A LOADING AND BALANCING METHODOLOGY FOR JOB SHOP CONTROL

A THESIS
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By
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This research presents a loading and balancing methodology for job shop control.

The importance of achieving shop balance in many types of manufacturing job shops is shown and a large number of indices for measuring balance in the job shop are developed. In addition to the balance measures, other measures of performance indicating ability to meet due dates and levels of work in process are also employed.

A method to provide good control in the operation of the job shop with respect to most measures of performance is presented. This method consists of setting up a pool of jobs prior to releasing them to the job shop and establishing a mathematical programming algorithm to select jobs to be loaded in the shop from the pool.

It is shown by this research that most of the balance measures calculated, as well as all of the work in process level measures, are significantly improved by the control methodology derived.

The job shop control methodology is also employed in conjunction with a variety of conditions such as shops with few interactions, job arrival distributions with static and dynamic means, and allowance of alternative machine operations.

A job shop simulation model is utilized to test the control methodology.
CHAPTER I

INTRODUCTION

A job shop is a collection of distinct machine groups and jobs which require processing on the machines. Each job will require processing on a certain number of the machines. Furthermore, a job could require any ordering of processing by the machines such that there is no common pattern of movement from machine to machine. The lack of a common routing for all jobs is characteristic of a job shop.

Job shop scheduling research has centered on the sequencing problem. This problem consists of determining the sequence in which units are to be processed at each of the machine centers. A solution to the job shop scheduling problem has not been developed, in fact, there is no general agreement as to what the solution should be. The most common approach has been to develop a sequencing rule and then to attempt to show that this rule performs adequately or better than other rules with respect to some measures of performance. The most commonly employed measures of performance have been concerned with the ability to meet due dates and with job flow times, but the level of work in process has also been used. A group of criteria that have been almost completely overlooked are the measures of shop workload balance.

The purpose of this research has been to develop and test a loading and balancing methodology for job shop control. Loading in this research is taken to mean the release of jobs to the shop. The definition of job
shop balance is of primary concern in this research. It will be shown that different measures of shop balance may be devised for different types of shops. All of these measures will be analyzed in detail later. Briefly, however, it can be said that balancing the shop involves the scheduling of jobs in the shop so that a shop related measure (i.e. work output, queue size, etc.) is spread as evenly as possible over time or over all machines. The specific objective has been to improve the balance and work in process measures of the shop while still operating within due date constraints.

Most of the job shop scheduling research to date has attempted to optimize a measure of performance related to individual jobs such as the frequency with which assigned due dates are met, minimization of mean flow time, maximum flow time, etc. The attempts to obtain these objectives have usually consisted of the use of various dispatching rules. This research introduces a higher degree of shop control by the use of a different approach. This approach makes use of a pool of jobs in front of the shop and an algorithm to select the jobs to be released, or loaded, from the job pool to the shop.

The job pool concept is used explicitly in some industries (apparel, leather products) and implicitly in many others where a manufacturing lot is ready "on paper" to be placed in the shop long before this is actually done. This research, however, introduces additional realism in job shop research by developing a formal way of utilizing the job pool.

The algorithm employed to select jobs from the pool is primarily concerned with maintaining a balanced aggregate workload in the shop for each machine, while still allowing the jobs to meet their due dates. The
utilization of this objective function is based on the fact that every job shop is physically set up to operate with a given workload mixture among the machines and at a certain overall load level and output. Any deviation from this workloading causes implicit or explicit costs, that is, load fluctuations from period to period for a given machine and/or across machines in a given period create costs of idle machinery and labor, costs of overtime premiums, or costs of performing some operations in other than their normal machines at increased costs.

The final measure of a methodology in an industrial situation lies on its ability to reduce costs and thereby increase profits. This research shows that a balanced shop workload allows the shop to operate at a lower work-in-process level. The work in process level and the improvement in shop operating conditions mentioned in the preceding paragraph result in very important cost reductions. The most important cost reduction in some industries, however, is due to the smaller risk caused by the ability to delay final production decisions while a job is in the job pool until the moment that the job is moved into the shop. A good example where this situation occurs is the fashion industry where the ability to postpone a cutting decision of a wide cuff pant for two or three weeks could mean the difference between $10,000 profit and $2,000 loss in a production lot. This is due to the fact that many fashion producers manufacture to stock in anticipation of store orders and styles in fashion ordered by stores and chains sometimes "die" in a matter of days.

