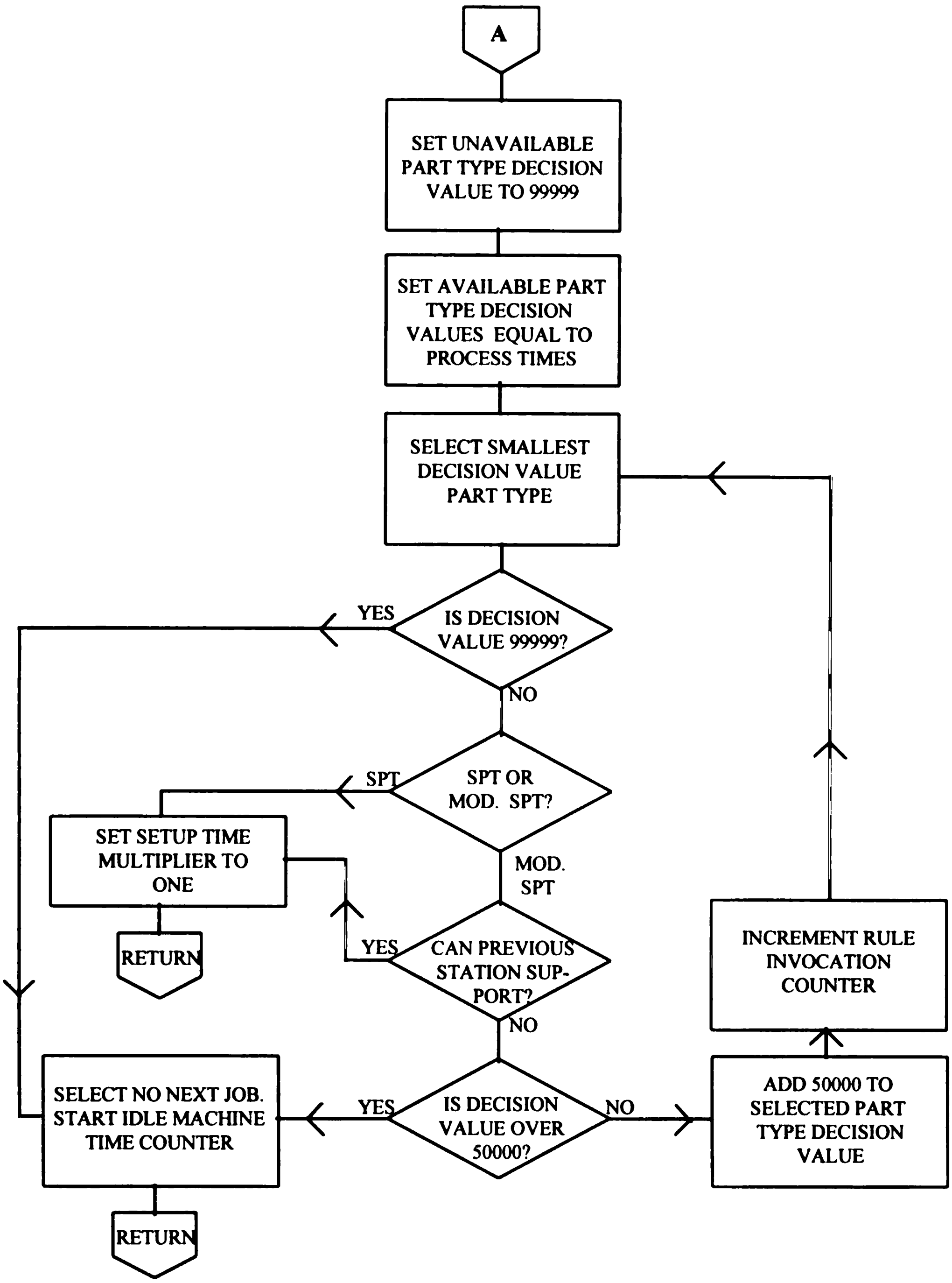

Figure 4-2
Queue Management Decision Logic Flow Chart (cont.)

The Jacobs and Bragg model framework was further modified to include the ability to implement the modification to the SPT rule. The logic used for this purpose is shown in Figure 4-1 and Figure 4-2. Figure 4-1 begins by checking if a complete release batch has finished processing. If the release batch has not finished processing and no more transfer batches are available, the event is noted as not minimizing setups. Figure 4-1 also shows that, if a release batch has completed processing and a second release batch of the same part type is available, it will only be selected for processing if it can be supported throughout all transfer batches. Note that, in Figure 4-2, the values of 99999 and 50000 used for the "Decision Value" are model specific, and would need to be evaluated for appropriateness in a different model or job shop environment.

4.2 Model Validation

The SIMAN code was verified by running the model in single step mode through many iterations of the model flow, verifying the routing accuracy and logic associated with the code. Temporary FORTRAN exits were also written that recorded the transactional paths of individual entities. These "trails" were audited to verify that proper time assignments and delays were employed, and that proper sequencing decisions were made under straight SPT and Modified SPT queue management rules.

After verifying the code, levels of the factors in the model were set to match a portion of the Jacobs and Bragg work. Flow time records for this validation effort were set

Table 4-1 Raw Data - Validation Runs

BATCH SIZE	100	120	130	140	150	200	250	300
PERIOD 1	80.9561	80.8556	79.7066	76.7274	80.0206	75.6237	80.0103	81.2673
PERIOD 2	90.9201	88.5298	88.8925	84.7497	83.5845	81.4697	86.4237	88.9204
PERIOD 3	82.2985	85.0624	80.5892	82.0717	80.6830	82.5347	86.0739	86.9390
PERIOD 4	86.2347	80.2185	80.4535	82.3949	86.9030	80.3600	84.9291	85.8895
PERIOD 5	87.0839	85.3742	83.1140	86.1667	82.0501	77.3304	81.1706	88.1234
GRAND MEAN	85.4986	84.0081	82.5511	82.4221	82.6482	79.4637	83.7215	86.2279
STD.DEV.	3.9788	3.4541	3.7706	3.6053	2.7434	2.8963	2.9400	3.0029
L.C.L.	80.5592	79.7200	77.8700	77.9462	79.2425	75.8680	80.0716	82.4999
U.C.L	90.4381	88.2962	87.2323	86.8979	86.0540	83.0594	87.3714	89.9560

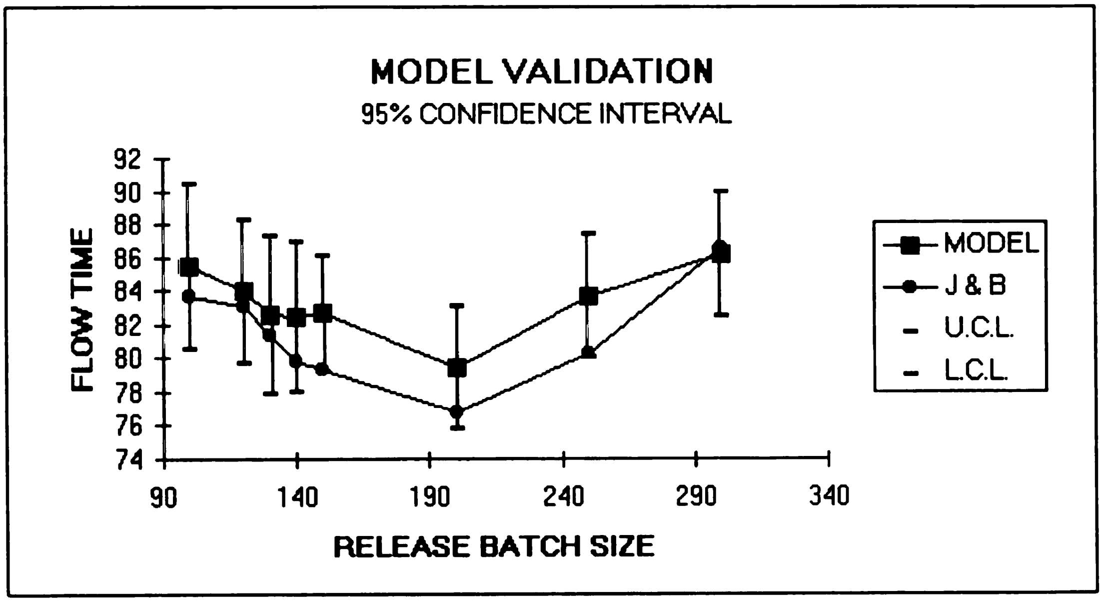

Figure 4-3

Model Validation, 95% Confidence Interval

to capture the transfer batch flow time to duplicate the Jacobs and Bragg model. Flow time statistics were retained for five periods of fifty simulated weeks each. The model was run for fifty weeks to initialize and stabilize the system, and the data collection periods were separated by twenty weeks. The queue management rule was set to shortest operation time, and runs were made at each of the eight release batch sizes that Jacobs and Bragg reported, with a transfer batch size of ten.

The mean flow times from each period were then analyzed by calculating the grand mean and constructing a 95% confidence interval around each grand mean (Figure 4-3). The results show that, for all eight reported release batch sizes, the Jacobs and Bragg values fall within the confidence interval for the same release batch size. It is also significant that the shapes of the curves produced by connecting the mean flow time value points produced by the model are similar to Jacobs and Bragg's model. This similarity in the slope of the response curve shows that the two models respond similarly to changes in release batch size.

4.3 PILOT RUNS

After validation runs were completed, the data collection process was changed to capture flow time, performance to due date, and cohesiveness values on the completion of the last transfer batch of a release batch.

For this discussion of pilot run analysis, a release batch will be referred to as an "observation" since each release batch is treated as a whole in these performance measures.

The model was run to produce data representative of the final measurements to be taken. These data were then analyzed for initialization bias using the Schruben, Singh, and Tierney (1983) test, autocorrelation based on the Von Neumann (Klelijnen, 1987) test, and normality based on the Filliben (1975) test. The FORTRAN code for this series of tests is presented in Appendix C. The results of these tests, analyzing the first 10,000 flow time values produced by the model are, shown in Table 4-2. The minimum, maximum, and mean values for all cells are shown in the last three rows.

The largest number of observations to be discarded to prevent initialization bias in any one cell was calculated to be 30 in cell 2. Therefore, the model was conservatively set to discard the first 100 flow time value observations in each configuration.

The smallest group size used in the analysis of normality and the test for autocorrelation was 100 observations, with the group size to be increased in increments of 100 observations if necessary. The 100 observation size proved to be suitable for all shop configuration sets, indicating that some smaller size may also have been acceptable. The 100 observation size was retained, however, because it performed acceptably, was an

Table 4-2 Pilot Runs Results

CONFIG. CELL NUMBER	INITIAL DISCARD NUMBER	BATCH SIZE FOR INDEPENDENCE	BATCH SIZE FOR NORMALITY	ESTIMATE OF MEAN	ESTIMATE OF VARIANCE
1	16	100	100	99.76	1363.35
2	30	100	100	105.30	1365.42
3	14	100	100	90.92	1036.63
4	11	100	100	99.56	1237.89
5	12	100	100	98.59	1036.28
6	16	100	100	99.35	951.55
7	15	100	100	91.86	925.96
8	9	100	100	97.86	976.80
9	16	100	100	115.63	1595.59
10	23	100	100	119.75	1697.94
11	16	100	100	109.35	1800.86
12	19	100	100	121.27	1939.36
13	15	100	100	108.25	1100.56
14	17	100	100	108.37	1119.03
15	14	100	100	103.10	1119.85
16	14	100	100	111.22	1052.70
17	22	100	100	97.22	1166.26
18	10	100	100	99.11	1107.01
19	24	100	100	92.21	1283.70
20	11	100	100	93.18	1066.96
21	12	100	100	98.14	1029.24
22	9	100	100	101.25	969.25
23	15	100	100	93.43	932.50
24	8	100	100	97.01	842.21
25	20	100	100	121.32	2016.51
26	10	100	100	119.32	1486.94
27	25	100	100	105.56	1523.34
28	15	100	100	113.88	1764.94
29	20	100	100	107.01	1205.12
30	15	100	100	109.46	1101.79
31	14	100	100	102.60	1076.46
32	10	100	100	118.64	1408.01
MAX	30	100	100	121.32	2016.51
MIN	8	100	100	90.92	842.21
MEAN	15.53	100	100	104.67	1259.38

easy unit size to manipulate, and did not create excessively long run times.

The output of the pilot runs was then treated as indicated above, with the first 100 values truncated, and the remainder divided into 100 observation groups. The means of these groups were used to calculate the parameter Φ (related to the noncentrality parameter δ) for a series of possible sample sizes (Table 4-3). Examination of tables of Operating Characteristic Curves (Montgomery, 1983) indicated that the value of Φ that would produce a β of .10 would be somewhere in the range of 2.25 to 2.75 with an α of .05. As shown in the table, fifty groups (replications) in each cell would produce the required results.

The model parameters were then revised to produce a minimum of 5100 observations for each of the model's treatments (50 groups X 100 observations/group + 100 observations discarded for model stability). The run order of the factor level combinations was randomized, and a

Table 4-3 Calculation of Phi

Φ	SAMPLE
0.985669	9
1.038986	10
1.272493	15
1.469348	20
2.323243	50
3.285562	100

Table 4-4 Factor Level Coding

FACTOR	LEVEL	
	1	2
QUEUE RULE	SPT	MOD. SPT
SHOP LOADING	90%	95%
SETUP RATIO	1/4	4/5
TRANS BATCHES	4	10
PROCESS VAR	1	6.4

Table 4-5 Run Order

RUN NUMBER	ORIG ORDER	QUEUE RULE	SHOP LOADING	SETUP RATIO	TRANS BATCHES	PROCESS VAR	RUN NUMBER	ORIG ORDER	QUEUE RULE	SHOP LOADING	SETUP RATIO	TRANS BATCHES	PROCESS VAR
1	1	1	1	1	1	1	26	17	2	1	1	1	1
9	2	1	1	1	1	2	17	18	2	1	1	1	2
12	3	1	1	1	2	1	10	19	2	1	1	2	1
11	4	1	1	1	2	2	21	20	2	1	1	2	2
8	5	1	1	2	1	1	23	21	2	1	2	1	1
25	6	1	1	2	1	2	15	22	2	1	2	1	2
19	7	1	1	2	2	1	2	23	2	1	2	2	1
24	8	1	1	2	2	2	16	24	2	1	2	2	2
27	9	1	2	1	1	1	31	25	2	2	1	1	1
14	10	1	2	1	1	2	3	26	2	2	1	1	2
6	11	1	2	1	2	1	28	27	2	2	1	2	1
30	12	1	2	1	2	2	20	28	2	2	1	2	2
4	13	1	2	2	1	1	7	29	2	2	2	1	1
18	14	1	2	2	1	2	29	30	2	2	2	1	2
22	15	1	2	2	2	1	13	31	2	2	2	2	1
5	16	1	2	2	2	2	32	32	2	2	2	2	2

factor level code created to identify the cell setting. The factor value coding is presented in Table 4-4 and the run order is shown in Table 4-5.

4.4 Residual Analysis

After the simulation runs were completed, an ANOVA was done using SPSS. The first order of business was to examine the residuals to determine the appropriateness of using ANOVA to evaluate these data.

Normalized residual plots for the six selected indicators of performance are shown in Figure 4-4. The plots for release batch flow time (FLOW), lateness (LATE), flow time variance (F.VAR), and lateness variance (L.VAR) all fit expectations reasonably well with minor departures from linearity well out on the tails of the distributions. This fit is a good indicator that these performance measures are reasonably close to being normally distributed.

Percent tardy and cohesiveness (COHES), on the other hand, present a different picture. Percent tardy and, to a greater extent, cohesiveness, show what appears to be a bi-modal distribution.

The Anderson-Darling (1954) goodness of fit test was used to analyze the normality of the distributions of the residuals. This test was selected because it is sensitive to departures from normality particularly in the tail areas, where most of these residual plots show departures. This procedure tests a hypothesis of normality, to be rejected if

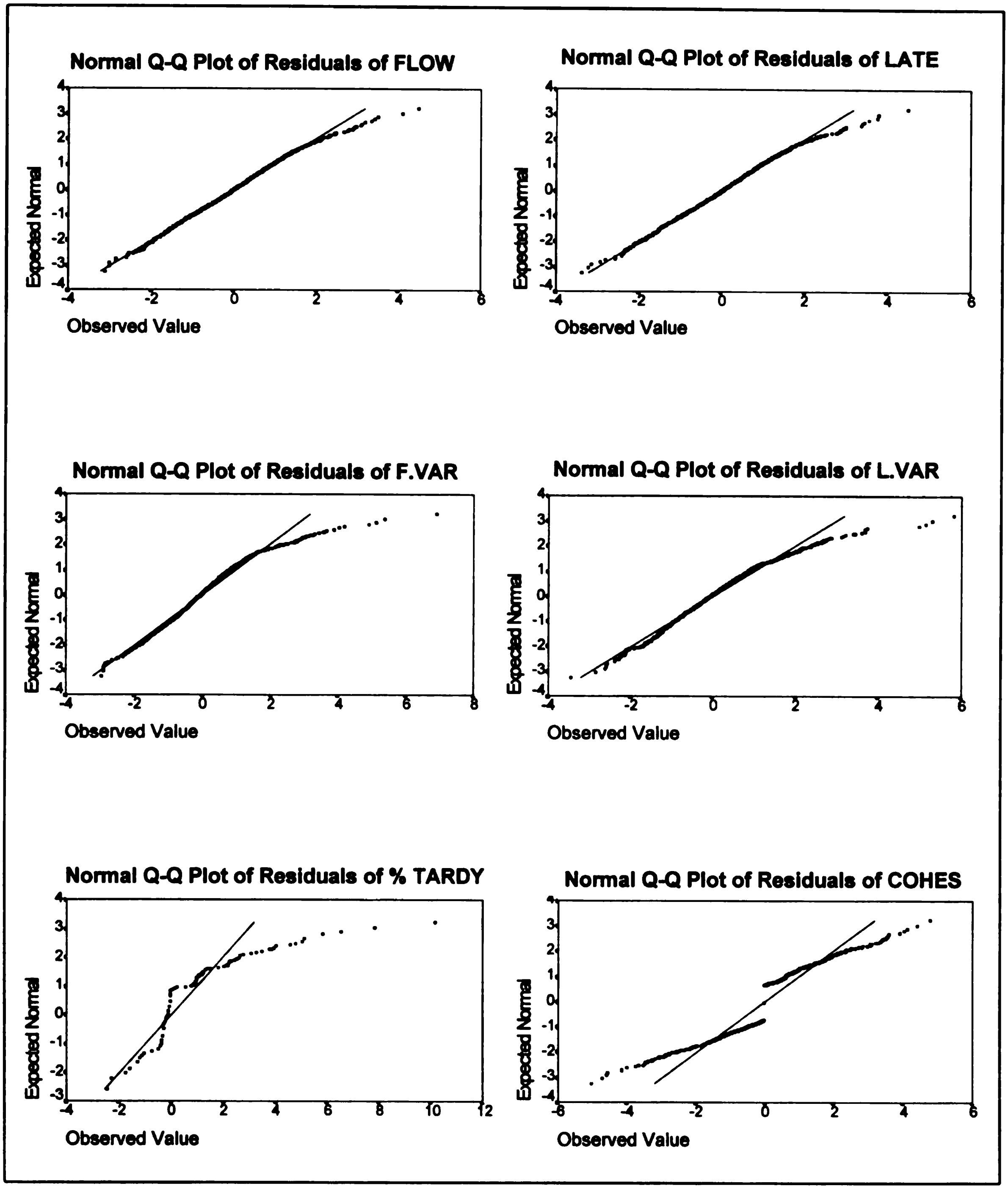

Figure 4-4 Normal Residual Value Plots

Table 4-6 Anderson-Darling Test Results

MEASURE	A-D VALUE	THRESHOLD VALUE (α=.10)	RESULTS
FLOW	1.370084	1.933	NOT REJECT
FLOW VARIANCE	10.53952	1.933	REJECT
LATENESS	1.626916	1.933	NOT REJECT
LATENESS VARIANCE	8.695247	1.933	REJECT
PERCENT TARDY	141.1475	1.933	REJECT
COHESIVENESS	132.1997	1.933	REJECT

the test statistic exceeds a threshold limit. The results of these tests of residuals is presented in Table 4-6.

Note that only mean flow time and mean late measures have values below the threshold limit, and therefore the hypothesis of normality was not rejected. The two variance measures, even though showing a very similar normalized distribution plot characteristics to the mean flow and lateness measures, do not fall below the threshold limit, and the hypothesis is rejected. The last two measures, as expected from the normalized distribution plots, exceeded the threshold value dramatically, and the normality hypothesis is rejected.