The loading algorithm permits the loading frequency to be controlled directly by the production planner, thus allowing discrete releasing of the jobs at fixed time intervals (for instance once per shift). Also the
weight attached in the algorithm to meeting due dates can be varied and the level of work in process in the shop as well as the degree of balance obtained can also be controlled.

The primary purpose of this research has been to develop a methodology to provide better job shop balance and control. This led to the formalization of the job pool concept, the development of the discrete releasing approach and the mathematical programming job loading algorithm. It is evident that many balance measures could be formulated with different ones being appropriate for different shops and conditions. Therefore, several balance measures and their usefulness have been identified by this research. It must also be recognized that other constraints face the job shop manufacturing facility in addition to the "balance" conditions. These are the ability to meet assigned due dates and the level of work in process inventory.

Three basic types of performance measures are employed in this research. They are:

1. Shop Balance Oriented Measures
2. Measures Related to Work in Process Levels
3. Measures Dealing with the Ability to Meet Job Due Dates

Several criteria which can be classified into the three groups above are studied throughout this research and their relationships under different loading (scheduling) and dispatching rules are analyzed. No attempt has been made to assign weights to the various measures of performance employed. The problem is approached in this way because the cost structure for the various criteria will vary from shop to shop and probably even within the same shop at different times.
The loading and balancing methodology developed by this research was tested through the use of a job shop simulation model. The reason for the use of a simulation model for this purpose is the scarcity of theoretical results in the queuing network area. In fact, Conway (1967), has stated that "a harsh critic could conclude that there are no network queuing results."

The following chapters present the results of this research. Chapter II gives a description of the job shop and the measures of performance studied and it also provides a review of relevant literature. In Chapter III a number of balance measures are presented and their potential applications are discussed.

Chapter IV provides a description of the loading and balancing methodology developed by this research. These include the maintenance of a job pool, discrete job selection, and job loading from the pool. The loading algorithm is formulated and its control aspects are explained. Also a loading heuristic as an alternative to the loading algorithm is shown.

Chapter V presents the testing vehicle. It starts with a description of the job shop parameters and the dispatching rules and then gives a brief explanation of the job shop simulator which is a GASP II simulation program. The chapter includes the description of the simulation programs with reference to the flow charts. Some variations of the simulation program are used to investigate special conditions such as a job arrival distribution with a static and a dynamic mean, shops with few interactions, and shops with a non-symmetric transition matrix.
Chapter VI is concerned with the validation of the simulation and the design of the experiment including the validation and testing of the random number generator. Chapter VII presents the results obtained when using the job pool and the loading algorithm and analyzes the comparison of these results with the output of an "uncontrolled" shop. Chapter VIII presents some additional theoretical models.

Finally, Chapter IX presents the conclusions and provides an overall interpretation of the research as well as presenting suggestions for possible extensions of the work presented here.
CHAPTER II

JOB SHOP FRAMEWORK AND LITERATURE REVIEW

2.1 Job Shop Framework

2.1.1 Brief Description of the Job Shop

A job shop is considered in this research to be a production shop with distinct machine centers which performs different types of operations. There are one or more machines in each one of these machine centers. Therefore, the machine centers may have different capacities.

A job to be performed by the shop requires several operations for completion and therefore may require time in different machine centers. Each job may also follow a different machine operation sequence before it is completed and in fact the same machine center may appear more than once in the operation sequence.

Jobs become available to the shop in a continuous stream with random interarrival times. They enter a job pool from which they are selected in groups every period (for instance, daily) to be loaded into the manufacturing shop. At this time they are allowed to enter the queue at their first respective operation and the jobs then remain in the shop until completion.

A ten-machine shop was utilized for most of the investigations in this research. Ten machines are enough to allow the interactions and complexities of a "real world shop" to develop while at the same time the shop size is small enough to maintain the computer time required in the simulation within reasonable bounds.
The job arrival process was generated by using exponential inter-
arrival times and the processing time per operation consisted also of
samples from an exponential distribution. A job due date was assigned to
each job as it entered the shop with the due date being a function of the
work content of the job.

The above shop conditions were deemed reasonable and are generally
representative of shop conditions in several industries such as the apparel
style shop. It has not been the intent of this research, however, to re-
produce a particular shop, but rather to model a shop structure which is
a reasonable image of existing shops in many industries in order to eval-
uate the effects of the proposed shop loading methodology. In fact, Con-
way and others (1967, p. 220) state that, "$... there is no evidence to
suggest that the use of actual shop data and dimensions significantly
alters the comparative performance of key procedures." The shop charac-
teristics employed in this research have been generally accepted by pre-
vious research studies by Baker and Dzielsinski (1960), Nanot (1963),
Conway, et al. (1965, 1967), Gere (1966), Bulkin et al. (1966), and Deane
(1972).