The time plots of the residuals of the four measures for which the normality hypothesis was rejected (Figure 4-5) confirm that there are definite patterns in the distributions of these residuals. Examination of the

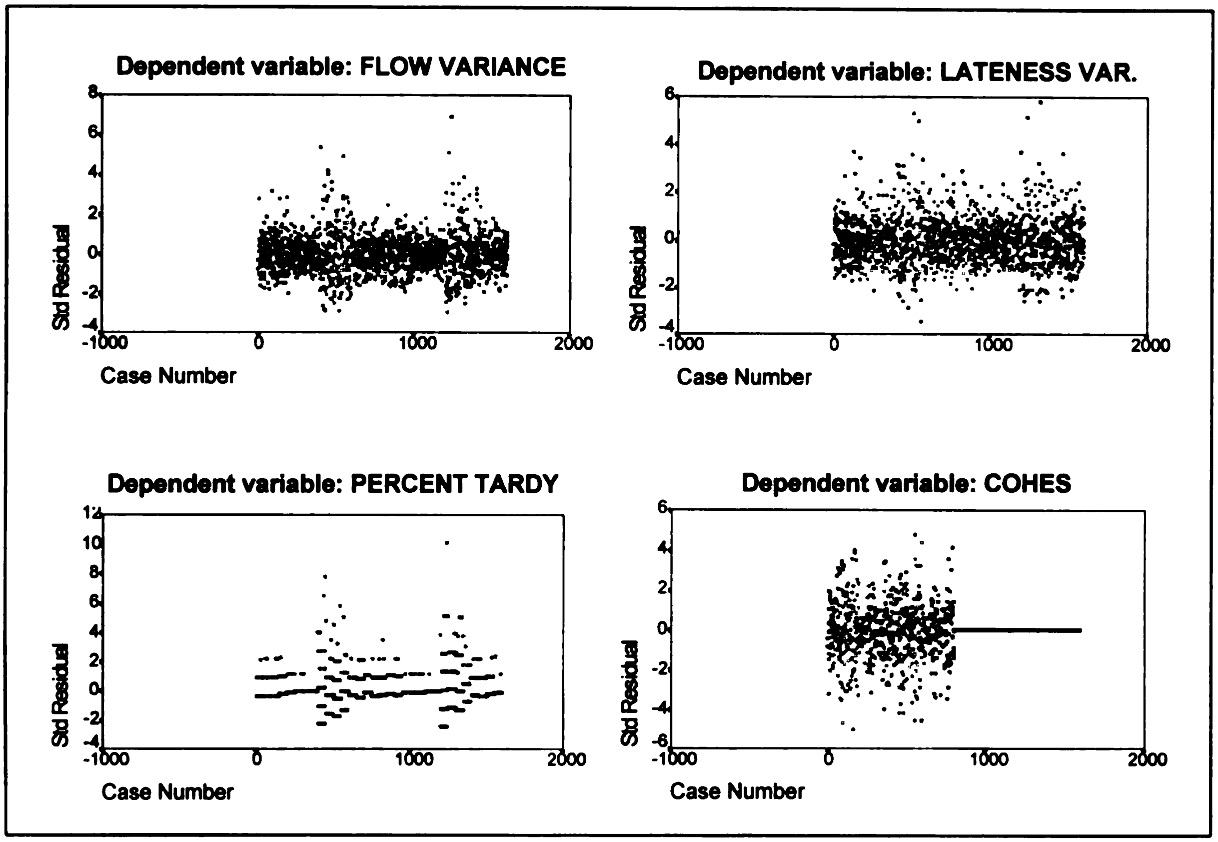

Figure 4-5 Time Order Plot of Residuals

patterns indicates that the cohesiveness measure is driven by the introduction of the Modified SPT rule. Examination of the raw data shows that Modified SPT drives the cohesiveness measure to be precisely 1.0, as designed. This significant departure from normality and common variance makes ANOVA a questionable evaluation tool for this performance measure.

A similar examination of the other three measures shows that they, too, are impacted by the changes in level of one particular parameter to varying degrees. In this case, the parameter that is driving the change is the ratio of setup to process times. When this parameter changes, the distribution of the residuals visibly changes. It is interesting to note the amount by which the calculated Anderson-Darling statistic exceeds the threshold value is reflected in pronounced departures from the central band of residuals as the setup to process time ratio equals the high setting.

Regarding the adequacy of the ANOVA assumptions for the flow variance and lateness variance measures, ANOVA is fairly robust to small departures from the normal distribution, by the Central Limit Theorem (Montgomery, 1983). Visual analysis of the normal plot of residuals shows these two measures to have very similar distributions to the two measures for which the normal distribution hypothesis was not rejected. The Anderson-Darling statistics, while larger than the threshold value, was not comparatively large, indicating that the departure from normality was also not comparatively large. It is also important to remember that, as pointed out in Section 3.3, these two measures are of somewhat limited importance in real world job shops. Given these considerations, no transformation of the data was attempted to improve the "fit" of the residuals for these two measures.

The departure from normality for the percent tardy measure is large. This measure also shows indications of the possibility of two distinct distributions with separate variances. This measure is also of limited importance in the real world applications, as discussed in Section 6-1. Consequently, while the output of the ANOVA process will be used in the evaluation process, results for the percent tardy performance measure should be interpreted with caution.

CHAPTER 5

RESULTS AND ANALYSIS

This chapter presents of the results of the ANOVA applied to the experimental results. The formal hypotheses from Section 3.4 are evaluated based on information supplied by the ANOVA. The main factor effects are analyzed first, followed by the factor interactions. This chapter also contains an evaluation of the relative importance of each of the factors as to their impact on the value of Modified SPT.

5.1 Main Effects

The significance probability values produced by the ANOVA runs for all six measurement variables are shown in Table 5-1. The first notable aspect of the values shown in this table is that, with two exceptions, all five main effects in all six performance measures are found to be significant at a 5% level. The first exception is for the factor, process time variance, corresponding to the measure, lateness variance. The second exception is for the factor, ratio of setup to process time, for the lateness measure. The result that factors other than the decision rule are statistically significant was expected. Some were chosen because previous research showed them to be important to flow time and, therefore, to the other measures as well. Others were chosen under the expectation that they may significantly impact the value of setup minimization.

For the purposes of this dissertation, the most important aspect of this first observation is that the queue

Table 5-1 Factors and Interactions

FACTORS AND INTERACTIONS	SIGNIFICANCE						SIGNIFICANT TO 95%					
	FLOW	F. VAR	LATE	L. VAR	% TARDY	COHES	FLOW	F. VAR	LATE	L. VAR	% TARDY	COHES
RULE	0.000	0.000	0.000	0.080	0.016	0.000	X	X	X		X	X
LOAD	0.000	0.000	0.000	0.000	0.000	0.000	X	X	X	X	X	X
RATIO	0.000	0.000	0.704	0.000	0.000	0.000	X	X		X	X	X
BATCHES	0.000	0.003	0.000	0.001	0.000	0.000	X	X	X	X	X	X
P.VAR	0.000	0.000	0.000	0.000	0.000	0.000	X	X	X	X	X	X
RULE BY LOAD	0.570	0.817	0.562	0.369	0.130	0.000						X
RULE BY RATIO	0.000	0.000	0.000	0.028	0.067	0.000	X	X	X	X		X
RULE BY BATCHES	0.000	0.147	0.000	0.404	0.256	0.000	X		X			X
RULE BY P.VAR	0.000	0.000	0.000	0.188	0.115	0.000	X	X	X			X
LOAD BY RATIO	0.000	0.000	0.000	0.000	0.000	0.019	X	X	X	X	X	X
LOAD BY BATCHES	0.992	0.897	0.993	0.141	0.002	0.503					X	
LOAD BY P.VAR	0.221	0.002	0.211	0.000	0.005	0.000		X		X	X	X
RATIO BY BATCHES	0.000	0.224	0.000	0.348	0.014	0.038	X		X		X	X
RATIO BY P.VAR	0.000	0.979	0.000	0.000	0.000	0.000	X		X	X	X	X
BATCHES BY P.VAR	0.003	0.040	0.002	0.563	0.283	0.000	X	X	X			X
RULE BY LOAD BY RATIO	0.326	0.093	0.304	0.813	0.487	0.019						X
RULE BY LOAD BY BATCHES	0.669	0.392	0.686	0.222	0.312	0.503						
RULE BY LOAD BY P.VAR	0.684	0.825	0.682	0.544	0.230	0.000						X
RULE BY RATIO BY BATCHES	0.103	0.486	0.095	0.249	0.412	0.038						X
RULE BY RATIO BY P.VAR	0.005	0.012	0.004	0.008	0.613	0.000	X	X	X	X		X
RULE BY BATCHES BY P.VAR	0.170	0.718	0.162	0.084	0.752	0.000						X
LOAD BY RATIO BY BATCHES	0.922	0.890	0.933	0.578	0.027	0.767					X	
LOAD BY RATIO BY P.VAR	0.269	0.126	0.243	0.679	0.000	0.004					X	X
LOAD BY BATCHES BY P.VAR	0.654	0.630	0.661	0.419	0.185	0.828						
RATIO BY BATCHES BY P.VAR	0.676	0.823	0.655	0.471	0.256	0.000						X
RULE BY LOAD BY RATIO BY BATCHES	0.570	0.034	0.546	0.469	0.344	0.767		X				
RULE BY LOAD BY RATIO BY P.VAR	0.967	0.537	0.979	0.906	0.899	0.004						X
RULE BY LOAD BY BATCHES BY P.VAR	0.561	0.175	0.547	0.461	0.658	0.828						
RULE BY RATIO BY BATCHES BY P.VAR	0.315	0.608	0.314	0.984	0.377	0.000						X
LOAD BY RATIO BY BATCHES BY P.VAR	0.146	0.051	0.137	0.046	0.101	0.694				X		
FIVE-WAY INTERACTION	0.735	0.802	0.756	0.851	0.312	0.694						

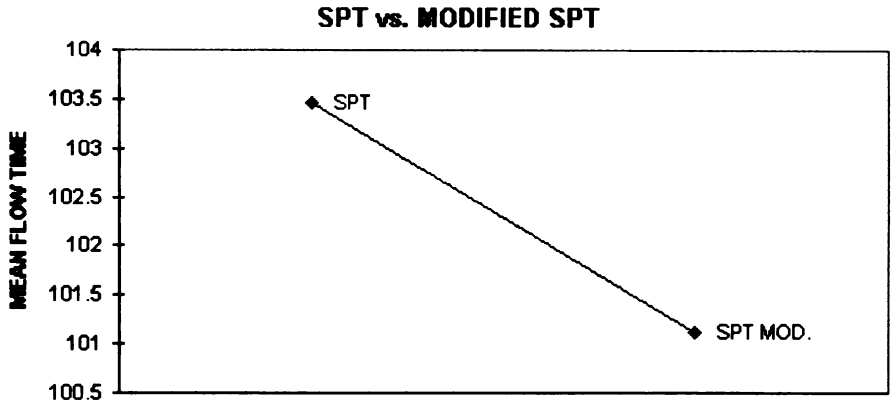

Figure 5-1 Mean Flow Time - SPT vs. Modified SPT

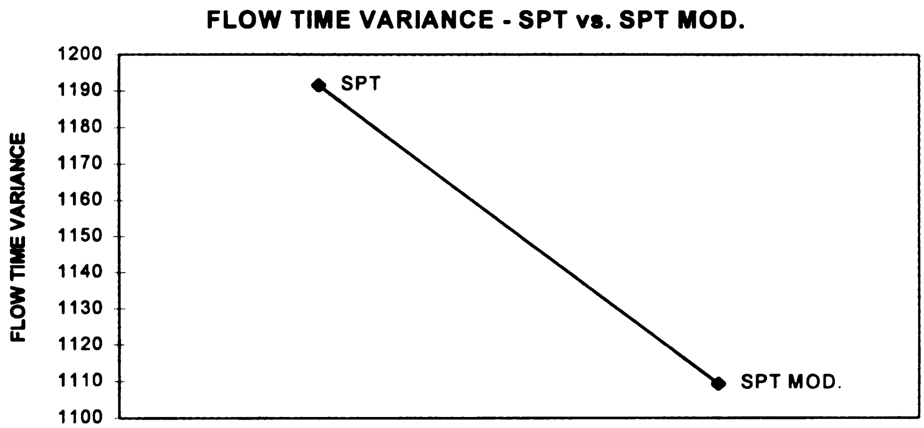

Figure 5-2 Flow Time Variance - SPT vs. SPT Modified

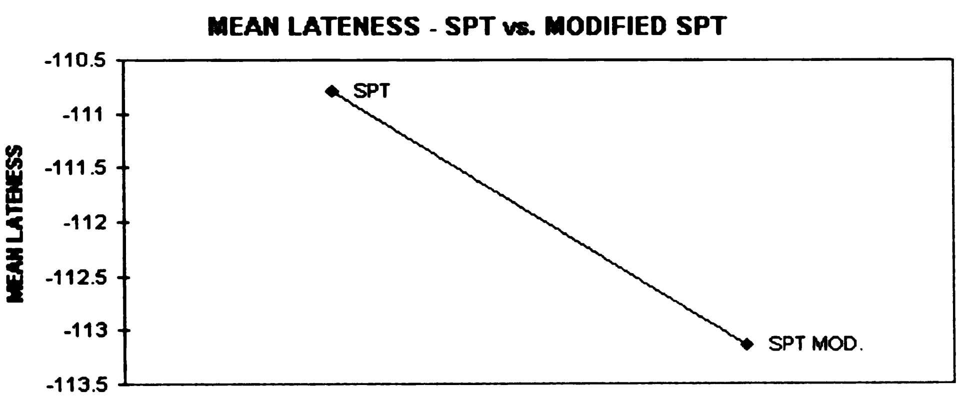

Figure 5-3 Mean Lateness - SPT vs. Modified SPT

management rule has a significant impact on the three most important performance measures. This importance is based on the fact that these measures are the ones specifically identified in the formal hypotheses, namely flow time, flow time variance, and lateness. These measures will be reviewed individually.

As shown in Figure 5-1, the change in mean flow time produced by the Modified SPT rule is a decrease. Therefore, Modified SPT produces a significant decrease in mean flow time. Due to the presence of significant interactions, this fact alone does not allow the rejection of the first null hypothesis.

Figure 5-4 graphically represents the results of a Duncan Multiple Range procedure performed on the mean flow time data. Cell means are listed in increasing order, with brackets enclosing cell ranges deemed to be not statistically different by the procedure.

In Figure 5-5, the mean flow values for SPT and Modified SPT are overlaid, aligning the cells with common factor levels for each of the two queue management rules. All significantly different value pairs, as evaluated by the Duncan procedure, are identified on the chart with an arrow. Note that, in all significantly different value pairs, the Modified SPT value is lower than the SPT value, indicating improvement. These results mean that the null hypothesis:

H_0 = In a transfer batching context, a Modified SPT rule does not lead to a decrease in mean flow time.

should be rejected.

CELL NUMBER	FLOW TIME MEAN
19	88.4658
3	90.3274
20	91.4604
23	92.4765
7	92.5981
24	94.3578
17	96.2703
1	96.4736
21	97.0523
5	97.4422
8	97.4716
22	98.4123
4	98.6466
6	98.8779
18	99.1514
15	101.6308
31	101.8844
32	103.0740
2	103.2490
27	104.8084
13	105.8094
29	105.9108
16	105.9481
30	107.4246
28	107.8264
14	108.0770
11	108.3479
9	114.5464
26	114.5624
25	114.7956
12	116.1672
10	119.7300

CELL NUMBER	LATENESS MEAN
19	-127.487
3	-125.6362
20	-124.47779
23	-120.0736
7	-119.94308
17	-119.67577
1	-119.48269
24	-118.20602
4	-117.28675
18	-116.80022
21	-115.48265
5	-115.08965
8	-115.06341
22	-114.12488
6	-113.66012
2	-112.68855
27	-111.16031
15	-110.93474
31	-110.6629
32	-109.46233
28	-108.15921
11	-107.62518
13	-106.75461
29	-106.64426
16	-106.62254
30	-105.12793
14	-104.42912
26	-101.43824
9	-101.42749
25	-101.21199
12	-99.803305
10	-96.264992

Figure 5-4 Duncan Multiple Range - Flow and Lateness

Similarly, Figure 5-3 shows that Modified SPT produces improvements in mean latenessperformance measure, on average, across all cells. The Duncan Multiple Range analysis in Figure 5-4 combined with the presentation of cell-by-cell comparisons provided in Figure 5-6 for this measure shows a nearly identical performance. Mean lateness shares the same significantly different cell set as mean flow and adds cell pairs 8,24 and 16,32 to the list. Note that here, too, all significant differences show improvements in mean lateness when Modified SPT is the queue management rule, leading to the rejection of Hypothesis 1 for this measure as well.

Figures 5-7 and 5-8 present a nearly identical picture for the analysis of the flow variance measure relative to

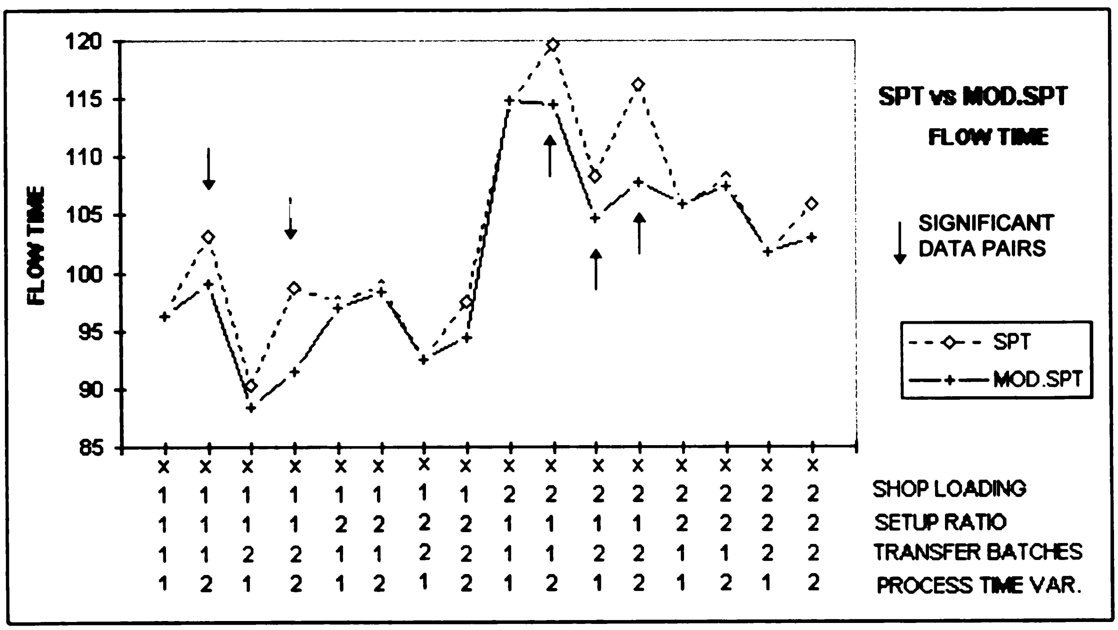

Figure 5-5 SPT vs. SPT Modified - Flow Time

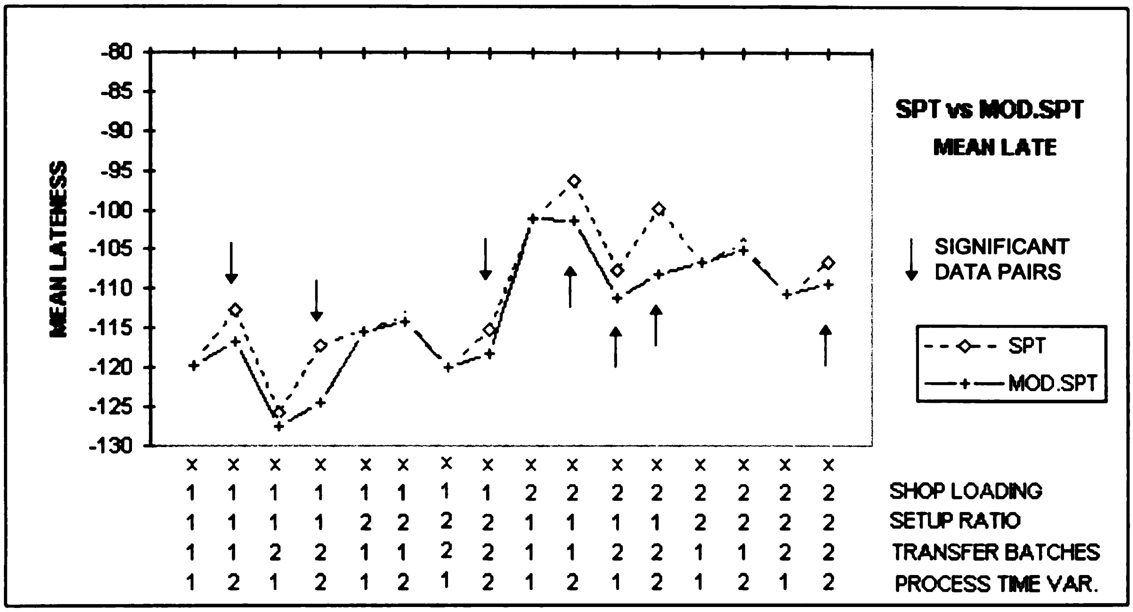

Figure 5-6 SPT vs. SPT Modified - Lateness

Hypothesis 1. Overall, the Modified SPT rule improves (decreases) flow variance. Also, comparing all tested conditions, all cells for which the Duncan Multiple Range procedure finds a significant difference also show that the use of Modified SPT is superior to SPT. Hypothesis 1 is therefore rejected for this performance measure as well.

5.2 Two-Way Factor Interactions

Shifting attention to the two-way interactions of factors, Table 5-1 shows that the queue management rule does not have a significant interaction with the factor shop loading for any of the measures for which formal hypotheses were tested. This lack of significance means that the null hypothesis:

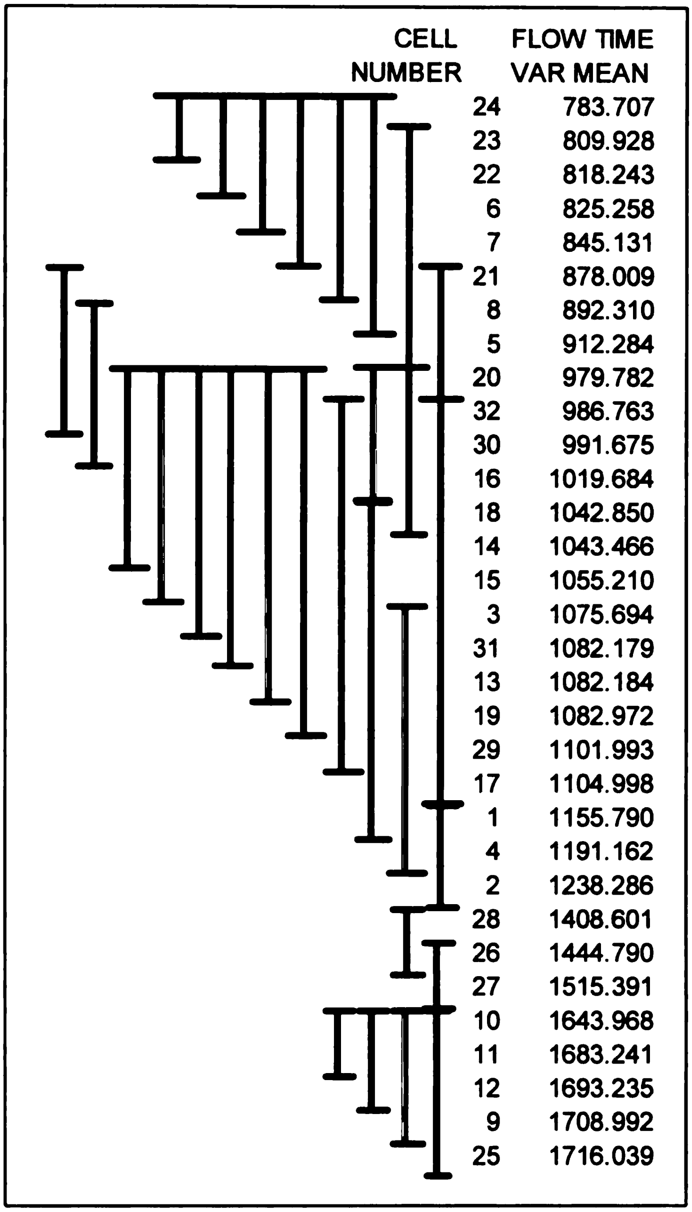

Figure 5-7 Duncan Multiple Range for Flow Variance

H_0 = There is no difference in mean flow time under SPT modification as shop loading level increases.

cannot be rejected.

To observe this lack of interaction as well as the significant two-way and three-way interactions, Figure 5-5

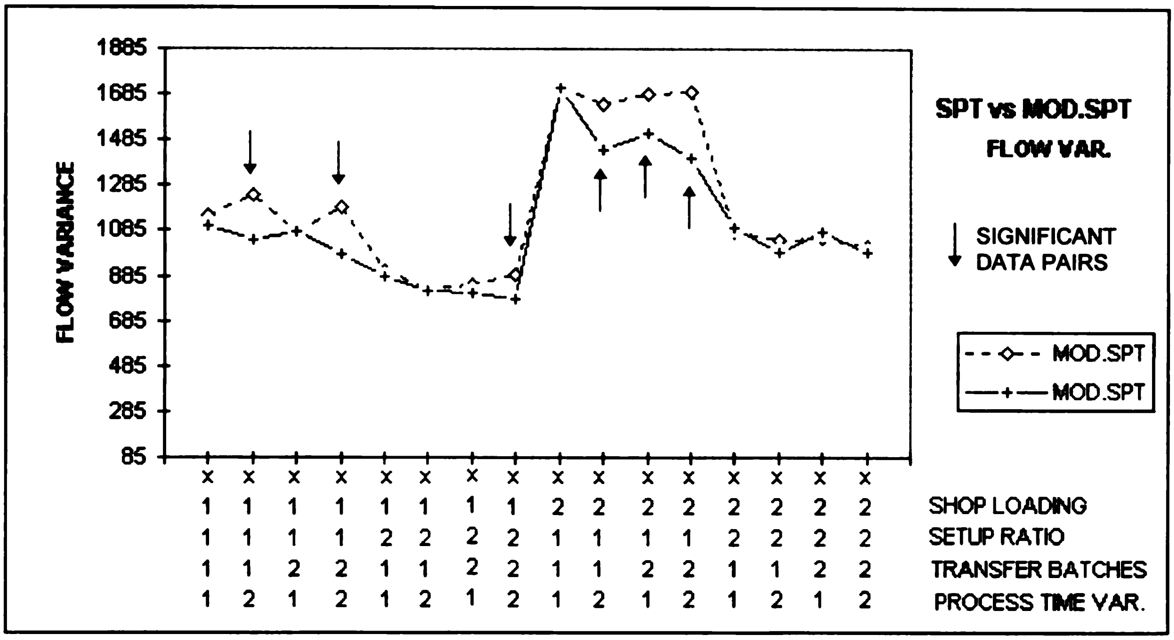

Figure 5-8 SPT vs. SPT Modified - Flow Variance

shows an overlay of the mean flow times of corresponding cells for SPT and Modified SPT. The cell coding along the X-axis indicates the level for each of the factors, the translation of which is contained in Table 4-5. Note that the first pair of data points and the ninth pair, where shop loading increases, are graphically very similar in their separation, highlighting the lack of interaction. In three cells, SPT has a nominally smaller mean, but in none of these cells is this difference statistically significant. The only cells in which a significant difference occurs are those in which Modified SPT is better than SPT.

Two of the remaining two-way interactions involving the queue management rule are significant for all three of the primary performance measures noted in the hypotheses. The two are, first, interactions between queue rule and setup to process time ratio and, second, interactions between queue rule and process time variance. Since the hypotheses involving these two-way interactions were written as two-tailed tests ("no difference" as opposed to "no reduction") the direction of change for these hypotheses is not important to the acceptance or rejection of the hypotheses. Both the null hypothesis:

> H_0 = There is no difference in mean flow time under SPT modification as the ratio of setup time to processing time increases.

and the null hypothesis:

> H_0 = There is no difference in mean flow time under SPT modification as the station-to-station processing time variance increases.

are rejected at the 5% level.

The fourth two-way interaction, that of queue rule and number of transfer batches, is somewhat less clear. For all measures except flow time variance, the interaction is significant. Therefore, the null hypothesis:

> H_0 = There is no difference in mean flow time under SPT modification as the number of transfer batches increases.

must be rejected for the flow time and lateness measures and cannot rejected for the flow time variance measure.

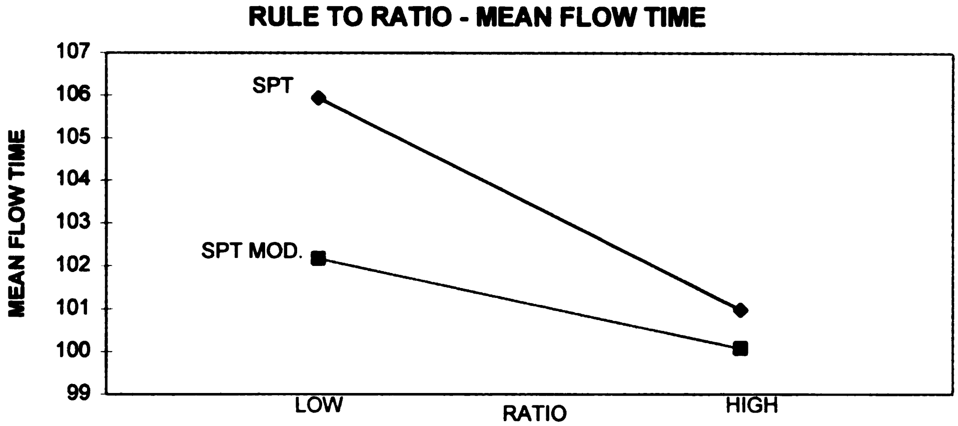

Figure 5-9 Rule to Ratio Interaction - Flow Time

Figure 5-9 graphically represents the interaction between queue rule and the setup to process time ratio for the flow time mean performance measure. Clearly, the flow time improvement value of the queue rule is greater for situations where the setup to process time ratio is smaller. This would indicate that, when the setup time is large relative to process time, the inclusion of setup time in the SPT decision rule's time to process a job at a work station limits excessive setups to a certain extent. When the setup time becomes large in comparison to the process time, the preceding work station will more frequently be able to supply the entire transfer batch for contiguous processing.

Figure 5-10 presents a similar graphic presentation of the interaction between queue rule and the setup to process time ratio for the flow time variance performance measure. Not surprisingly, the relative slopes and positions of the respective lines are similar to the slopes and positions of

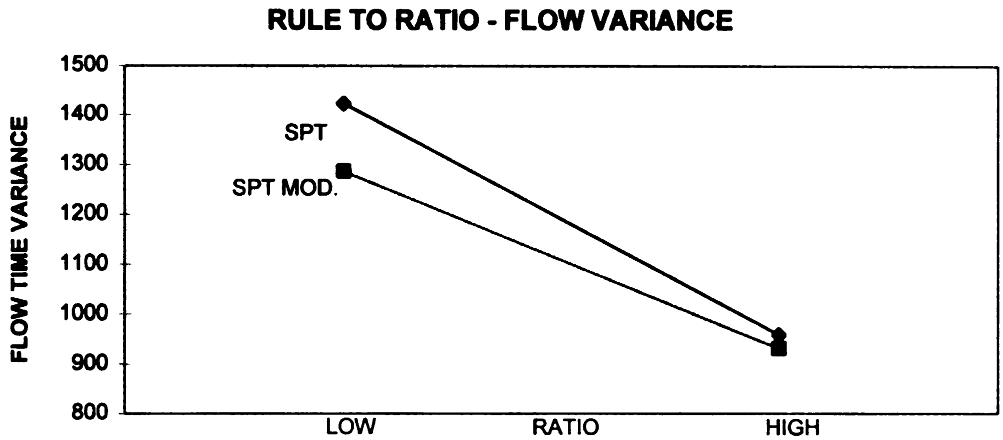

Figure 5-10 Rule to Ratio Interaction - Flow Variance

the lines in the flow time measure. The slope of the SPT line is more negative and positioned above the Modified SPT line with no crossing of lines over this range of values. The same conclusions are reached about the interaction of these two factors. Changing from SPT to the SPT modification is of decreasing value as the ratio of setup to process time increases. Note, however, that the ratio tested at these two levels does not adversely affect performance, but merely decreases the relative value of the rule.

Examining the lateness measure for the interaction between the queue rule and the setup to process time ratio presents a slightly different picture. Figure 5-11 shows this interaction graphically. As can be seen in the figure, rather than showing a decrease in lateness for both queue management rules as the setup to process time ratio increases, as was noted in the previous two performance

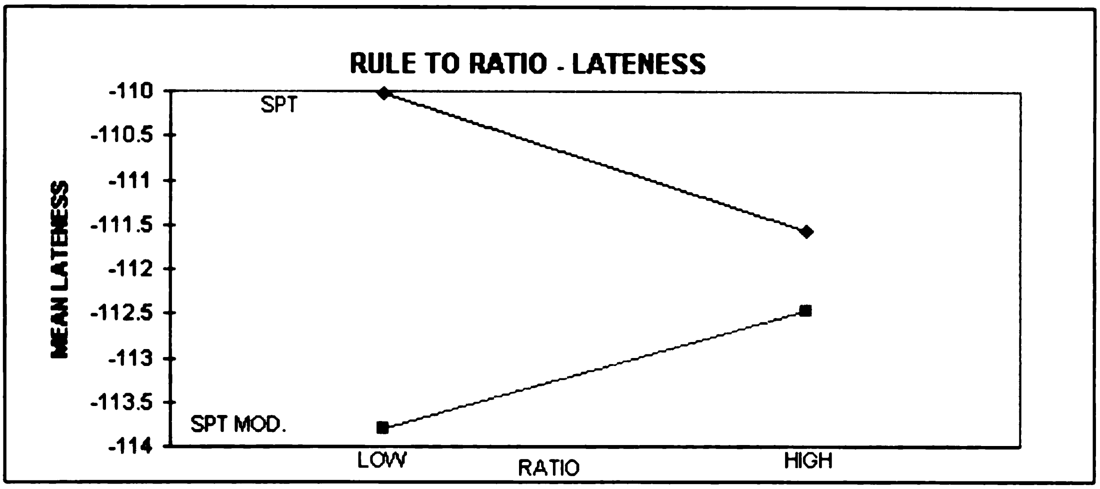

Figure 5-11 Rule to Ratio Interaction - Lateness

measures, this measure shows a deterioration in the performance measure under Modified SPT with the setup ratio high. To further examine this duality of a decreasing mean flow time and an increasing mean lateness, Figure 5-12 was created to overlay the two performance measures. The

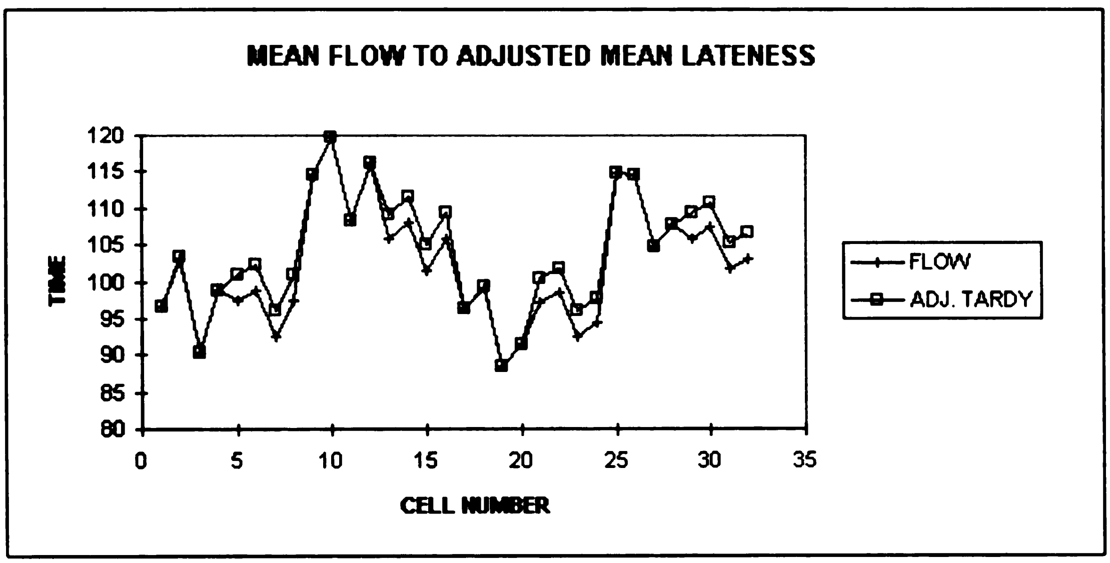

Figure 5-12 Flow Time and Adjusted Lateness

graphic technique employed was simply a linear translation of the lateness measure by adding a fixed value to each data point.

It becomes easy to see that, even though the general movement of the data from each of the measures is similar, there are four series of four points each during which flow times are better (lower) than the adjusted mean lateness values. Examination of the related cell numbers and settings showed that the cells of departure correspond exactly with the change from low setup ratios to high setup ratios. The reason for the difference now becomes clear. The model uses total work to set due date. When the setup to process time ratio goes from low to high, the values used in the model for each setup increases and the corresponding processing time decreases to maintain shop floor loading at a constant level. The values used to set due dates are therefore smaller, setting a due date that is nearer term. The total routing time delay for a release batch has not changed, however, and jobs become more late. Therefore, the mean flow time measure can improve slightly over a series of cells while the mean lateness measure can deteriorate slightly for the same series of cells using these methods.

It is important to note that the overall performance of the Modified SPT rule is still better than the performance of straight SPT in all three of the performance measures for the two levels of setup ratio chosen here. It is also important to note that the relative value of the queue rule decreases for all three performance measures as the setup to process time ratio increases. A conclusion to be drawn is that the queue rule is most valuable under conditions of smaller setup to process time ratios.

Examining the interaction between the queue rule and the station to station process time variance, we find a different set of conditions. Figure 5-13 shows this interaction graphically for the flow time performance measure. In this instance, the value of the decision rule is greater as the process time variance increases. Logically, as the difference in process times from station to station increases, the significance of that size difference to release batch continuity will also increase. The probability that the current processing station will run out of transfer batches of a job type before the preceding station can complete all processing on a release batch increases. Therefore, a rule that checks for preceding station support for the entire release batch should have more value than when the processing times are more similar. This appears to be the case shown in this figure.

Examining the lateness measure for the same queue rule to process time variance interaction, Figure 5-13 presents a similar picture. Both the SPT and the Modified SPT values increase as the process time variance increases, with the SPT lateness increasing faster. Clearly, the same mechanisms are functioning here as in the flow time measurement.

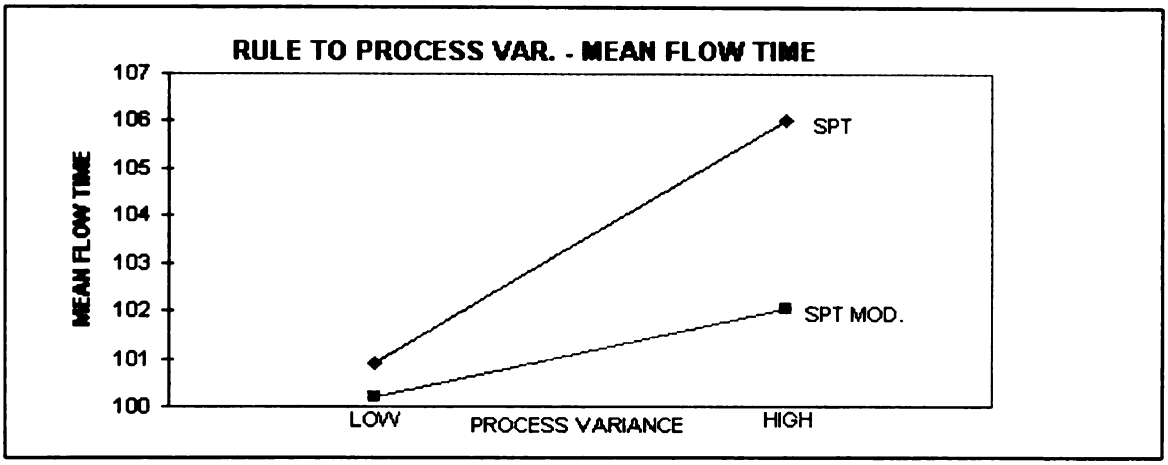

Figure 5-13 Rule to Process Variance - Mean Flow Time

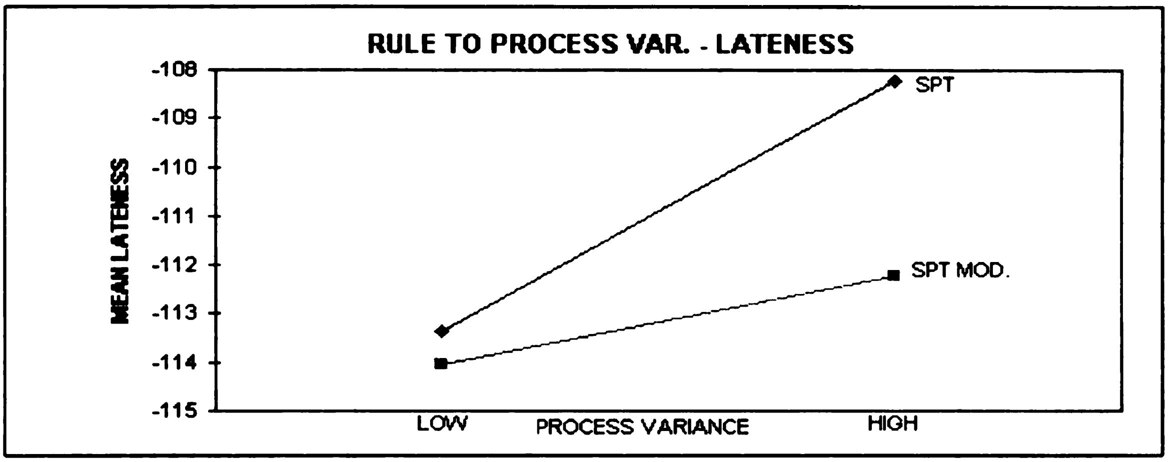

Figure 5-14 Rule to Process Variance - Mean Lateness

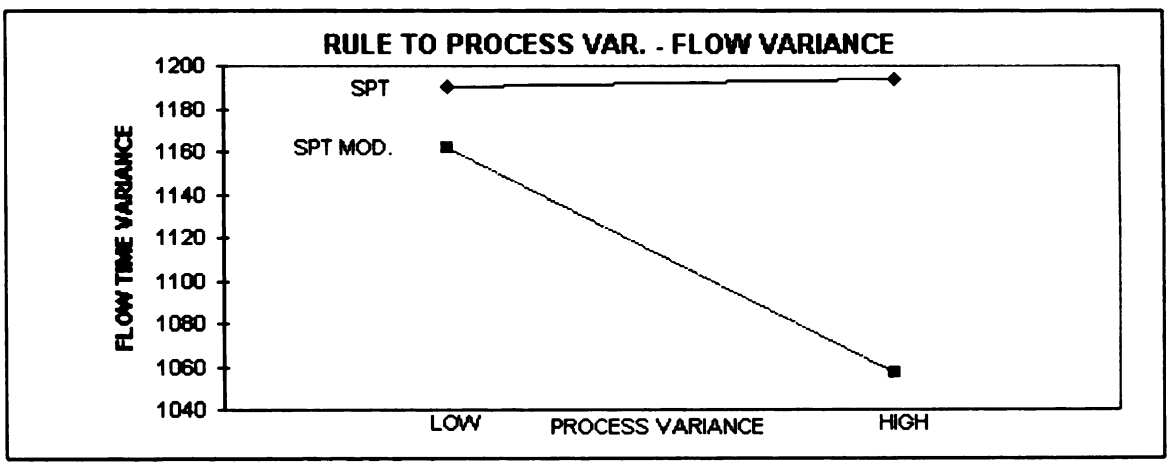

Figure 5-15 Rule to Process Variance - Flow Time Variance

The flow time variance measure produces a somewhat different representation of the interaction, as shown in Figure 5-15. Note that for the flow time variance measure, rather than the Modified SPT producing a measurement deteriorating at a slower rate than regular SPT as the process time variance increases, here the flow time variance improves under Modified SPT with increasing process time variance. Under regular SPT, the variance deteriorates, but only slightly.