It is evident that in actual shops the arrival pattern does not
follow exactly the exponential distribution. Job arrivals tend sometimes
to be grouped together more closely than would be indicated by the expo-
nential interarrival times. Other times the job arrivals are more widely
spaced than is justified by the mean time between arrivals being used.
These two conditions seem to occur in cycles and therefore in order to
add realism to the job arrival pattern an option has been provided in the
job shop simulator to allow the mean time between arrivals to fluctuate.
This in effect creates a mean time between arrivals that is dynamic with respect to time rather than static as has been commonly done. The time for the next arrival is obtained by sampling an exponential distribution with a dynamic mean time between arrivals.

Other assumptions used in developing the models presented here are common to most job shops. These assumptions serve to simplify the study and the most important ones are listed below:

a) Each machine is continuously available for assignment
b) Each operation can be performed by only one type of machine in the shop
c) Each job can be processed on only one machine at a time
d) Jobs are strictly-ordered sequences of operations, without assembly or partitions
e) Pre-emptions of jobs on machines is not allowed
f) There is no set-up required for operations
g) Each machine can handle at most one operation at a time
h) A job is considered immediately available for its next operation when it finishes the current one.

2.1.2 Traditional Scheduling and Job Shop Classifications

Scheduling problems can be classified in several ways. The most common classifications are the following:

a) Classifications according to the job arrival pattern

1 - There is a fixed finite number of jobs in the shop. This is normally called the static case.

2 - The jobs arrive to the shop in a continuous stream and at
random intervals. This case is called a dynamic job shop.

b) Classifications according to the number of machines in the shop
1 - There is only one machine in the shop.
2 - There are two or more machines.

c) Classification according to the type of set-up times considered
1 - The set-up times are independent of the job sequence and therefore can be incorporated within the production time.
2 - The set-up times are dependent on job sequence.

d) Classification according to the job routing in the shop
1 - All jobs have identical routings through the shop. The shop is then called a flow shop.
2 - The jobs have non-identical routing through the shop.
   This is a job shop and if the routing is completely random, the shop is called a pure job shop.

e) Classification according to the job dispatching rule used
1 - First come first served
2 - Random
3 - Earliest due date
4 - Shortest processing time
5 - Minimum slack
6 - Dynamic slack per operation
7 - Minimum slack per operation
8 - Minimum work in next queue
9 - Longest processing time, etc.

f) Classification according to measures of job or shop performance
1 - Ability to meet specified completion dates
2 - Variance of the lateness distribution
3 - Average job flow time
4 - Maximum job flow time
5 - Work in process in total hours of work in the shop
6 - Work in process in hours of work done in the shop, etc.

The studies conducted in this research fit the following classification conditions given above: a.2, b.2, c.1, d.2, e.1, e.4, e.6, e.8, f.1, f.2, f.5, and f.6.

2.1.3 Measures of Performance

Measures of performance of primary interest in this research are those dealing with workload balance. However, the discussion of these will be deferred until balance measures are defined in the next chapter.

Other measures of performance obtained by the job shop simulator are:

Measures of performance related to work in process
a) Average work in process in hours of work in the shop.
b) Average number of jobs in the shop.
c) Average number of operations performed for jobs in the shop.
d) Average hours of work done for jobs in the shop. This measure gives an indication of the investment made in work performed for work in process in the shop.
e) Average queue length.

Measures of performance related to the ability to meet due dates
f) Average job lateness.
g) Variance of the lateness distribution.
h) Average job tardiness.

i) Average tardiness variance.

No attempt has been made to develop a composite performance criterion by assigning weights to the various measures of performance since these would vary from shop to shop. Instead, a subset of the above measures, based on their importance and/or how representative of their group they are, has been selected for statistical analysis and detailed study. The measures selected were a, d, g, and h. The average work in process in hours of work in the shop was selected because it is probably the most commonly accepted measured of work in process in both industry and in the literature. The average hours of work done for jobs in the shop is of particular interest to this research because it is an objective of the work to prove that the controlled shop loading methodology keeps away from the shop jobs that would be partially completed otherwise, and not only jobs at the end of their first queues.

The variance of the lateness distribution was selected because in many job shop situations the inability to predict completion dates, that is, the variability of the completion date with respect to the due date causes more problems than missing the due date itself. Finally, the average job tardiness was selected because it is the statistic most commonly accepted to measure due date performance.