A reasonable explanation for the difference in the results provided by these three measures is that variation in process time from station to station does not have a particularly large influence on flow time variance under SPT, even though the effect is significant. However, the elimination of the randomly occurring extra setups through the modification to the SPT rule can and actually does reduce the variance.

In all three of the performance measures used to evaluate the interactions of the queue rule and process time variance, the benefit of the rule was greater for the higher levels of process time variance. Therefore, job shops with relatively large differences in their station to station processing times would benefit more from employing this rule than shops with more homogeneous process times.

The last of the two-way interactions to be examined is the queue management rule with the number of transfer batches. This interaction is significant for mean flow time and mean lateness measures, and is not significant for flow time variance. Figure 5-16 shows the impact of the interaction on mean flow time. The steeper negative slope of the Modified SPT line indicates that, as the number of transfer batches increases, both queue management rules benefit, but the Modified SPT performs better. This finding that increasing transfer batches improves mean flow time under SPT is consistent with previous research (Jacobs and Bragg, 1988). When this interactive effect was discussed in Section 3.1.4, the expectation was that a larger number of transfer batches would more often create situations in which the modified queue management rule would be beneficial. Logically, the larger the number of transfer batches, the greater the opportunities for SPT to break up a release batch. As the total release batch processing time is broken up into incrementally smaller pieces, the probability that the supply from a previous station would be interrupted is

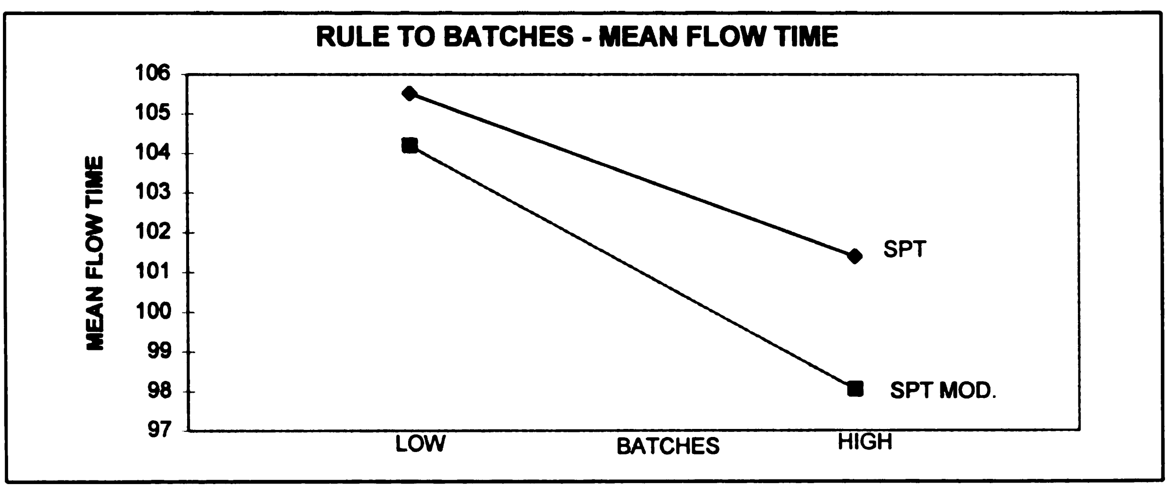

Figure 5-16 Rule to Transfer Batches - Mean Flow Time

greater. This would mean increased setups and longer mean flow times with SPT, as indicated in the figure.

Examination of the lateness measure for the queue rule to transfer batches interaction in Figure 5-17 shows a similar pattern. As the number of transfer batches increases, both queue rules perform better, with the Modified SPT rule improving slightly faster.

In general, the interaction between queue rule and the number of transfer batches indicates that the rule has more value as the number of transfer batches increases. The mechanism of more frequent opportunity for release batch interruption outlined above appears to hold for both time measures.

5.3 Three-Way Interaction

The only significant three-way interaction is among queue rule, setup ratio, and process time variance. This

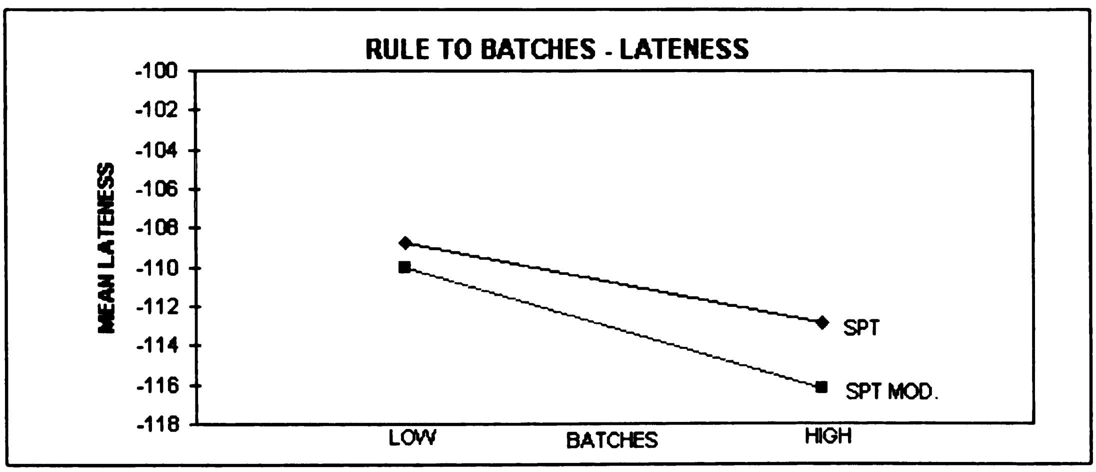

Figure 5-17 Rule to Transfer Batches - Mean Lateness

interaction is significant for all three of the performance measures of interest for which formal hypotheses were tested. The interaction was also significant for two of the three additional measures, namely flow variance and cohesiveness. The percent tardy measure was the only one for which this three way interaction was not significant. The formal hypothesis:

> H_0 = There is no difference in mean flow time under SPT rule modification, increasing shop loading, and increasing setup time to processing time ratio

cannot be rejected, as this particular three-way interaction did not prove significant. However, the same hypothesis, written for the significant three-way interaction as:

> H_0 = There is no difference in mean flow time under SPT rule modification, increasing station to station processing time variance, and increasing setup time to processing time ratio

can be rejected.

Examination of the effects of this interaction will begin with the mean flow time measure. Figure 5-18 and Figure 5-19 together show four perspectives on the interaction of these three factors. Note that, unlike previous figures, Figures 5-18 and 5-19 have common scales for the ordinate in all four charts to make effect size comparisons more straightforward. The first pair of charts in Figure 5-18 examines the conditions as the setup ratio factor changes from the low setting to the high setting, in the first chart with process time variance set low, and, in the second chart, at the high setting. The conclusions to be drawn from these first two charts are similar to those to

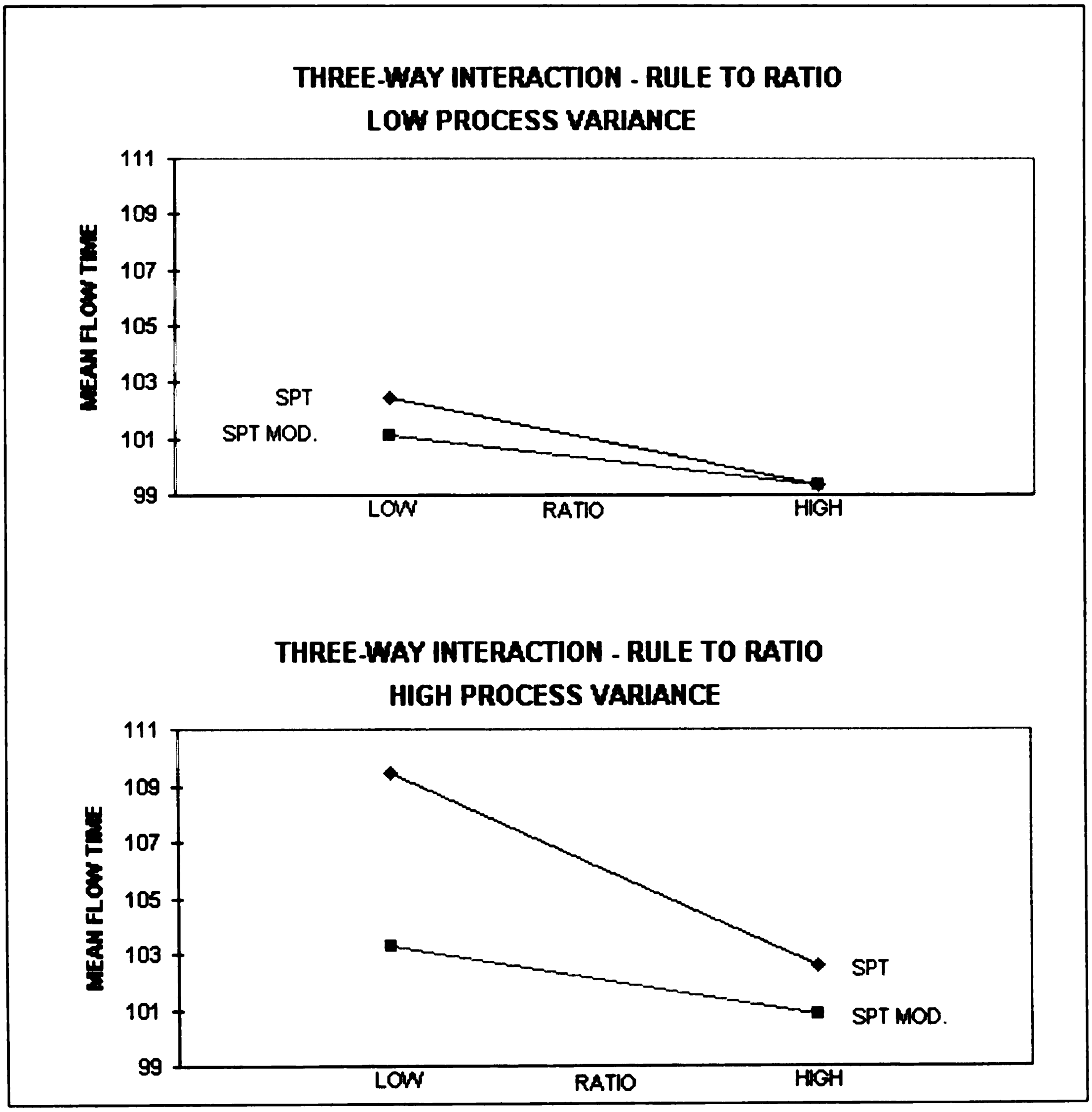

Figure 5-18

Mean Flow 3-Way for Separate Process Variance

be drawn from the two-way interactions. First, the modification to the SPT rule becomes less important as setup time increases relative to process time. When process time variance is low and the setup ratio is high, there is no difference in the performance of the two rules. When the

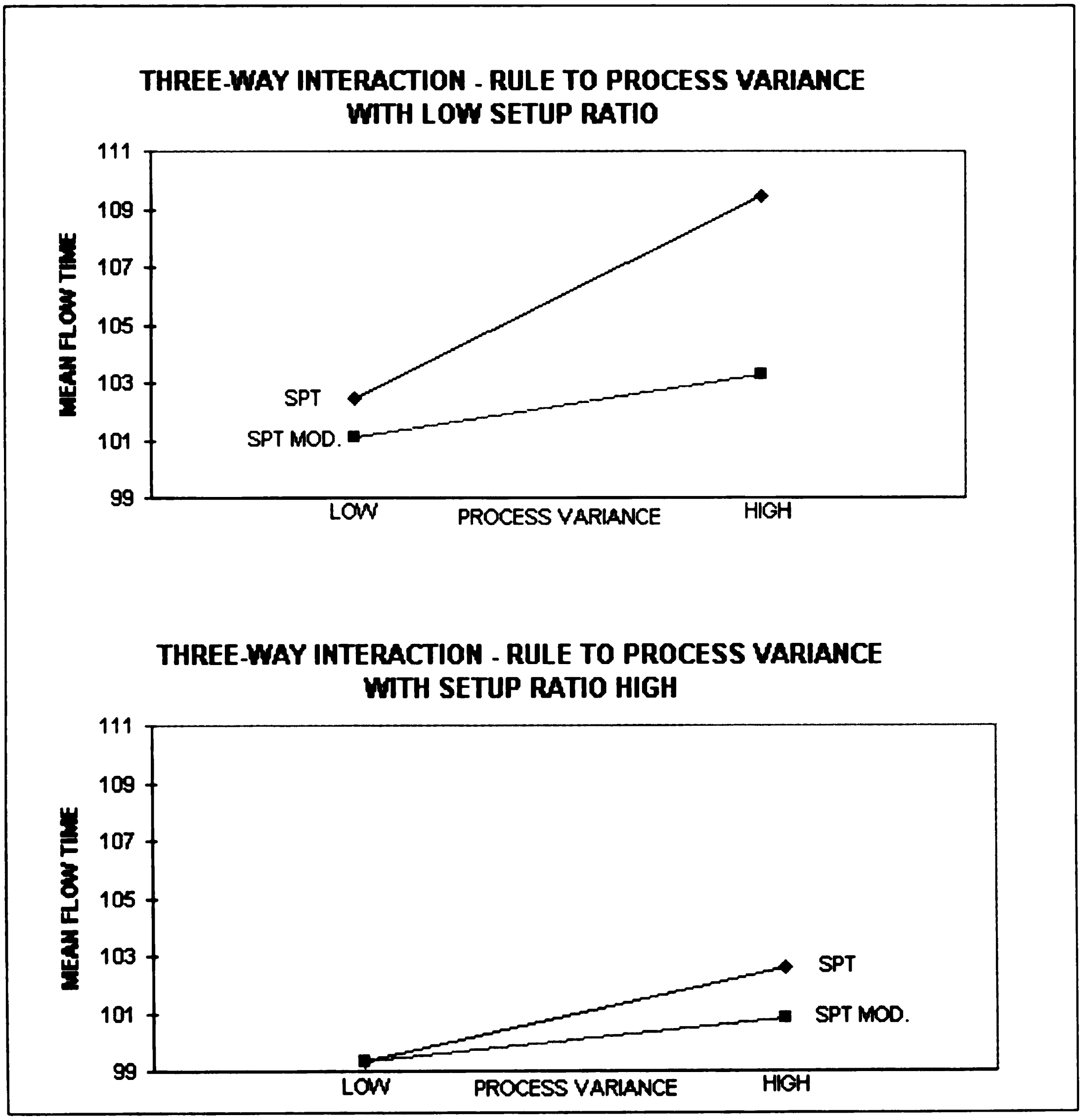

Figure 5-19

Mean Flow 3-Way for Separate Setup Ratio

process time variance is high, however, there is an advantage to using the modification to the rule, although the advantage diminishes as the setup ratio increases. It is also important to note that there is no crossover of any of these response lines, indicating that, for the ranges of factor values tested, Modified SPT never causes performance to deteriorate relative to SPT.

The pair of charts in Figure 5-19 shows the same interaction, viewed from a different perspective. Here, the first chart shows the interaction of the queue rule and the process time variance as the setup ratio is held constant at the low setting. The second chart of the pair shows the same interaction with the setup ratio held at the high setting. This pair of charts shows that the Modified SPT rule has an increasing advantage as the process time variance increases. They also show that, if the setup to process time ratio is low, the benefit of the modification is always there. If the setup to process time ratio is high and the process time variance is low, there is little advantage to the rule modification, but still no disadvantage.

The next two sets of charts, shown in Figure 5-20 and Figure 5-21, present the same contrasts in the same order for the flow time variance performance measure. The first two show a definite advantage for the queue rule modification any time the setup ratio is low, which is enhanced when the process time variance is high. Similarly,

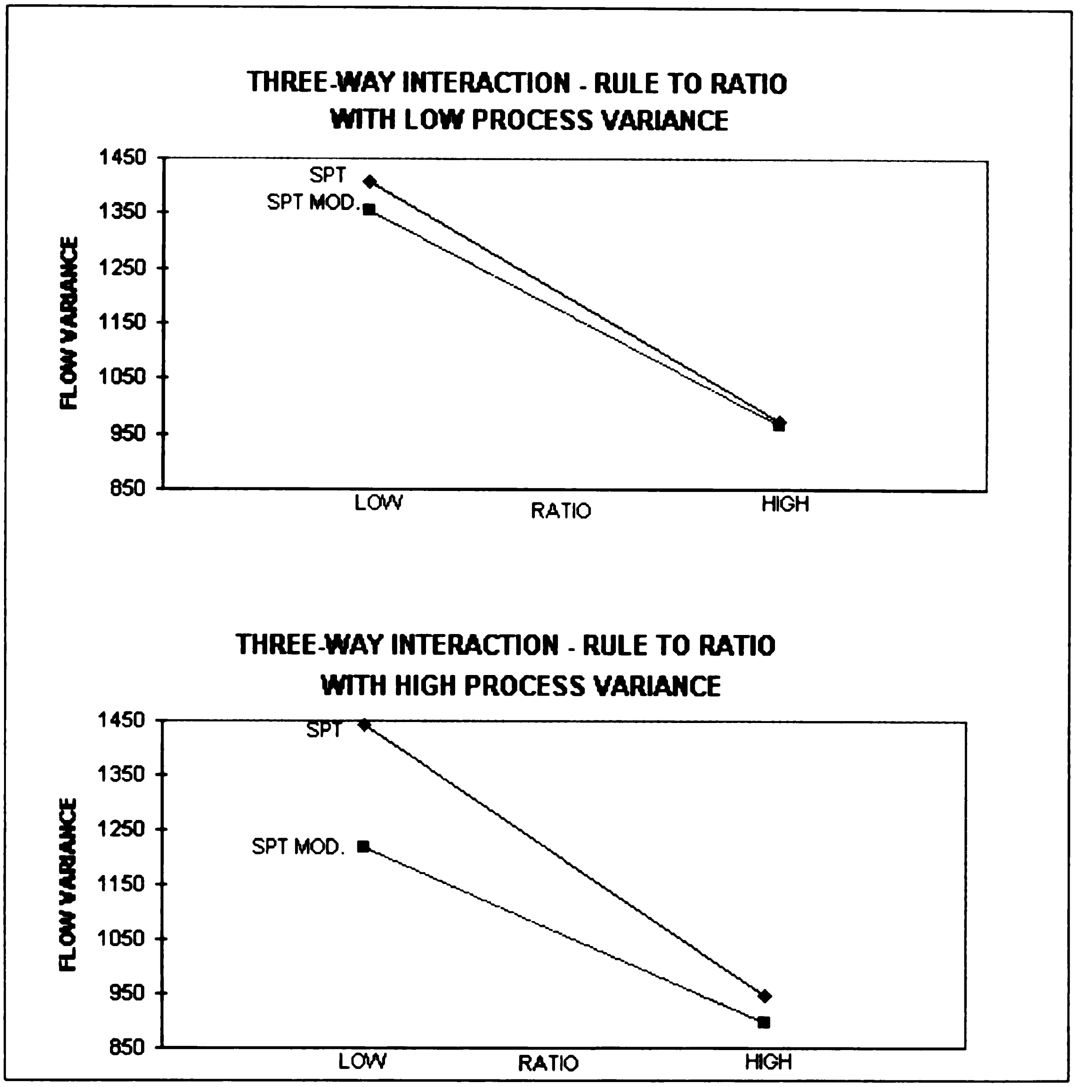

Figure 5-20

Flow Variance 3-Way for Separate Process Variances

when viewed from the perspective of holding the setup ratio constant at each of its two levels as in the second pair of charts (Figure 5-21), increasing levels of station to station process time variance enhances the ability of the modified rule to reduce flow variance. One slight variation