2.2 Literature Review

The classifications provided before serve to give an underlying structure to the literature. The review, however, will be presented according to methodology, shop structure, and measure of performance used.
The number of articles in the general area of shop scheduling is extremely large. This research lists close to 200, Conway (1967) gives 202, Buffa and Taubert (1972) list 61, Day and Hottenstein (1970) include 162, and although there is some duplication in these sources, there are many other sources. Most of these articles deal with queuing problems, the problem of sequencing jobs in a static flow shop or they are concerned with simulation studies of a dynamic job shop using a job related measure of performance.

Very good and comprehensive reviews in the sequencing and scheduling area are provided in the book by Conway (1967) and the paper by Day and Hottenstein (1970). Other reviews given by Elmaghraby (1968), Mellor (1966), and Sisson (1959) are also available. The literature review presented here will not attempt to duplicate these reviews. An attempt, however, is made to highlight those articles from the literature which are directly relevant to this research as well as providing a sketch of the breadth of shop scheduling literature.

2.2.1 Analytical Approaches (Flow Shops, Restricted Problems)

The analytical approaches that have been used are algebraic, integer programming, dynamic programming, enumerative, branch and bound and graph theoretic. The initial ones were primarily algebraic and the majority of the most recent ones have used branch and bound.

Johnson (1954) considered the problem of minimizing maximum flow time in a two machine flow shop. In this frequently cited paper he developed a rule to minimize the maximum flow time.

Smith (1956) did extensive work on the one machine job problem. Among other results he showed that the mean flow time is minimized by
sequencing the jobs in order of non-decreasing processing time. It is also true in this case that SPT sequencing minimized mean lateness and mean number of jobs in the shop.

Smith and Dudek (1967) developed an algorithm for makespan minimization in a flow shop with no passing.

Ignall and Schrage (1965) and Lomnicki (1965) are generally credited with first using the branch and bound approach to the solution of flow shop problems. The basic idea in this approach is to partition the set of possible solutions into subsets and to use a lower bound of the schedule time in a solution subset to eliminate some of the subsets. Backtracking, of course, is required to guarantee optimality. Burton and McMahon (1967) expanded the previous work by Ignall and Schrage (1965) by introducing a job based bound in addition to the machine based bound.

Ashour (1969) applies a graph theoretic approach to the flow shop problem. This approach generates a sequence of "j" jobs in "j" iterations regardless of the number of machines involved.

In another article, Ashour (1970) presents a comparative evaluation of flow shop scheduling techniques and concludes that branch and bound techniques without backtracking give the best results at present when computer time is considered.

2.2.2 Analytical Approaches (General or Job Shops)

There have been several attempts at formulating the shop scheduling problem in terms of a mathematical programming model. Probably the most compact one is the one by Manne (1960). The formulation by Manne can handle several objective functions including minimization of mean flow time, maximum flow time, or mean tardiness. This approach, however, is
of theoretical interest only since it becomes computationally prohibitive for even very small problems.

Brooks and White (1965) use the branch and bound approach to solve the M machine, N job, job shop problem. Several measures of performance are considered but the paper concentrates on minimizing the time for completion (makespan) and minimizing average lateness.

Greenberg (1968) presents an approach for minimizing makespan or idle time in the M machine job shop. The approach formulates the shop as an integer programming problem and then uses branch and bound to solve it by transforming the integer programming problem into a series of linear programs to be solved at every branch. Charlton and Death (1970) have developed a branch and bound approach that can be applied to a wide variety of machine scheduling problems and they show how the algorithm reduces to methods previously published under special conditions.

There have been some analytical papers that approach a job shop as a network of queues. The most significant result in these papers has been to develop sufficient conditions under which a network of queues can be treated as an aggregation of independent queues, Jackson (1963). Burke (1972) presents a summary of the results obtained in this area.

2.2.3 Computer Simulation Approaches

Computer simulation has been practically the only approach used to study the dynamic job shop problem.

The earlier work in this area was done by Jackson (1957), and Le Grande (1963), Baker and Dzielinski (1960), Nanot (1963), Bulkin, Colley, and Steinhoff (1966), and others. The general objective in most of these studies was to compare the effectiveness of dispatching rules with respect
Good reviews have been provided by Sisson (1959) and Moore and Wilson (1967). Buffa and Taubert (1972) provide a good summary of several of the above articles.