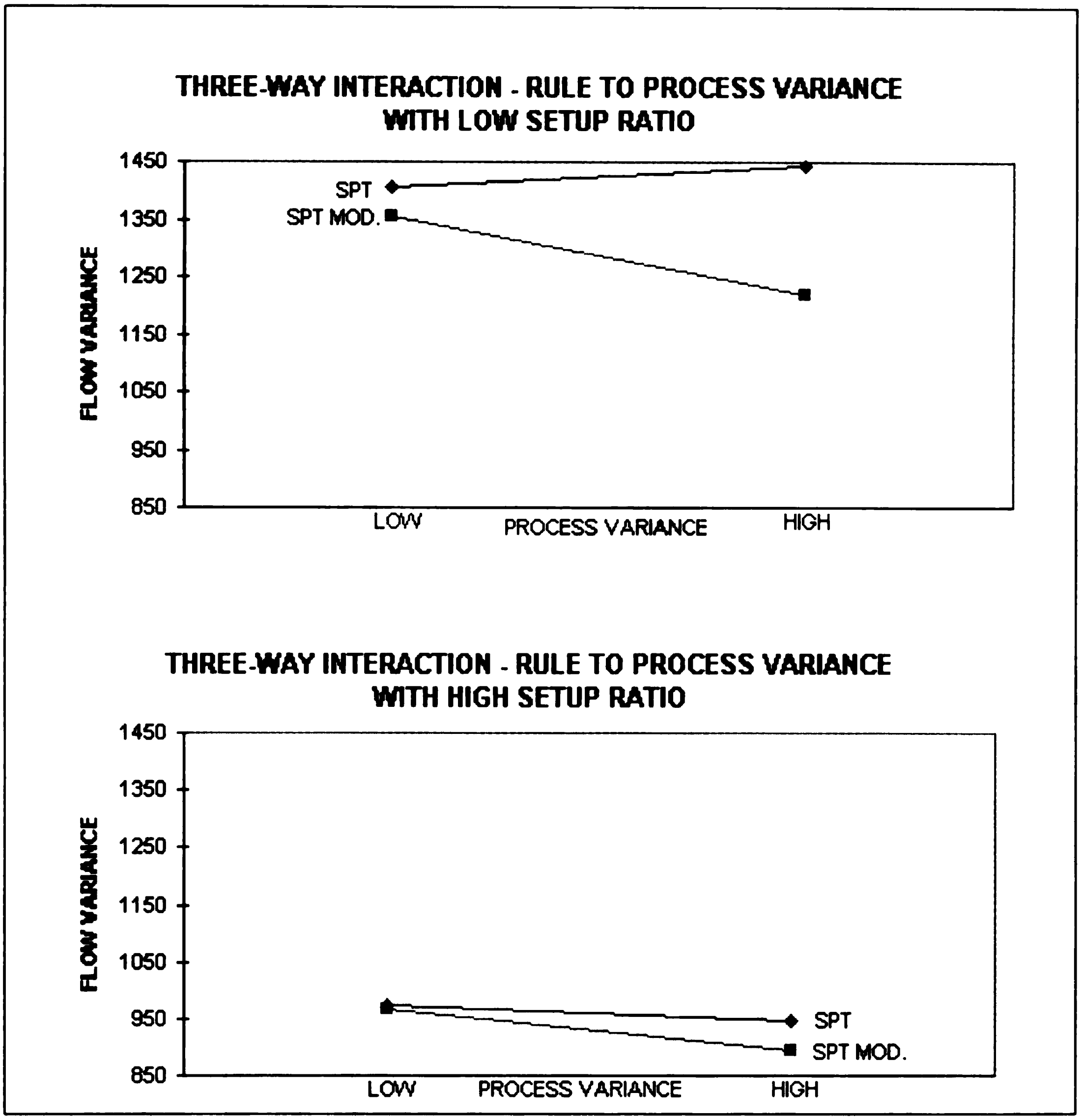

Figure 5-21

Flow Variance 3-Way for Separate Setup Ratio

in this set of charts, however, is the slight deterioration shown for the straight SPT rule as process time variance increases while the setup ratio is held low. The third and final set of charts, presented in Figure 5-22 and in Figure 5-23, shows the three-way interaction as it impacts the lateness measure. These pairs of charts are set up in the

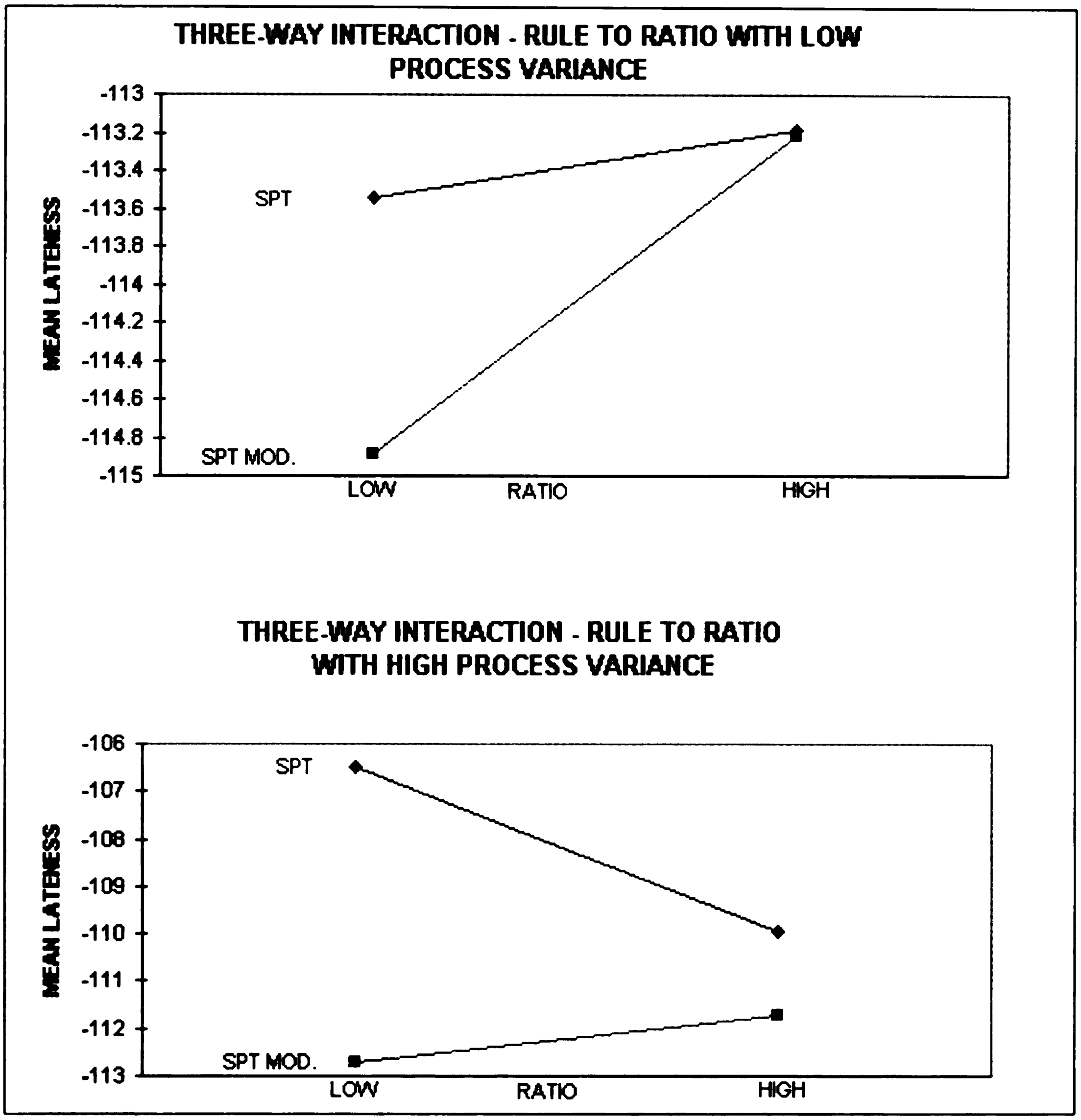

Figure 5-22

Mean Lateness 3-Way for Separate Process Variance

same way. Figure 5-22 shows the relationship of the queue rule to setup ratio for each of the process time variance values. Figure 5-23 shows the other perspective, with queue rule to process time variance for each of the setup ratio

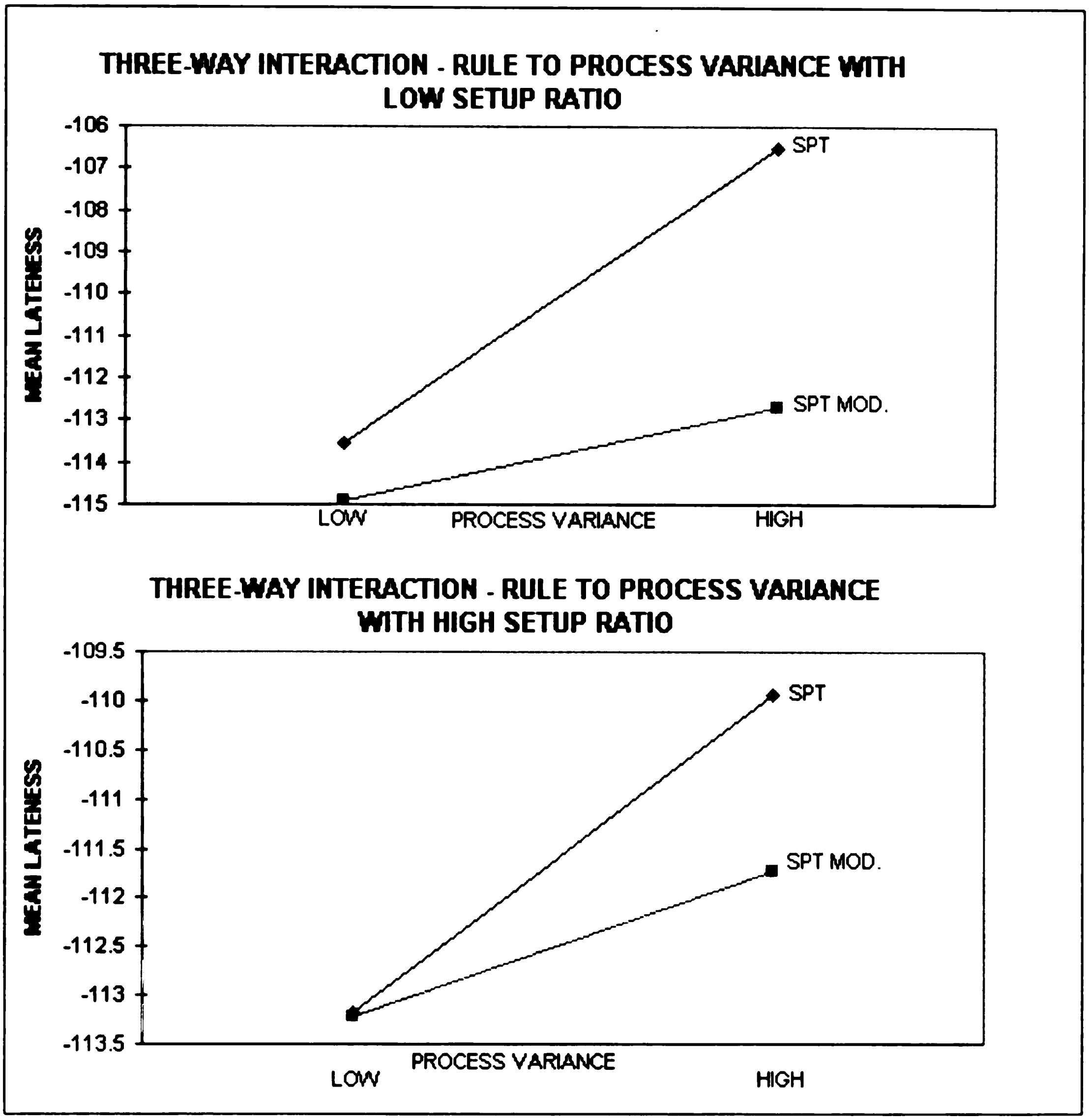

Figure 5-23

Mean Lateness 3-Way for Separate Setup Ratio

values. These charts present very much the same message and result with only slight variations. The lower the setup time ratio and the higher the station to station process time variance, the greater is the improvement impact of the Modified SPT rule.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This chapter begins with a summary of the results discussed in Chapter 5. An analysis of the importance of each of the factors in creating an environment favorable to Modified SPT is also included. The chapter concludes with a discussion of future research opportunities.

6.1 Discussion and Results

Figure 6-1 presents a tabulation of the findings of the study relative to the test of formal hypotheses. First and most important to this study, the Modified SPT rule, as shown is Section 5.2, proved to be always as good or better

#	HYPOTHESES	MEAN FLOW	MEAN LATE	FLOW VARIANCE
1	NO CHANGE - SPT vs. MOD. SPT	REJECT	REJECT	REJECT
2	NO CHANGE - SHOP LOAD AND MOD. SPT INTERACTION	NOT REJECT	NOT REJECT	NOT REJECT
3	NO CHANGE - SETUP RATIO AND MOD. SPT INTERACTION	REJECT	REJECT	REJECT
4	NO CHANGE - TRANS. BATCHES AND MOD. SPT INTERACTION	REJECT	REJECT	NOT REJECT
5	NO CHANGE - PROCESS TIME VAR. AND MOD. SPT INTERACT.	REJECT	REJECT	REJECT
6	NO CHANGE - RULE, LOAD, AND PROCESS VAR. INTERACT.	NOT REJECT	NOT REJECT	NOT REJECT
6.1	NO CHANGE - RULE, RATIO, AND PROCESS VAR. INTERACT.	REJECT	REJECT	REJECT

Figure 6-1 Tabulation of Hypotheses

than the straight application of SPT, for the combinations of factor values tested here. The factor interactions provided insight into conditions that would indicate that the SPT rule modification would improve the performance measures considered in this research. The best conditions for this rule would be a job shop that has the resources and management direction to break release batches into many transfer batches, and that produces parts with low setup to process time ratios and high station to station process time variances. Equally interesting and important to the understanding of the mechanisms at work in this environment is the discovery, that shop loading does not have a significant interaction with the modified SPT rule. This result is particularly useful and important to real world environments because shop work loads will often fluctuate over the course of seasons or from year to year. A rule that is sensitive to this type of fluctuating environment would be less useful. The finding that Modified SPT is robust to shop loading is valuable indeed.

This study has shown that a queue management decision rule that limits job selection to those jobs that can be continuously supported by the preceding work station improves several key performance measures under a variety of conditions. The fact that the rule modification apparently does not penalize the job shop performance measures under less advantageous conditions is somewhat remarkable.

This study also produced useful information about the workings of job shops under transfer batching. The fact that preventing the system from selecting the very shortest processing time for the next batch did not create a large negative effect was probably true only because there were future delays to be traded off against.

It is hoped that this study would create opportunities to implement transfer batching in job shops that have not considered themselves candidates for its implementation. These would be shops that require contiguous arrival of release batches at the shipping dock or at critical work stations that require a single, documented, and verified setup for whole release batches.

6.2 Future Research

This study, interesting and informative as it is, leaves several research issues open for investigation. The first of these is the impact of random breakdown of machines and the supply uncertainty at processing stations on the performance of the modified SPT decision rule. The model tested did not consider this type of uncertainty in order to limit the number of factors investigated and to assess if higher levels of potential performance were to be had. In order to truly identify the value of this type of decision rule, the effect of this type of uncertainty must be explored and appropriate responses developed.

Another type of variance, extant in actual job shops, that was not included in this research was process and setup time uncertainty. While this type of uncertainty and variation is probably smaller than that caused by breakdown or other supply interruption, it does exist and could impact the performance of a decision rule that makes choices based on expected arrivals of further batches.

Future research should be planned to explore the impacts of these two types of uncertainties. Would the best response be to hold the current setup while waiting for the delayed transfer batch or accept an additional setup? Should expected delay information with its own level of uncertainty be used to decide to tear down a setup or to wait?

Another series of questions not answered in this work is the shape of the factor response curves. The flow time data in particular suggests that the process time variance interaction with the queue rule may be curvilinear. The slope would probably flatten out as the variance continued toward zero. Whether the slope becomes steeper at higher levels of variance should be tested. Understanding more about the rate of change in system response to changing process time varinace would help determine which job shops would find this type of modified SPT beneficial.

An additional opportunity for continuing research stems from the lack of evidence showing deterioration in performance measures while using the modified rule. The conditions tested were selected with some expectation that the rule would perform well. Now the question to be answered is whether conditions could be created in which the rule modification would perform more poorly than straight SPT. These tests should be performed with a model in a similar state as this model, with the uncertainties removed.

Also left open in this work are the costs associated with the additional shop floor information required to implement the proposed type of rule. These costs could be significant for some job shops that do not have distributed information systems currently installed. However, if this type of decision rule indeed does make the difference in allowing a job shop to embrace transfer batching, the substatntial gains in flow time improvement and the associated inventory cost savings would go a long way toward financing the installation of such a system.

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Appendix A

The problem setting of this study is a manufacturing system which produces ten different items. The shop consists of ten different machines, each capable of processing a single operation at any point in time with no preemption of operations allowed. Each item's weekly demand is randomly generated from a uniform distribution with a 100-unit average and a range from 60 to 140 units. Processing requirements for each item are determined by a fixed routing specifying the number of operations, machine assignments, setup times, and run times per unit. All routing parameters are randomly assigned.

The average number of operations is five per item with a range of four to six operations. The machine assignments approximate a random-routed job shop with all machines having equal likelihood of being assigned as the first or last operation in the routing (and also having an equal likelihood for selection as the next operation). Each machine is assigned exactly five operations, with no machine assigned twice within any item's routing.

Using a target operation batch size of 200 units, setup times and run times are generated to maintain an equal work load for all machines. Assuming this operation batch size, 90 percent of the total available capacity is allocated to setup and run time in a ratio of 1 to 4. Available capacity, therefore, is divided into 10 percent idle time, 18 percent setup time, and 72 percent run time. The setup times for each operation average one-fifth the total setup time available for the machine. Actual setup times averaged 2.88 hours per setup and ranged between 3.19 and 3.56 hours for all operations at all machines. This can be verified through the following calculation: (2.99 hours/setup) x (5 operations) x (.5 expected setups/week/operation)=7.2 hours/week (the expected setup time on each machine per week). This is 19 percent of the 40 hours available for each machine. The percentage of time required for setup exceeds .778 setups/week/operation, setup requirements exceed 28 percent of system capacity and the system will become unstable.

Similar to setup times, run times are generated with the total run requirement for each operation averaging one-fifth the total run time available at a machine. The system has 72 percent of total capacity available for run time. Actual run times average .0576 hours per unit and range between .0458 and .0782 hours for all operations at all machines. Given that the same demand patterns are always used, these total run-time requirements do not change between simulation runs.

The simulation model is based on a weekly cycle consisting of 40 simulated hours. At the beginning of each week, order release batches are determined using time-phased order-point logic and the fixed-order-quantity (FOQ) lot-sizing rule. For the purposes of this study, a zero lead-time offset was used since flow time is the only performance measure and no forecasting errors are present.

Five replications were generated for all runs, with each replication based on an observation period of 50 consecutive weeks. A 50-week period was used to initialize the system, and each observation period was separated by a 20-week interval. Since the longest observed flow time in any simulation run was less than 10 weeks, the 20-week interval is sufficient to maintain independence between the observations. No transient effects were detected between successive observation periods.

Weekly order releases are made using the fixed release-batch sizes based on FOQ logic or corresponding transfer-batch quantities (depending on whether the RL option is in effect). Using the standard approach, all required processing and material movement is executed while maintaining the entire order quantity. With RL, each release batch is divided into an integer number of transfer batches. Each transfer batch is then released into the shop as a separate job. If the release-batch size is not an integer multiple of the transfer batch, the number of transfer batches is rounded up to the next larger integer. Cumulative release quantities are maintained to insure weekly releases are sufficient to meet all demand requirements.

Sequencing decisions are made based on the rule in effect. All orders waiting for processing at a machine are ranked by either FISFS or SOT. When transfer batches are not used (i.e., the transfer batch equals the release batch) the job is selected in strict first-in-queue (FIQ) order. With RL, either FISFS or SOT sequencing is used, and job selection logic attempts to locate a job of the same type as the job just completed. If a job of the same type is in the queue, it is selected to be processed next with no additional setup time required. If no jobs of the same type are present, the first job in the queue is selected and processing starts following a setup delay. Regardless of the option used, any job arriving at an idle machine starts processing immediately. All machines maintain their last setup until a different type of job is processed.

APPENDIX B
SIMAN CODE LISTING

```
BEGIN,1,1,YES,job10,YES;
;
;          SET PROBABILISTIC DEMAND FOR THE WEEK
;
           CREATE,1,0.0:40.0,X(41):MARK(1);
           EVENT:6;
           ASSIGN:X(41)=32000;
           DELAY:0:DISPOSE;
;
           CREATE,X(1),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=1;
           ASSIGN:A(10)=1:NEXT(GOHERE);      !  ATTRIB. 10 IS PART TYPE
;
           CREATE,X(2),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=2;
           ASSIGN:A(10)=2:NEXT(GOHERE);
;
           CREATE,X(3),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=3;
           ASSIGN:A(10)=3:NEXT(GOHERE);
;
           CREATE,X(4),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=4;
           ASSIGN:A(10)=4:NEXT(GOHERE);
;
           CREATE,X(5),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=5;
           ASSIGN:A(10)=5:NEXT(GOHERE);
;
           CREATE,X(6),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=6;
           ASSIGN:A(10)=6:NEXT(GOHERE);
;
           CREATE,X(7),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=7;
           ASSIGN:A(10)=7:NEXT(GOHERE);
;
           CREATE,X(8),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=8;
           ASSIGN:A(10)=8:NEXT(GOHERE);
;
           CREATE,X(9),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=9;
           ASSIGN:A(10)=9:NEXT(GOHERE);
;
           CREATE,X(10),0.0:40.0,x(41):MARK(1);
           ASSIGN:NS=10;
           ASSIGN:A(10)=10:NEXT(GOHERE);
;
```

```
GOHERE  EVENT:4;                ! SET RELEASE BATCH INDEX NUMBER
        DUPLICATE:X(42);        ! CREATE FOQ ENTITIES
        EVENT:1;  !  ATTACHES ROUTING, SETUP, AND PROCESS TIMES
        ASSIGN:A(4)=1;
        ASSIGN:J=A(4);
        ASSIGN:A(5)=A(J+10);
        EVENT:7;                ! PLACES THE JOB IN THE APPROPRIATE QUEUE
;
        STATION,1;
        QUEUE,101;
        SEIZE,1:MACH(1),1;
        DELAY:X(M+10)*A(6);        ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);        ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(1),1;
        ASSIGN:S(1)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,2;
        QUEUE,102;
        SEIZE,1:MACH(2),1;
        DELAY:X(M+10)*A(6);        ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);        ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(2),1;
        ASSIGN:S(2)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,3;
        QUEUE,103;
        SEIZE,1:MACH(3),1;
        DELAY:X(M+10)*A(6);        ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);        ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(3),1;
        ASSIGN:S(3)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,4;
        QUEUE,104;
        SEIZE,1:MACH(4),1;
        DELAY:X(M+10)*A(6);        ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);        ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(4),1;
        ASSIGN:S(4)=TNOW;
        EVENT:5;
```

```
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,5;
        QUEUE,105;
        SEIZE,1:MACH(5),1;
        DELAY:X(M+10)*A(6);          ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                  ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);          ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(5),1;
        ASSIGN:S(5)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,6;
        QUEUE,106;
        SEIZE,1:MACH(6),1;
        DELAY:X(M+10)*A(6);          ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                  ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);          ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(6),1;
        ASSIGN:S(6)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,7;
        QUEUE,107;
        SEIZE,1:MACH(7),1;
        DELAY:X(M+10)*A(6);          ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                  ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);          ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(7),1;
        ASSIGN:S(7)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,8;
        QUEUE,108;
        SEIZE,1:MACH(8),1;
        DELAY:X(M+10)*A(6);          ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                  ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);          ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(8),1;
        ASSIGN:S(8)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,9;
        QUEUE,109;
        SEIZE,1:MACH(9),1;
        DELAY:X(M+10)*A(6);          ! SETUP DELAY (X IS 0-1)
```

```
        DELAY:A(7);                     ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);            ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(9),1;
        ASSIGN:S(9)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
        STATION,10;
        QUEUE,110;
        SEIZE,1:MACH(10),1;
        DELAY:X(M+10)*A(6);             ! SETUP DELAY (X IS 0-1)
        DELAY:A(7);                     ! MACHINE DELAY
        ASSIGN:X(M+20)=A(10);            ! SET TYPE OF LAST JOB DONE
        ASSIGN:X(M+30)=(A(9)/1000)+A(8);
        RELEASE:MACH(10),1;
        ASSIGN:S(10)=TNOW;
        EVENT:5;
        ASSIGN:A(4)=A(4)+1:NEXT(COMM); ! INCREASE ROUTING STEP NUMBER
;
COMM    ASSIGN:J=A(4);
        ASSIGN:A(5)=A(J+10);
        BRANCH,1:
         IF,A(5).LT.11,THIS1:
         ELSE,THIS2;
THIS1   EVENT:7;
THIS2   ROUTE:0.0,A(5);
;
;
        STATION,11;                  !  EXIT STATION TO COLLECT DATA
        EVENT:3;
        EVENT:2;
        QUEUE,111;
        TALLY:6,INT(2):DISPOSE;
;
END;
```

APPENDIX C
FORTRAN EXIT CODE LISTING

```
SUBROUTINE PRIME
       COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
       COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
C   INITIALIZE INCREMENTAL LABLES
       X(44) = 1
       X(41)=10
C   6
C    SET NUMBER OF TRANSFER BATCHES (X42 = TRANSFER BATCHES - 1),
C    TRANSFER BATCH QUANTITY MULTIPLIER ( X46), AND RULE INDICATOR
       IF (NRUN .EQ. 1) THEN
       X(42) = 3.0
       X(46) = 0
       X(47) = 1.0
       X(48) = 200
       ENDIF
       PRINT *, "CELL NUMBER 1"
       PRINT *, "CELL 1"
       PRINT *, "TRANSFER BATCHES = ",(X(42)+1)
       PRINT *, "JOB SELECTION RULE (1=SPT,2=MODSPT) = ",X(47)
       PRINT *, "RELEASE BATCH = ", X(48)
30     CONTINUE
C   26
       OPEN(15,FILE='PROCLTSV.DAT',ACCESS='SEQUENTIAL',
     +         STATUS='OLD')
       PRINT *,"PROCESS TIME FILE IS 'PROCLTSV.DAT' "
       DO 33 I=1,70
       READ(15,700) OPTIME(I)
       OPTIME(I) = (OPTIME(I)/100*X(48)) / (X(42)+1)
C       PRINT *, I, OPTIME(I)
 33    CONTINUE
 700   FORMAT(F5.3)
       CLOSE(15)
       OPEN(15,FILE='SEQUENC1.DAT',ACCESS='SEQUENTIAL',
     +         STATUS='OLD')
       DO 34 I=1,70
       READ(15,701) ROUTE(I)
 34    CONTINUE
 701   FORMAT(F5.1)
       CLOSE(15)
 60    CONTINUE
       CLOSE(1)
       OPEN(15,FILE='SETSMALL.DAT',ACCESS='SEQUENTIAL',
     +         STATUS='OLD')
       PRINT *,"SETUP TIME FILE IS 'SETSMALL.DAT' "
       DO 35 I=1,70
       READ(15,702) SETUP(I)
 35    CONTINUE
 702   FORMAT(F5.3)
       CLOSE(15)
```

```
      RETURN
      END
C*****************************************************************
C  55
      SUBROUTINE EVENT(JOB,N)
      COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
      COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
      GOTO(1,2,3,4,5,6,7),N
C  60
1     CALL SETVAR(JOB,N)
      RETURN
C  63
2     CALL TEST(JOB,N)
      RETURN
C  66
3     CALL COHESIVE(JOB,N)
      RETURN
C  69
4     CALL SETBATCH(JOB,N)
      RETURN
C  72
5     CALL PICKBAT(JOB,N)
      RETURN
C  75
6     CALL SETDMND(JOB,N)
      RETURN
C  78
7     CALL QUEUEIT(JOB,N)
      RETURN
      END
C********1*********2*********3*********4*********5*********6*********7**
C  83
      SUBROUTINE TEST(JOB,N)
      COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
      COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
C      OPEN(1,FILE='GRP.RAW',ACCESS='SEQUENTIAL',
C    +         STATUS='OLD')
C      T1=N
C      ICOUNT = ICOUNT + 1
C      IF (MOD(ICOUNT,100) .EQ. 1) THEN
C      PRINT *,A(JOB,10),ICOUNT,TNOW
C      PRINT *,X(1),X(2),X(3),X(4),X(5)
C    +        ,X(6),X(7),X(8),X(9),X(10)
C      ENDIF
C      CLOSE(1)
      RETURN
      END
C********1*********2*********3*********4*********5*********6*********7**
C  106
      SUBROUTINE SETVAR(JOB,N)
      COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
      COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
C
C  111 DO LOOP TO LOAD ROUTE TO ATTRIBUTES 11-17
```

```
C
      T1=N
      TYPE=A(JOB,10)
      DO 39 I=1,7
      SPOT=(7*(TYPE-1))+I
      ITT=10+I
      CALL SETA(JOB,ITT,ROUTE(SPOT))
 39   CONTINUE
C  136
      PAR1=A(JOB,8)
      IF (PAR1 .NE. X(45)) THEN
      X(45) = PAR1
      X(43) = 1.0
      ENDIF
      CALL SETA(JOB,9,X(43))
      X(43) = X(43) + 1
      SPOT=(7*(TYPE-1))
      DATE1 = OPTIME(SPOT+1)+OPTIME(SPOT+2)+OPTIME(SPOT+3)
      DATE2 = OPTIME(SPOT+4)+OPTIME(SPOT+5)+OPTIME(SPOT+6)
      DATE3 = OPTIME(SPOT+7)
      DATE4 = SETUP(SPOT+3)+SETUP(SPOT+4)+SETUP(SPOT+5)
      DATE5 = SETUP(SPOT+6)+SETUP(SPOT+7)+SETUP(SPOT+1)
     +    +SETUP(SPOT+2)
      RDATE = ((DATE1+DATE2+DATE3)*(X(42)+1)+DATE4+DATE5)*3
      RDATE1 = RDATE + TNOW
      CALL SETA(JOB,2,RDATE1)
      RETURN
      END
C  151
C **********************************************************************
      SUBROUTINE COHESIVE(JOB,N)
      COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
      COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
      T1=N
      NINE = A(JOB,9)
C     IF THIS IS THE FIRST TBATCH TO COMPLETE, SET COMPLETION TIME
      IF (NINE .EQ. 1) THEN
      S(10+A(JOB,10)) = TNOW
      ENDIF
C     IF THIS IS THE LAST TRANSFER BATCH, CALC. # OF TBATCHES LESS ONE
C     MULTIPLIED BY THE PROCESSING TIME OF THE LAST STATION
      IF (NINE .EQ. (X(42)+1)) THEN
      X(49) = X(49) + 1
      LSTEP = (A(JOB,4)-1)+.5
      PTIME = OPTIME(((A(JOB,10)-1)*7) + LSTEP)
      PTMIN = PTIME*X(42)
      TIMDIF = (TNOW - S(10+A(JOB,10)))
      COHES1 = PTMIN / TIMDIF
      COHES = (REAL(INT(COHES1*100+.5)))/100
      FLOW = TNOW-A(JOB,1)
      LATE = TNOW - A(JOB,2)
          IF (LATE .LT. 0)THEN
          ILATE = 0
          ELSE
```

```
           ILATE = 1
           ENDIF
       CALL TALLY(7,COHES)
          OPEN(1,FILE='CELL01.DAT',ACCESS='SEQUENTIAL',
     +         STATUS='UNKNOWN')
          WRITE(1,201) X(49), FLOW, COHES, LATE, ILATE, X(50)
 201      FORMAT(F10.4, F10.4, F10.4, F10.4, I4, F10.4)
            IF (X(49) .EQ. 100) THEN
            CALL SUMRY
            ENDIF
            IF (X(49) .EQ. 5100) THEN
            CALL SUMRY
            X(41)=0
            ENDIF
       ENDIF
       TDIF = TNOW - A(JOB,1)
           CALL TALLY(1,TDIF)
           QSET = A(JOB,18)
           DSET = A(JOB,19)
           DSEQ = A(JOB,20)
           DLOT = A(JOB,21)
           CALL TALLY(8,QSET)
           CALL TALLY(9,DSET)
           CALL TALLY(10,DSEQ)
           CALL TALLY(11,DLOT)
 300   RETURN
       END
C ********************************************************************
C  201
       SUBROUTINE SETBATCH(JOB,N)
       COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
       COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
       T1=N
       CALL SETA(JOB,8,X(44))
       X(44)=X(44)+1
       RETURN
       END
C ********************************************************************
C  211
       SUBROUTINE PICKBAT(JOB,N)
       COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
       COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
       DIMENSION B(10,2)
       T1=N
C    CALCULATE THE BLOCK OF QUEUES OF INTEREST
       NBLOK = 10*(A(JOB,5)-1)+.01
       NQUEUE = NBLOK + A(JOB,10)
       L1 = A(JOB,5)
       L2 = NR(L1)
       PARA = ((A(JOB,9)/1000)+A(JOB,8))
       PAR1 = X(A(JOB,5) + 10)
       PAR2 = X(A(JOB,5) + 20)
       PAR3 = X(A(JOB,5) + 30)
C  226
```

```
C    IF THIS IS THE FIRST BATCH, GO RIGHT TO JOB SELECTION
       IF (PAR3 .EQ. 0) THEN
       GOTO 200
       ENDIF
C     CALCULATE THE LAST TRANSFER BATCH PROCESSED
       LONE = INT(PAR3)
       LTWO = ((PAR3 - LONE)*1000)+.5
       LTHREE = X(20 + A(JOB,5))+.5
       LASTQ = NBLOK + LTHREE
       NUMQ = NQ(LASTQ)
C  237 LAST TRANSFER BATCH, YES
       IF (LTWO .GT. (X(42)+.5)) THEN
C           ANOTHER RELEASE BATCH OF SAME KIND IN Q, YES
           QNOW = LFR(LASTQ)
           IF ( QNOW .GT. 0) THEN
C               IS JOB SELECTION RULE MODIFIED SPT, YES
               IF ( X(47) .EQ. 2) THEN
C                   CAN PREVIOUS STATION SUPPORT SELECTION, YES
                   ISEQ = A(LFR(LASTQ),4)+.01
                   PREPRO = OPTIME(((A(LFR(LASTQ),10)-1)*7)+(ISEQ-1))
                   WAIT=((X(42)+1-NUMQ)*PREPRO)
                   PTIME=(X(42) * A(LFR(LASTQ),7))
                   IF ((NUMQ .GT. X(42)) .OR. ( WAIT .LT. PTIME)) THEN
                   GO TO 300
C                   CAN PREVIOUS STATION SUPPORT SELECTION, NO
                   ELSE
                   CALL COUNT(2,1)
                   GOTO 200
                   ENDIF
               ELSE
               GOTO 300
               ENDIF
C           ANOTHER RELEASE BATCH OF SAME KIND IN Q, NO
           ELSE
           GO TO 200
           ENDIF
C  262  LAST TRANSFER BATCH, NO
       ELSE
C           MORE TRANSFER BATCHES AVAILABLE, YES
           QNOW = LFR(NBLOK + LTHREE)
           IF (QNOW .GT. 0) THEN
           GOTO 300
C           MORE TRANSFER BATCHES AVAILABLE, NO
           ELSE
C           INCREMENT MIN SETUP VIOLATION COUNTER, THEN SELECT NEXT
               IF (PAR3 .NE. 0) THEN
               CALL COUNT(1,1)
               ENDIF
           GOTO 200
           ENDIF
       ENDIF
C        SET DECISION MATRIX WITH RUN TIMES
C        IF NEW JOB TYPE REQIRED, SET EMPTY QUEUE PROCESSING TIME
C 279    TO LARGE (99999) AND SELECT QUEUE ASSOCIATED WITH THE
```

```
C        MIN. PROCESS TIME
 200    DO 25 I=1,10
          IF (LFR(NBLOK+I) .GT. 0) THEN
          B(I,1) = A(LFR(NBLOK+I),7)
C    + A(LFR(NBLOK+I),6)
          ELSE
          B(I,1) = 99999
          ENDIF
 24     B(I,2) = I
 25     CONTINUE
 26     DO 29 I=1,9
          IF (B(I,1) .LT. B(I+1,1)) THEN
          BTEMP1 = B(I,1)
          BTEMP2 = B(I,2)
          B(I,1) = B(I+1,1)
          B(I,2) = B(I+1,2)
          B(I+1,1) = BTEMP1
          B(I+1,2) = BTEMP2
          ENDIF
 29     CONTINUE
        IF (B(10,1) .GT. 90000) THEN
        GOTO 600
        ENDIF
        NEXTQ = B(10,2)
        NEXT1=LFR(NBLOK+NEXTQ)
C           IS JOB SELECTION RULE MODIFIED SPT
            IF ( X(47) .EQ. 2) THEN
            NUMQ = NQ(NBLOK+NEXTQ)
            ISEQ = A(NEXT1,4)+.001
            PREPRO = OPTIME(((A(NEXT1,10)-1)*7)+(ISEQ-1))
            WAIT=((X(42)+1-NUMQ)*PREPRO)
            PTIME=(X(42) * A(NEXT1,7)) + A(NEXT1,6)
C 310           CAN JOB IN B(10,2) BE SUPPORTED BY PREV. STATION
                IF (WAIT .LT. PTIME) THEN
                X(10 + L1) = 1
                GOTO 500
                ELSE
C                   WAS THIS PART CHECKED BEFORE?
                    IF ( B(10,1) .LT. 50000) THEN
C                   INCREMENT RULE INVOCATION COUNTER
                    CALL COUNT(2,1)
                    B(10,1) = B(10,1) + 50000
                    GOTO 26
                    ELSE
C        'COMMENT' THE NEXT LINE OUT TO ALLOW 'RULE OVERRIDE'.  EXIT
C        AT THIS POINT PREVENTS SELECTION OF UNSUPPORTABLE BATCH.
                    GOTO 600
C                     COUNT NUMBER OF RULE OVERRIDES
                    CALL COUNT(3,1)
                    ENDIF
                ENDIF
            ENDIF
        X(10 + L1) = 1
        GOTO 500
```

```
C 332   SELECT SAME JOB TYPE FOR CONTINUED PROCESSING
 300    NEXTQ=PAR2 + .5
        NEXT1=LFR(NBLOK + NEXTQ)
        X(10 + A(JOB,5)) = 0
 500    INDIC = 1
C         SET TIME OF THE START OF AN ACTUAL SETUP
          IF ( (X(10 + A(JOB,5))) .EQ. 1) THEN
          S(30 + L1) = TNOW
          S(40 + L1) = TNOW + A(NEXT1,6)
          ENDIF
C       CALCULATE DELAY VALUES
        QSET = MAX( (S(30 + L1) - A(NEXT1,3)) , 0)
        QSET1 = QSET + A(NEXT1,18)
        DSET = MAX( (S(40 + L1) - MAX (S(30 + L1),A(NEXT1,3)) ),0 )
        DSET1 = DSET + A(NEXT1,19)
        DSEQ = MAX(TNOW,S(40 + L1)) - MAX ( S(40 + L1), A(NEXT1,3) )
        DSEQ1 = DSEQ + A(NEXT1,20)
        DLOT = A(NEXT1,7)
        DLOT1 = DLOT + A(NEXT1,21)
C       STORE DELAY VALUES
        CALL SETA(NEXT1,18,QSET1)
        CALL SETA(NEXT1,19,DSET1)
        CALL SETA(NEXT1,20,DSEQ1)
        CALL SETA(NEXT1,21,DLOT1)
        CALL REMOVE(NEXT1,(NBLOK + NEXTQ))
        CALL ENTER(NEXT1,L1)
C       SET
        TIME = TNOW - S(L1)
        TIME1 = ((TNOW - S(L1)) * 10) + .5
        ITIME = INT(TIME1/10)
        X(50) = X(50) + TIME
        CALL COUNT(4,ITIME)
 600    CONTINUE
        INDIC = 0
        RETURN
        END
C 376
C *********************************************************************
C 378
        SUBROUTINE SETDMND(JOB,N)
        COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
        COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
        T1 = N
        T2 = JOB
        DO 25 I=21,30
        X(I-20) = 0
            IF(X(41) .EQ. 0) THEN
            GOTO 25
            ENDIF
        IQUAN = UN(11,1)
        IQUAN = IQUAN + X(46)
        S(I) = S(I) + IQUAN
 10     CONTINUE
        IF (S(I) .GT. 0) THEN
```

```
      S(I) = S(I) - X(48)
      X(I-20) = X(I-20) + 1
      GOTO 10
      ENDIF
 25   CONTINUE
      RETURN
      END
C 397
C **********************************************************************
C 399
      SUBROUTINE QUEUEIT(JOB,N)
      COMMON/SIM/D(50),DL(50),S(50),SL(50),X(50),DTNOW,TNOW,TFIN,J,NRUN
      COMMON/LOT/ROUTE(70),OPTIME(70),SETUP(70),SEQ,JOBNO
      T1 = N
C    CALCULATE THE BLOCK OF QUEUES OF INTEREST
      NBLOK = 10*(A(JOB,5)-1)+.01
      NQUEUE = NBLOK + A(JOB,10)
      L1 = A(JOB,5)
      L2 = NR(L1)
      PARA = ((A(JOB,9)/1000)+A(JOB,8))
      PAR3 = X(A(JOB,5) + 30)
      PROCES = OPTIME((A(JOB,10)-1)*7 + A(JOB,4))
      SETUPT = SETUP((A(JOB,10)-1)*7 + A(JOB,4))
      CALL SETA(JOB,6,SETUPT)
      CALL SETA(JOB,7,PROCES)
C  413
C    FOLLOWING TEST, IF TRUE, INDICATES EVENT PRECEDING QUEUE
      IF (PARA .NE. PAR3) THEN
      CALL SETA(JOB,3,TNOW)
      CALL INSERT(JOB,NQUEUE)
      ENDIF
      IF (L2 .EQ. 0) THEN
      CALL PICKBAT(JOB,N)
      ENDIF
      RETURN
      END
```

APPENDIX D
DICTIONARY OF VARIABLES

GLOBAL VARIABLES

X1 THROUGH X10 - RANDOMLY GENERATED WEEKLY DEMAND BY PART TYPE
X11 - X20 - 0-1 MULTIPLIER FOR SETUP TIME DELAY
X21 - X30 - SET TO LAST PART TYPE RUN AT MACHINE (M+20)
X31 - X40 - SET TO LAST RELEASE AND TRANSFER BATCH NUMBER AT A MACHINE (RRRRRR.TTT)
X41 - MAXIMUM NUMBER OF ENTITIES OF EACH TYPE TO GERNEATE
X42 - NUMBER OF DUPLICAT BATCHES TO MAKE (X42 = TRANSFER BATCHES - 1)
X43 - LAST TRANSFER BATCH INDEX NUMBER ASSIGNED
X44 - RELEASE BATCH NUMBER - SERIALIZED
X45 - CURRENT RELEASE BATCH FOR SERIALIZING TRANSFER BATCHES
X47 - JOB SELECTION RULE INDICATOR (1=SPT,2=MODSPT)
X48 - RELEASE BATCH QUANTITY

STATE VARIABLES
S1 - S10 - TIME OF COMPLETION OF PROCESSING AT EACH STATION
S11 - S20 - TIME OF ARRIVAL OF FIRST TRANSFER BATCH OF RELEASE BATCH
S21 - S30 - ORDER BACKLOG BY PART TYPE
S31 - S40 - START TIME OF LAST SETUP BY STATION (30+M)
S41 - S50 - END TIME OF LAST SETUP BY STATION (40+M)
ATTRIBUTES

A1 - ORDER RELEASE TIME
A2 - DUE DATE ASSIGNED
A3 - TIME STAMP ENTRY TO QUEUE
A4 - MODEL-SET SEQUENCE STEP NUMBER (INDEXED AS EACH STEP IS COMPLETED)
A5 - CURENT STATION NUMBER
A6 - CURRENT STATION SETUP DELAY
A7 - CURRENT STATION OPERATION TIME
A8 - RELEASE BATCH NUMBER
A9 - TRANSFER JOB INDEX NUMBER
A10 - PART TYPE (1 - 10)
A11 - PROCESSING STATION NUMBER 1
A12 - PROCESSING STATION NUMBER 2
A13 - PROCESSING STATION NUMBER 3
A14 - PROCESSING STATION NUMBER 4
A15 - PROCESSING STATION NUMBER 5
A16 - PROCESSING STATION NUMBER 6
A17 - PROCESSING STATION NUMBER 7
A18 - QUEUE DELAY TIME STORAGE
A19 - SETUP DELAY TIME STORAGE
A20 - SEQUENCE DELAY TIME STORAGE
A21 - LOT DELAY TIME STORAGE
A22 -
A23 -
A24 -
A25 -
A26 -
A27 -

A28 -
A29 -
A30 -
A31 -
A32 -
A33 -
A34 -
A35 -
A36 -
A37 -
A38 -
A39 -
A40 -

SEQUENCE OF PROCESSING - SEQUENCE.DAT (I3 7X10)
SETUP TIMES BY PART TYPE AND MACHINE - SETTIMES.DAT (F6.3 7X10)
PROCESSING TIMES BY PART AND MACHINE - PROCTIME.DAT (F6.3 7X10)

TALLIES
1 PROCESS TIME 1
2 PROCESS TIME 2
3 PROCESS TIME 3
4 PROCESS TIME 4
5 PROCESS TIME 5
6 TARDINESS
7 COHESIVENESS
8 QUEUE DELAY
9 SETUP DELAY
10 SEQUENCE DELAY
11 LOT DELAY

COUNTS
1 MIN SETUP VIOL
2 RULE INVOKED
3 RULE OVERRIDDEN
4 MACH. IDLE TIME

APPENDIX E
PILOT DATA ANALYSIS CODING
ORIGINAL CODING BY V. KANNON
MODIFIED FOR THIS APPLICATION

```
      PROGRAM PILOT
      INTEGER END,CELLNO,BATCHS,START,FINISH
      REAL CUM(1000),MOMENT(100),MBAR,NTMP,JOB(1000),JOBFT,
     +   NORMAL(100),LRAVE,LRVAR,ITMP,MEAN(100)
      LOGICAL SORT
*
* 07
*
      OPEN(01,FILE='CELL01.DAT',ACCESS='SEQUENTIAL',STATUS='UNKNOWN')
      OPEN(02,FILE='01OUT.OUT',ACCESS='SEQUENTIAL',STATUS='UNKNOWN')
      CELLNO = 01
*
*
* PERCENTAGE POINTS FOR CORRELATION COEFFICIENT TEST FOR NORMALITY
*
      NORMAL(1)=.879
      NORMAL(2)=.879
      NORMAL(3)=.879
      NORMAL(4)=.879
      NORMAL(5)=.879
      NORMAL(6)=.890
      NORMAL(7)=.899
      NORMAL(8)=.905
      NORMAL(9)=.912
      NORMAL(10)=.917
      NORMAL(11)=.922
      NORMAL(12)=.926
      NORMAL(13)=.931
      NORMAL(14)=.934
      NORMAL(15)=.937
      NORMAL(16)=.940
      NORMAL(17)=.942
      NORMAL(18)=.945
      NORMAL(19)=.947
      NORMAL(20)=.95
      NORMAL(21)=.952
      NORMAL(22)=.954
      NORMAL(23)=.955
      NORMAL(24)=.957
      NORMAL(25)=.958
      NORMAL(26)=.959
      NORMAL(27)=.960
      NORMAL(28)=.962
      NORMAL(29)=.962
      NORMAL(30)=.964
      NORMAL(31)=.965
```

NORMAL(32)=.966
NORMAL(33)=.967
NORMAL(34)=.967
NORMAL(35)=.968
NORMAL(36)=.968
NORMAL(37)=.969
NORMAL(38)=.970
NORMAL(39)=.971
NORMAL(40)=.972
NORMAL(41)=.972
NORMAL(42)=.973
NORMAL(43)=.973
NORMAL(44)=.973
NORMAL(45)=.974
NORMAL(46)=.974
NORMAL(47)=.974
NORMAL(48)=.975
NORMAL(49)=.975
NORMAL(50)=.977
NORMAL(51)=.977
NORMAL(52)=.977
NORMAL(53)=.977
NORMAL(54)=.977
NORMAL(55)=.978
NORMAL(56)=.978
NORMAL(57)=.978
NORMAL(58)=.978
NORMAL(59)=.978
NORMAL(60)=.98
NORMAL(61)=.98
NORMAL(62)=.98
NORMAL(63)=.98
NORMAL(64)=.98
NORMAL(65)=.981
NORMAL(66)=.981
NORMAL(67)=.981
NORMAL(68)=.981
NORMAL(69)=.981
NORMAL(70)=.982
NORMAL(71)=.982
NORMAL(72)=.982
NORMAL(73)=.982
NORMAL(74)=.982
NORMAL(75)=.983
NORMAL(76)=.983
NORMAL(77)=.983
NORMAL(78)=.983
NORMAL(79)=.983
NORMAL(80)=.984
NORMAL(81)=.984
NORMAL(82)=.984
NORMAL(83)=.984
NORMAL(84)=.984
NORMAL(85)=.985

```
      NORMAL(86)=.985
      NORMAL(87)=.985
      NORMAL(88)=.985
      NORMAL(89)=.985
      NORMAL(90)=.985
      NORMAL(91)=.985
      NORMAL(92)=.985
      NORMAL(93)=.985
      NORMAL(94)=.985
      NORMAL(95)=.986
      NORMAL(96)=.986
      NORMAL(97)=.986
      NORMAL(98)=.986
      NORMAL(99)=.986
      NORMAL(100)=.987
      WRITE(02,5) CELLNO
 5    FORMAT('FOR CELL NUMBER ',I2)
      PRINT*,'READING DATA . . .'
C* * *
      SUMX=0.0
      SUMXSQ=0.0
      DO 10 I=1,1000
C          WRITE(1,201) X(49), FLOW, COHES, LATE, ILATE, X(50)
C    "JOBFT" IS THE NAME TO USE TO GET A PARTICULAR VARIABLE PROCESSED
        READ(01,15) X1, HJOBFT, GJOBFT, JOBFT, ILATE, X2
        JOB(I)=JOBFT
        IF(I.GT.500) THEN
          SUMX=SUMX+JOBFT
          SUMXSQ=SUMXSQ+(JOBFT**2)
        ENDIF
C      PRINT *,JOBFT
 10   CONTINUE
      LRAVE=SUMX/500.0
      LRVAR=(SUMXSQ-((SUMX**2)/500.0))/499.0
*
  15      FORMAT(F10.4, F10.4, F10.4, F10.4, I4, F10.4)
C 15   FORMAT(F10.4)
*
* TEST FOR INITIALIZATION BIAS BASED ON SCHRUBEN ET. AL
*
      PRINT*,'BEGINNING TEST FOR INITIALIZATION BIAS . . .'
      END=1
 20   AVE=0.0
      T=0.0
      DO 30 I=1,END
        ITMP=I
        AVE=AVE+JOB(I)
        CUM(I)=AVE/ITMP
 30   CONTINUE
      ENDTMP=END
      AVE=AVE/ENDTMP
      DO 40 I=1,END
        ITMP=I
        T=T+(1-ITMP/ENDTMP)*ITMP*(AVE-CUM(I))
```

```
 40   CONTINUE
      T=T*(45**.5)/((ENDTMP**1.5)*(LRVAR**.5))
      IF(T.GT.1.645) THEN
        PRINT 42, END
        WRITE(02,42) END
 42     FORMAT(1X,'DISCARD FIRST ',I4,' JOBS TO ELIMINATE ',
     C         'INITIALIZATION BIAS')
        GOTO 45
      ELSE
        END=END+1
        GOTO 20
      ENDIF
*
* TEST FOR AUTOCORRELATION BASED ON VON NEUMANN STATISTIC
*
 45   PRINT*,'BEGINNING TEST FOR AUTOCORRELATION . . .'
      BATCHS=0
 50   AVE=0.0
      BATCHS=BATCHS+100
      NBATCH=INT((1000-END)/BATCHS)
      IF(NBATCH.GE.100) THEN
        NBATCH=100
      ENDIF
      NTMP=NBATCH
      START=END+1
      FINISH=END+BATCHS
      DO 60 I=1,NBATCH
        BATCHFT=0.0
        DO 70 J=START,FINISH
          BATCHFT=BATCHFT+JOB(J)
 70     CONTINUE
        BATCHTMP=BATCHS
        MEAN(I)=BATCHFT/BATCHTMP
        AVE=AVE+MEAN(I)
        START=START+BATCHS
        FINISH=FINISH+BATCHS
 60   CONTINUE
      AVE=AVE/NTMP
      QNUM=0.0
      QDEN=0.0
      DO 80 I=1,NBATCH-1
        QNUM=QNUM+((MEAN(I)-MEAN(I+1))**2)
 80   CONTINUE
      DO 90 I=1,NBATCH
        QDEN=QDEN+((MEAN(I)-AVE)**2)
 90   CONTINUE
      Q=QNUM/QDEN
      VARQ=(4.0*(NTMP-2.0))/((NTMP-1.0)*(NTMP+1.0))
      STAT=2.0-(1.96*(VARQ**.5))
      IF(Q.GE.STAT) THEN
        PRINT 92, BATCHS,NBATCH
        WRITE(02,92) BATCHS,NBATCH
 92     FORMAT(1X,'BATCH SIZE FOR INDEPENDENCE IS ',I4,' BASED ON ',I3,
     C          ' BATCHES')
```

```
          GOTO 100
        ELSE
          GOTO 50
        ENDIF
*
* SORT BATCH MEANS IN ORDER TO PREPARE FOR NORMALITY TEST BASED ON ORDER
* STATISTICS
*
 100    PRINT*,'BEGINNING TEST FOR NORMALITY . . .'
 102    SORT=.TRUE.
 105    IF(SORT) THEN
          SORT=.FALSE.
          DO 108 I=1,NBATCH-1
            IF(MEAN(I).GT.MEAN(I+1)) THEN
              TMPA=MEAN(I)
              TMPB=MEAN(I+1)
              MEAN(I)=TMPB
              MEAN(I+1)=TMPA
              SORT=.TRUE.
            ENDIF
 108      CONTINUE
          GOTO 105
        ENDIF
*
* TEST FOR NORMALITY
*
        XBAR=0.0
        DO 110 I=1,NBATCH
          XBAR=XBAR+MEAN(I)
 110    CONTINUE
        XBAR=XBAR/NTMP
*
        MOMENT(1)=1-(.5**(1/NTMP))
        MOMENT(NBATCH)=.5**(1/NTMP)
        DO 120 I=2,NBATCH-1
          ITMP=I
          MOMENT(I)=(ITMP-.3175)/(NTMP+.365)
 120    CONTINUE
        MBAR=0.0
        DO 130 I=1,NBATCH
          A=MOMENT(I)**.14
          B=(1.0-MOMENT(I))**.14
          MOMENT(I)=4.91*(A-B)
          MBAR=MBAR+MOMENT(I)
 130    CONTINUE
        MBAR=MBAR/NTMP
        A=0.0
        B=0.0
        C=0.0
        DO 140 I=1,NBATCH
          A=A+((MEAN(I)-XBAR)*(MOMENT(I)-MBAR))
          B=B+((MEAN(I)-XBAR)**2)
          C=C+((MOMENT(I)-MBAR)**2)
 140    CONTINUE
```

```
      R=A/((B*C)**.5)
      IF(R.GE.NORMAL(NBATCH)) THEN
        PRINT 141, BATCHS,NBATCH
        WRITE(02,141) BATCHS,NBATCH
141     FORMAT(1X,'BATCH SIZE TO MEET ASSUMPTION OF NORMALITY IS ',I4,
     C          ' BASED ON ',I3,' BATCHES')
        PRINT 142, LRAVE
        WRITE(02,142) LRAVE
142     FORMAT(1X,'ESTIMATE OF MEAN IS ',F8.2)
        PRINT 143, LRVAR
        WRITE(02,143) LRVAR
143     FORMAT(1X,'ESTIMATE OF VARIANCE IS ',F9.2)
        GOTO 180
      ELSE
        BATCHS=BATCHS+100
        NBATCH=INT((1000-END)/BATCHS)
        IF(NBATCH.GT.9) THEN
          NBATCH=100
        ENDIF
        NTMP=NBATCH
        START=END+1
        FINISH=END+BATCHS
        DO 150 I=1,NBATCH
          BATCHFT=0.0
          DO 160 J=START,FINISH
            BATCHFT=BATCHFT+JOB(J)
160       CONTINUE
          BATCHTMP=BATCHS
          MEAN(I)=BATCHFT/BATCHTMP
          START=START+BATCHS
          FINISH=FINISH+BATCHS
150     CONTINUE
        GOTO 102
      ENDIF
180   PRINT*,'TESTING COMPLETE'
```

APPENDIX F
ANOVA TABLE FOR FLOW TIME MEASURE

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******Analysis of Variance--design 1******

Tests of Significance for FLOW using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	48490.41	1568	30.93		
RULE	2186.71	1	2186.71	70.71	0.000
LOAD	67476.60	1	67476.60	2181.94	0.000
RATIO	4966.91	1	4966.91	160.61	0.000
BATCHES	10581.61	1	10581.61	342.17	0.000
P.VAR	4829.69	1	4829.69	156.17	0.000
RULE BY LOAD	10.01	1	10.01	0.32	0.570
RULE BY RATIO	818.34	1	818.34	26.46	0.000
RULE BY BATCHES	407.95	1	407.95	13.19	0.000
RULE BY P.VAR	1087.88	1	1087.88	35.18	0.000
LOAD BY RATIO	6738.29	1	6738.29	217.89	0.000
LOAD BY BATCHES	0.00	1	0.00	0.00	0.992
LOAD BY P.VAR	46.32	1	46.32	1.50	0.221
RATIO BY BATCHES	838.35	1	838.35	27.11	0.000
RATIO BY P.VAR	501.72	1	501.72	16.22	0.000
BATCHES BY P.VAR	273.44	1	273.44	8.84	0.003
RULE BY LOAD BY RATI O	29.83	1	29.83	0.96	0.326
RULE BY LOAD BY BATC HES	5.67	1	5.67	0.18	0.669
RULE BY LOAD BY P.VA R	5.14	1	5.14	0.17	0.684
RULE BY RATIO BY BAT CHES	82.34	1	82.34	2.66	0.103
RULE BY RATIO BY P.V AR	243.66	1	243.66	7.88	0.005
RULE BY BATCHES BY P .VAR	58.24	1	58.24	1.88	0.170
LOAD BY RATIO BY BAT CHES	0.30	1	0.30	0.01	0.922
LOAD BY RATIO BY P.V AR	37.83	1	37.83	1.22	0.269
LOAD BY BATCHES BY P .VAR	6.23	1	6.23	0.20	0.654
RATIO BY BATCHES BY P.VAR	5.40	1	5.40	0.17	0.676
RULE BY LOAD BY RATI O BY BATCHES	9.97	1	9.97	0.32	0.570
RULE BY LOAD BY RATI	0.05	1	0.05	0.00	0.967

O BY P.VAR					
RULE BY LOAD BY BATC HES BY P.VAR	10.47	1	10.47	0.34	0.561
RULE BY RATIO BY BAT CHES BY P.VAR	31.30	1	31.30	1.01	0.315
LOAD BY RATIO BY BAT CHES BY P.VAR	65.27	1	65.27	2.11	0.146
RULE BY LOAD BY RATI O BY BATCHES BY P.VA	3.53	1	3.53	0.11	0.735

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******Analysis of Variance -- design 1******

Tests of Significance for FLOW using UNIQUE sums of squares (Cont.)

Source of Variation	SS	DF	MS	F	Sig of F
R					
(Model)	101359	31	3269.65	105.73	0
(Total)	149849.4	1599	93.71		

R-Squared = .676
Adjusted R-Squared = .670

Effect Size Measures and Observed Power at the .0500 Level

Source of Variation	Partial ETA Sqd	Noncen - trality	Power
RULE	0.043	70.71	1
LOAD	0.582	2181.9	1
RATIO	0.093	160.61	1
BATCHES	0.179	342.17	1
P.VAR	0.091	156.17	1
RULE BY LOAD	0	0.324	0.036
RULE BY RATIO	0.017	26.462	0.999
RULE BY BATCHES	0.008	13.191	0.952
RULE BY P.VAR	0.022	35.178	1
LOAD BY RATIO	0.122	217.89	1
LOAD BY BATCHES	0	0	0.031
LOAD BY P.VAR	0.001	1.498	0.228
RATIO BY BATCHES	0.017	27.109	1
RATIO BY P.VAR	0.01	16.224	0.98
BATCHES BY P.VAR	0.006	8.842	0.842
RULE BY LOAD BY RATI O	0.001	0.965	0.176

RULE BY LOAD BY BATCHES	0	0.183	0.046
RULE BY LOAD BY P.VAR	0	0.166	0.047
RULE BY RATIO BY BATCHES	0.002	2.663	0.371
RULE BY RATIO BY P.VAR	0.005	7.879	0.799
RULE BY BATCHES BY P.VAR	0.001	1.883	0.277
LOAD BY RATIO BY BATCHES	0	0.01	0.032
LOAD BY RATIO BY P.VAR	0.001	1.223	0.196
LOAD BY BATCHES BY P.VAR	0	0.201	0.044
RATIO BY BATCHES BY P.VAR	0	0.175	0.046
RULE BY LOAD BY RATIO BY BATCHES	0	0.322	0.035
RULE BY LOAD BY RATIO BY P.VAR	0	0.002	0.031
RULE BY LOAD BY BATCHES BY P.VAR	0	0.338	0.037
RULE BY RATIO BY BATCHES BY P.VAR	0.001	1.012	0.178
LOAD BY RATIO BY BATCHES BY P.VAR	0.001	2.111	0.305
RULE BY LOAD BY RATIO BY BATCHES BY P.VAR	0	0.114	0.047

APPENDIX G
ANOVA TABLE FOR FLOW VARIANCE MEASURE

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******Analysis of Variance--design 1******

Tests of Significance for F.VAR using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	101307720	1568	64610		
RULE	2714151	1	2714151	42.01	0.000
LOAD	47973085	1	47973085	742.51	0.000
RATIO	67194264	1	67194264	1040.01	0.000
BATCHES	569716.37	1	569716.37	8.82	0.003
P.VAR	1015703.93	1	1015703.90	15.72	0.000
RULE BY LOAD	3469.45	1	3469.45	0.05	0.817
RULE BY RATIO	1187868.39	1	1187868.40	18.39	0.000
RULE BY BATCHES	135714.09	1	135714.09	2.10	0.147
RULE BY P.VAR	1166236.59	1	1166236.60	18.05	0.000
LOAD BY RATIO	8588115.82	1	8588115.80	132.92	0.000
LOAD BY BATCHES	1074.87	1	1074.87	0.02	0.897
LOAD BY P.VAR	600309.62	1	600309.62	9.29	0.002
RATIO BY BATCHES	95661.68	1	95661.68	1.48	0.224
RATIO BY P.VAR	45.02	1	45.02	0.00	0.979
BATCHES BY P.VAR	272027.81	1	272027.81	4.21	0.040
RULE BY LOAD BY RATI O	182159.94	1	182159.94	2.82	0.093
RULE BY LOAD BY BATC HES	47268.60	1	47268.60	0.73	0.392
RULE BY LOAD BY P.VA R	3172.16	1	3172.16	0.05	0.825
RULE BY RATIO BY BAT CHES	31390.47	1	31390.47	0.49	0.486
RULE BY RATIO BY P.V AR	404306.36	1	404306.36	6.26	0.012
RULE BY BATCHES BY P .VAR	8445.97	1	8445.97	0.13	0.718
LOAD BY RATIO BY BAT CHES	1246.27	1	1246.27	0.02	0.890
LOAD BY RATIO BY P.V AR	151662.52	1	151662.52	2.35	0.126
LOAD BY BATCHES BY P .VAR	14972.53	1	14972.53	0.23	0.630
RATIO BY BATCHES BY P.VAR	3244.02	1	3244.02	0.05	0.823
RULE BY LOAD BY RATI O BY BATCHES	290289.83	1	290289.83	4.49	0.034
RULE BY LOAD BY RATI	24666.01	1	24666.01	0.38	0.537

O BY P.VAR					
RULE BY LOAD BY BATC HES BY P.VAR	118872.59	1	118872.59	1.84	0.175
RULE BY RATIO BY BAT CHES BY P.VAR	17023.30	1	17023.30	0.26	0.608
LOAD BY RATIO BY BAT CHES BY P.VAR	246515.20	1	246515.20	3.82	0.051
RULE BY LOAD BY RATI O BY BATCHES BY P.VA	4077.83	1	4077.83	0.06	0.802

******Analysis of Variance -- design 1******

Tests of Significance for F.VAR using UNIQUE sums of squares (Cont.)

Source of Variation	SS	DF	MS	F	Sig of F
R					
(Model)	133066757	31	4292476	66.44	0
(Total)	234374477	1599	146575.66		

R-Squared = .568
Adjusted R-Squared = .559

Effect Size Measures and Observed Power at the .0500 Level

Source of Variation	Partial ETA Sqd	Noncen-trality	Power
RULE	0.026	42.009	1.000
LOAD	0.321	742.508	1.000
RATIO	0.399	1040.010	1.000
BATCHES	0.006	8.818	0.841
P.VAR	0.010	15.721	0.977
RULE BY LOAD	0.000	0.054	0.040
RULE BY RATIO	0.012	18.385	0.990
RULE BY BATCHES	0.001	2.101	0.304
RULE BY P.VAR	0.011	18.051	0.989
LOAD BY RATIO	0.078	132.923	1.000
LOAD BY BATCHES	0.000	0.017	0.034
LOAD BY P.VAR	0.006	9.291	0.860
RATIO BY BATCHES	0.001	1.481	0.226
RATIO BY P.VAR	0.000	0.001	0.031
BATCHES BY P.VAR	0.003	4.210	0.534
RULE BY LOAD BY RATI O	0.002	2.819	0.389
RULE BY LOAD BY BATC	0.000	0.732	0.175

HES			
RULE BY LOAD BY P.VAR	0.000	0.049	0.040
RULE BY RATIO BY BATCHES	0.000	0.486	0.106
RULE BY RATIO BY P.VAR	0.004	6.258	0.702
RULE BY BATCHES BY P.VAR	0.000	0.131	0.047
LOAD BY RATIO BY BATCHES	0.000	0.019	0.034
LOAD BY RATIO BY P.VAR	0.001	2.347	0.334
LOAD BY BATCHES BY P.VAR	0.000	0.232	0.041
RATIO BY BATCHES BY P.VAR	0.000	0.050	0.040
RULE BY LOAD BY RATIO BY BATCHES	0.003	4.493	0.560
RULE BY LOAD BY RATIO BY P.VAR	0.000	0.382	0.049
RULE BY LOAD BY BATCHES BY P.VAR	0.001	1.840	0.272
RULE BY RATIO BY BATCHES BY P.VAR	0.000	0.263	0.037
LOAD BY RATIO BY BATCHES BY P.VAR	0.002	3.815	0.495
RULE BY LOAD BY RATIO BY BATCHES BY P.VAR	0.000	0.063	0.042

APPENDIX H
ANOVA TABLE FOR LATENESS MEASURE

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******Analysis of Variance -- design 1******

Tests of Significance for LATE using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	46522.83	1568	29.67		
RULE	2195.20	1	2195.20	73.99	0.000
LOAD	67242.45	1	67242.45	2266.33	0.000
RATIO	4.28	1	4.28	0.14	0.704
BATCHES	10583.69	1	10583.69	356.71	0.000
P.VAR	4843.64	1	4843.64	163.25	0.000
RULE BY LOAD	9.98	1	9.98	0.34	0.562
RULE BY RATIO	819.97	1	819.97	27.64	0.000
RULE BY BATCHES	403.26	1	403.26	13.59	0.000
RULE BY P.VAR	1095.04	1	1095.04	36.91	0.000
LOAD BY RATIO	6691.05	1	6691.05	225.51	0.000
LOAD BY BATCHES	0.00	1	0.00	0.00	0.993
LOAD BY P.VAR	46.40	1	46.40	1.56	0.211
RATIO BY BATCHES	825.89	1	825.89	27.84	0.000
RATIO BY P.VAR	500.55	1	500.55	16.87	0.000
BATCHES BY P.VAR	272.53	1	272.53	9.19	0.002
RULE BY LOAD BY RATI O	31.31	1	31.31	1.06	0.304
RULE BY LOAD BY BATC HES	4.84	1	4.84	0.16	0.686
RULE BY LOAD BY P.VA R	4.99	1	4.99	0.17	0.682
RULE BY RATIO BY BAT CHES	82.71	1	82.71	2.79	0.095
RULE BY RATIO BY P.V AR	242.72	1	242.72	8.18	0.004
RULE BY BATCHES BY P .VAR	58.07	1	58.07	1.96	0.162
LOAD BY RATIO BY BAT CHES	0.21	1	0.21	0.01	0.933
LOAD BY RATIO BY P.V AR	40.47	1	40.47	1.36	0.243
LOAD BY BATCHES BY P .VAR	5.69	1	5.69	0.19	0.661
RATIO BY BATCHES BY P.VAR	5.91	1	5.91	0.20	0.655
RULE BY LOAD BY RATI O BY BATCHES	10.83	1	10.83	0.36	0.546
RULE BY LOAD BY RATI	0.02	1	0.02	0.00	0.979

O BY P.VAR					
RULE BY LOAD BY BATC HES BY P.VAR	10.79	1	10.79	0.36	0.547
RULE BY RATIO BY BAT CHES BY P.VAR	30.10	1	30.10	1.01	0.314
LOAD BY RATIO BY BAT CHES BY P.VAR	65.75	1	65.75	2.22	0.137
RULE BY LOAD BY RATI O BY BATCHES BY P.VA	2.85	1	2.85	0.10	0.756

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******Analysis of Variance -- design 1******

Tests of Significance for LATE using UNIQUE sums of squares (Cont.)

Source of Variation	SS	DF	MS	F	Sig of F
R					
(Model)	96131.22	31	3101.01	104.52	0
(Total)	142654.1	1599	89.21		

R-Squared = .674
Adjusted R-Squared = .667

Effect Size Measures and Observed Power at the .0500 Level

Source of Variation	Partial ETA Sqd	Noncen-trality	Power
RULE	0.045	73.987	1.000
LOAD	0.591	2266.330	1.000
RATIO	0.000	0.144	0.047
BATCHES	0.185	356.711	1.000
P.VAR	0.094	163.250	1.000
RULE BY LOAD	0.000	0.337	0.037
RULE BY RATIO	0.017	27.636	1.000
RULE BY BATCHES	0.009	13.591	0.957
RULE BY P.VAR	0.023	36.907	1.000
LOAD BY RATIO	0.126	225.515	1.000
LOAD BY BATCHES	0.000	0.000	0.031
LOAD BY P.VAR	0.001	1.564	0.237
RATIO BY BATCHES	0.017	27.836	1.000
RATIO BY P.VAR	0.011	16.870	0.984
BATCHES BY P.VAR	0.006	9.185	0.856
RULE BY LOAD BY RATI O	0.001	1.055	0.181
RULE BY LOAD BY BATC	0.000	0.163	0.047

HES			
RULE BY LOAD BY P.VAR	0.000	0.168	0.047
RULE BY RATIO BY BATCHES	0.002	2.788	0.385
RULE BY RATIO BY P.VAR	0.005	8.181	0.813
RULE BY BATCHES BY P.VAR	0.001	1.957	0.286
LOAD BY RATIO BY BATCHES	0.000	0.007	0.032
LOAD BY RATIO BY P.VAR	0.001	1.364	0.212
LOAD BY BATCHES BY P.VAR	0.000	0.192	0.045
RATIO BY BATCHES BY P.VAR	0.000	0.199	0.044
RULE BY LOAD BY RATIO BY BATCHES	0.000	0.365	0.043
RULE BY LOAD BY RATIO BY P.VAR	0.000	0.001	0.031
RULE BY LOAD BY BATCHES BY P.VAR	0.000	0.364	0.043
RULE BY RATIO BY BATCHES BY P.VAR	0.001	1.014	0.178
LOAD BY RATIO BY BATCHES BY P.VAR	0.001	2.216	0.318
RULE BY LOAD BY RATIO BY BATCHES BY P.VAR	0.000	0.096	0.045

APPENDIX I

ANOVA TABLE FOR LATENESS VARIANCE MEASURE

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* * * * * * A n a l y s i s o f V a r i a n c e -- design 1 * * * * * *

Tests of Significance for T.VAR using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	89813245	1568	57278.86		
RULE	176340	1	176340	3.08	0.080
LOAD	6697495	1	6697496	116.93	0.000
RATIO	1297561	1	1297561	22.65	0.000
BATCHES	651901	1	651901	11.38	0.001
P.VAR	3737328	1	3737328	65.25	0.000
RULE BY LOAD	46328.11	1	46328.11	0.81	0.369
RULE BY RATIO	275646.01	1	275646.01	4.81	0.028
RULE BY BATCHES	39900.84	1	39900.84	0.70	0.404
RULE BY P.VAR	99564.44	1	99564.44	1.74	0.188
LOAD BY RATIO	3786147.28	1	3786147.30	66.10	0.000
LOAD BY BATCHES	123985.80	1	123985.80	2.16	0.141
LOAD BY P.VAR	1391401.78	1	1391401.80	24.29	0.000
RATIO BY BATCHES	50581.18	1	50581.18	0.88	0.348
RATIO BY P.VAR	14564610.16	1	14564610.00	254.28	0.000
BATCHES BY P.VAR	19192.93	1	19192.93	0.34	0.563
RULE BY LOAD BY RATI O	3214.13	1	3214.13	0.06	0.813
RULE BY LOAD BY BATC HES	85569.41	1	85569.41	1.49	0.222
RULE BY LOAD BY P.VA R	21053.54	1	21053.54	0.37	0.544
RULE BY RATIO BY BAT CHES	76058.34	1	76058.34	1.33	0.249
RULE BY RATIO BY P.V AR	402358.35	1	402358.35	7.02	0.008
RULE BY BATCHES BY P .VAR	171172.99	1	171172.99	2.99	0.084
LOAD BY RATIO BY BAT CHES	17749.08	1	17749.08	0.31	0.578
LOAD BY RATIO BY P.V AR	9823.65	1	9823.65	0.17	0.679
LOAD BY BATCHES BY P .VAR	37396.76	1	37396.76	0.65	0.419
RATIO BY BATCHES BY P.VAR	29758.47	1	29758.47	0.52	0.471
RULE BY LOAD BY RATI O BY BATCHES	30112.10	1	30112.10	0.53	0.469
RULE BY LOAD BY RATI	797.40	1	797.40	0.01	0.906

O BY P.VAR					
RULE BY LOAD BY BATC HES BY P.VAR	31108.93	1	31108.93	0.54	0.461
RULE BY RATIO BY BAT CHES BY P.VAR	24.40	1	24.40	0.00	0.984
LOAD BY RATIO BY BAT CHES BY P.VAR	227914.56	1	227914.56	3.98	0.046
RULE BY LOAD BY RATI O BY BATCHES BY P.VA	2029.33	1	2029.33	0.04	0.851

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******Analysis of Variance -- design 1******

Tests of Significance for T.VAR using UNIQUE sums of squares (Cont.)

Source of Variation	SS	DF	MS	F	Sig of F
R					
(Model)	34104126.5	31	1100133.1	19.21	0
(Total)	123917372	1599	77496.79		

R-Squared = .275
Adjusted R-Squared = .261

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Effect Size Measures and Observed Power at the .0500 Level

Source of Variation	Partial ETA Sqd	Noncen-trality	Power
RULE	0.002	3.079	0.418
LOAD	0.069	116.928	1.000
RATIO	0.014	22.653	0.998
BATCHES	0.007	11.381	0.920
P.VAR	0.040	65.248	1.000
RULE BY LOAD	0.001	0.809	0.175
RULE BY RATIO	0.003	4.812	0.589
RULE BY BATCHES	0.000	0.697	0.174
RULE BY P.VAR	0.001	1.738	0.259
LOAD BY RATIO	0.040	66.100	1.000
LOAD BY BATCHES	0.001	2.165	0.312
LOAD BY P.VAR	0.015	24.292	0.999
RATIO BY BATCHES	0.001	0.883	0.174
RATIO BY P.VAR	0.140	254.276	1.000
BATCHES BY P.VAR	0.000	0.335	0.037
RULE BY LOAD BY RATI O	0.000	0.056	0.041
RULE BY LOAD BY BATC	0.001	1.494	0.228

HES			
RULE BY LOAD BY P.VAR	0.000	0.368	0.044
RULE BY RATIO BY BATCHES	0.001	1.328	0.208
RULE BY RATIO BY P.VAR	0.004	7.025	0.752
RULE BY BATCHES BY P.VAR	0.002	2.988	0.408
LOAD BY RATIO BY BATCHES	0.000	0.310	0.035
LOAD BY RATIO BY P.VAR	0.000	0.172	0.046
LOAD BY BATCHES BY P.VAR	0.000	0.653	0.170
RATIO BY BATCHES BY P.VAR	0.000	0.520	0.125
RULE BY LOAD BY RATIO BY BATCHES	0.000	0.526	0.129
RULE BY LOAD BY RATIO BY P.VAR	0.000	0.014	0.033
RULE BY LOAD BY BATCHES BY P.VAR	0.000	0.543	0.138
RULE BY RATIO BY BATCHES BY P.VAR	0.000	0.000	0.031
LOAD BY RATIO BY BATCHES BY P.VAR	0.003	3.979	0.511
RULE BY LOAD BY RATIO BY BATCHES BY P.VAR	0.000	0.035	0.037

APPENDIX J
ANOVA TABLE FOR PERCENT LATE MEASURE

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******Analysis of Variance--design 1******

Tests of Significance for TAR.PC using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	0.10	1568	0.00		
RULE	0.00	1	0.00	5.76	0.016
LOAD	0.01	1	0.01	229.81	0.000
RATIO	0.01	1	0.01	224.10	0.000
BATCHES	0.00	1	0.00	18.45	0.000
P.VAR	0.00	1	0.00	19.00	0.000
RULE BY LOAD	0.00	1	0.00	2.30	0.130
RULE BY RATIO	0.00	1	0.00	3.36	0.067
RULE BY BATCHES	0.00	1	0.00	1.29	0.256
RULE BY P.VAR	0.00	1	0.00	2.49	0.115
LOAD BY RATIO	0.01	1	0.01	119.41	0.000
LOAD BY BATCHES	0.00	1	0.00	9.19	0.002
LOAD BY P.VAR	0.00	1	0.00	8.08	0.005
RATIO BY BATCHES	0.00	1	0.00	6.07	0.014
RATIO BY P.VAR	0.00	1	0.00	20.68	0.000
BATCHES BY P.VAR	0.00	1	0.00	1.15	0.283
RULE BY LOAD BY RATI O	0.00	1	0.00	0.48	0.487
RULE BY LOAD BY BATC HES	0.00	1	0.00	1.02	0.312
RULE BY LOAD BY P.VA R	0.00	1	0.00	1.44	0.230
RULE BY RATIO BY BAT CHES	0.00	1	0.00	0.67	0.412
RULE BY RATIO BY P.V AR	0.00	1	0.00	0.26	0.613
RULE BY BATCHES BY P .VAR	0.00	1	0.00	0.10	0.752
LOAD BY RATIO BY BAT CHES	0.00	1	0.00	4.89	0.027
LOAD BY RATIO BY P.V AR	0.00	1	0.00	14.36	0.000
LOAD BY BATCHES BY P .VAR	0.00	1	0.00	1.76	0.185
RATIO BY BATCHES BY P.VAR	0.00	1	0.00	1.29	0.256
RULE BY LOAD BY RATI O BY BATCHES	0.00	1	0.00	0.90	0.344
RULE BY LOAD BY RATI	0.00	1	0.00	0.02	0.899

O BY P.VAR					
RULE BY LOAD BY BATC HES BY P.VAR	0.00	1	0.00	0.20	0.658
RULE BY RATIO BY BAT CHES BY P.VAR	0.00	1	0.00	0.78	0.377
LOAD BY RATIO BY BAT CHES BY P.VAR	0.00	1	0.00	2.70	0.101
RULE BY LOAD BY RATI O BY BATCHES BY P.VA	0.00	1	0.00	1.02	0.312

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******Analysis of Variance--design 1******

Tests of Significance for TAR.PC using UNIQUE sums of squares (Cont.)

Source of Variation	SS	DF	MS	F	Sig of F
R					
(Model)	0.04	31	0	22.68	0
(Total)	0.14	1599	0		

R-Squared = .310
Adjusted R-Squared = .296

- -

Effect Size Measures and Observed Power at the .0500 Level

Source of Variation	Partial ETA Sqd	Noncen-trality	Power
RULE	0.004	5.761	0.666
LOAD	0.128	229.809	1.000
RATIO	0.125	224.100	1.000
BATCHES	0.012	18.449	0.990
P.VAR	0.012	18.995	0.992
RULE BY LOAD	0.001	2.298	0.328
RULE BY RATIO	0.002	3.355	0.447
RULE BY BATCHES	0.001	1.293	0.204
RULE BY P.VAR	0.002	2.494	0.351
LOAD BY RATIO	0.071	119.409	1.000
LOAD BY BATCHES	0.006	9.192	0.856
LOAD BY P.VAR	0.005	8.079	0.809
RATIO BY BATCHES	0.004	6.068	0.689
RATIO BY P.VAR	0.013	20.683	0.995
BATCHES BY P.VAR	0.001	1.153	0.189
RULE BY LOAD BY RATI O	0.000	0.483	0.104
RULE BY LOAD BY BATC	0.001	1.021	0.178

HES			
RULE BY LOAD BY P.VA R	0.001	1.440	0.221
RULE BY RATIO BY BAT CHES	0.000	0.674	0.173
RULE BY RATIO BY P.V AR	0.000	0.255	0.038
RULE BY BATCHES BY P .VAR	0.000	0.100	0.046
LOAD BY RATIO BY BAT CHES	0.003	4.887	0.595
LOAD BY RATIO BY P.V AR	0.009	14.363	0.966
LOAD BY BATCHES BY P .VAR	0.001	1.759	0.262
RATIO BY BATCHES BY P.VAR	0.001	1.293	0.204
RULE BY LOAD BY RATI O BY BATCHES	0.001	0.898	0.174
RULE BY LOAD BY RATI O BY P.VAR	0.000	0.016	0.034
RULE BY LOAD BY BATC HES BY P.VAR	0.000	0.195	0.045
RULE BY RATIO BY BAT CHES BY P.VAR	0.000	0.782	0.175
LOAD BY RATIO BY BAT CHES BY P.VAR	0.002	2.697	0.375
RULE BY LOAD BY RATI O BY BATCHES BY P.VA R	0.001	1.021	0.178

APPENDIX K
ANOVA TABLE FOR COGESIVENESS MEASURE

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******Analysis of Variance--design 1******

Tests of Significance for COHES using UNIQUE sums of squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	0.35	1568	0.00		
RULE	2.39	1	2.39	10636.47	0.000
LOAD	0.00	1	0.00	20.71	0.000
RATIO	0.48	1	0.48	2136.52	0.000
BATCHES	0.04	1	0.04	176.45	0.000
P.VAR	0.75	1	0.75	3332.06	0.000
RULE BY LOAD	0.00	1	0.00	20.71	0.000
RULE BY RATIO	0.48	1	0.48	2136.52	0.000
RULE BY BATCHES	0.04	1	0.04	176.45	0.000
RULE BY P.VAR	0.75	1	0.75	3332.06	0.000
LOAD BY RATIO	0.00	1	0.00	5.51	0.019
LOAD BY BATCHES	0.00	1	0.00	0.45	0.503
LOAD BY P.VAR	0.01	1	0.01	28.24	0.000
RATIO BY BATCHES	0.00	1	0.00	4.33	0.038
RATIO BY P.VAR	0.07	1	0.07	299.51	0.000
BATCHES BY P.VAR	0.01	1	0.01	63.77	0.000
RULE BY LOAD BY RATI O	0.00	1	0.00	5.51	0.019
RULE BY LOAD BY BATC HES	0.00	1	0.00	0.45	0.503
RULE BY LOAD BY P.VA R	0.01	1	0.01	28.24	0.000
RULE BY RATIO BY BAT CHES	0.00	1	0.00	4.33	0.038
RULE BY RATIO BY P.V AR	0.07	1	0.07	299.51	0.000
RULE BY BATCHES BY P .VAR	0.01	1	0.01	63.77	0.000
LOAD BY RATIO BY BAT CHES	0.00	1	0.00	0.09	0.767
LOAD BY RATIO BY P.V AR	0.00	1	0.00	8.45	0.004
LOAD BY BATCHES BY P .VAR	0.00	1	0.00	0.05	0.828
RATIO BY BATCHES BY P.VAR	0.00	1	0.00	12.90	0.000
RULE BY LOAD BY RATI O BY BATCHES	0.00	1	0.00	0.09	0.767
RULE BY LOAD BY RATI	0.00	1	0.00	8.45	0.004

O BY P.VAR					
RULE BY LOAD BY BATC HES BY P.VAR	0.00	1	0.00	0.05	0.828
RULE BY RATIO BY BAT CHES BY P.VAR	0.00	1	0.00	12.90	0.000
LOAD BY RATIO BY BAT CHES BY P.VAR	0.00	1	0.00	0.16	0.694
RULE BY LOAD BY RATI O BY BATCHES BY P.VA	0.00	1	0.00	0.16	0.694

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******Analysis of Variance -- design 1******

Tests of Significance for COHES using UNIQUE sums of squares (Cont.)

Source of Variation	SS	DF	MS	F	Sig of F
R					
(Model)	5.12	31	0.17	735.96	0
(Total)	5.47	1599	0		

R-Squared = .936
Adjusted R-Squared = .934

- -

Effect Size Measures and Observed Power at the .0500 Level

Source of Variation	Partial ETA Sqd	Noncen-trality	Power
RULE	0.872	10636.500	1.000
LOAD	0.013	20.711	0.995
RATIO	0.577	2136.520	1.000
BATCHES	0.101	176.449	1.000
P.VAR	0.680	3332.060	1.000
RULE BY LOAD	0.013	20.711	0.995
RULE BY RATIO	0.577	2136.520	1.000
RULE BY BATCHES	0.101	176.449	1.000
RULE BY P.VAR	0.680	3332.060	1.000
LOAD BY RATIO	0.004	5.514	0.647
LOAD BY BATCHES	0.000	0.449	0.083
LOAD BY P.VAR	0.018	28.236	1.000
RATIO BY BATCHES	0.003	4.327	0.545
RATIO BY P.VAR	0.160	299.513	1.000
BATCHES BY P.VAR	0.039	63.771	1.000
RULE BY LOAD BY RATI O	0.004	5.514	0.647
RULE BY LOAD BY BATC	0.000	0.449	0.083

HES			
RULE BY LOAD BY P.VAR	0.018	28.236	1.000
RULE BY RATIO BY BATCHES	0.003	4.327	0.545
RULE BY RATIO BY P.VAR	0.160	299.513	1.000
RULE BY BATCHES BY P.VAR	0.039	63.771	1.000
LOAD BY RATIO BY BATCHES	0.000	0.088	0.045
LOAD BY RATIO BY P.VAR	0.005	8.453	0.826
LOAD BY BATCHES BY P.VAR	0.000	0.047	0.039
RATIO BY BATCHES BY P.VAR	0.008	12.902	0.948
RULE BY LOAD BY RATIO BY BATCHES	0.000	0.088	0.045
RULE BY LOAD BY RATIO BY P.VAR	0.005	8.453	0.826
RULE BY LOAD BY BATCHES BY P.VAR	0.000	0.047	0.039
RULE BY RATIO BY BATCHES BY P.VAR	0.008	12.902	0.948
LOAD BY RATIO BY BATCHES BY P.VAR	0.000	0.155	0.047
RULE BY LOAD BY RATIO BY BATCHES BY P.VAR	0.000	0.155	0.047