Conway, Maxwell, and Miller (1967) reported a significant amount of new work done at Cornell University as well as an excellent general discussion of simulation approaches to the shop scheduling problem. The general conclusion of the simulation work done is that the shortest processing time rule minimizes the mean flow time, mean number of jobs in the shop, and the mean lateness. Most of the rules considered, however, were local dispatching rules, that is, rules that did not consider shop conditions except at the individual queue where the dispatching decision took place.

Emery (1969) introduces a job shop simulation program in which various dispatching rules are combined through the use of weights into a single job dispatching criterion and results slightly better than those produced by any of the individual rules are obtained. However, some of the more interesting rules are not included and the test results given are very limited.

2.2.4 Articles of Miscellaneous Interest

Several articles of general interest that could not be easily classified in any of the previous sections will be presented next.

Harding, Gentry, and Parker (1969) proposed a heuristic sequencing rule based on job due date, processing time, and status of the work center where the job will go next. They reported improvements in the percentage of jobs meeting their scheduled dates in an actual shop, but no controlled
Ebert (1972) analyzes the performance of intuitive decision making when compared with a mathematical model. A controlled experiment was used and it was concluded that in this case (aggregate production scheduling) the model decisions were superior to the intuitive decisions and that furthermore the superiority increases as the time-horizon complexity increases. No rigorous study of this type comparing mathematical models to an intuitive dispatcher was found in a job shop environment.

Von Lanzenauer (1970) presents a model to attack the scheduling as well as the sequencing problem. By scheduling he means how much and when to produce. The model is a 0-1 integer programming formulation with the objective of minimizing total costs. The terms in the objective function include set up, inventory, and shortage costs. This is a welcome attempt at integrating these two problems, however, the model in its present form cannot be utilized for realistic problems as the author recognizes.

Eilon and Christofides (1971) analyze a particular type of loading problem. This problem consists of allocating n objects or items of magnitude $Q_i$ to boxes, each box having a capacity C, in such a way that the capacity constraints are not violated and the number of boxes required is a minimum. They presented a zero-one programming solution and a heuristic algorithm and demonstrated that the algorithm obtained the optimal solution almost all the time. Greenberg (1972) uses this loading algorithm to allocate workloads over a number of identical stations or workers under static job conditions such that the resulting workloads are nearly equally balanced.
Ghare, Givens, and Torgersen (1969) presented a paper, "A Machine Release Scheme for the Job Shop," which considered several machines at each work station and the effect of operator learning on the performance of the shop. The job shop was viewed as a network of queues, with all the required restrictive assumptions. A scheme was developed to release machines to other assignments as learning takes place so as to maintain a relatively constant level of machine utilization. This is a very interesting paper, but not directly applicable to the work in this thesis. The title of the article is so closely related to this research, however, that a discussion of the article was deemed necessary.

Franklin (1969) proposes a framework for job shop research. He states that the value of a shop's output depends upon both the technique or rule employed for scheduling and the product mix or aggregation of jobs upon which the technique operates. Franklin also claims that there are four basic components in every experimental or theoretical approach to the job shop problem. These are:

a) the model of the process
b) the scheduling technique
c) the product mix, the particular problem under analysis
d) the objective function.

He further claims that the product mix is instrumental to every analysis and that the others, except for the objective function, can be expressed in terms of the variables describing this product mix. This is a good attempt at providing a framework, but should have been complemented with a presentation of several articles and problems in order to "test" the structure proposed.
Day and Hottenstein (1970) present a comprehensive review of sequencing research in which a classification scheme is provided. The primary classifications proposed are the following:

1. Numbers of component parts comprising a job
   a) Single component jobs
   b) Multi-component jobs which require assembly operations

2. Production factors possessed by the shop
   a) Machines
   b) Labors and machines

3. Jobs available for processing
   a) N jobs to be sequenced where N is finite (static problem)
   b) An undetermined number of jobs arrive continuously, but randomly at the shop for service.

Most of the articles in the literature are of the (1a-2a-3a) and (1a-2a-3b) variety and this research fits in the (1a-2a-3b) group. An additional scheme for classifying problems of these two varieties is also provided in the article. This is done by considering one machine and multimachine problems as well as the variations allowed by routing (flow shops, job shops). The article then proceeds to examine the accomplishments and the methods used to solve problems in each one of the cases citing several papers in each classification. The conditions that have been used in the literature related to the dynamic job shop problem, which is of special interest to this research, are covered in detail by Day and Hottenstein on pages 17-26. These conditions deal with job arrivals, processing times, shop size, job routing, assignment of due dates, types of priority rules used, initialization of job shop simulations, and
2.2.5 Articles of Direct Interest

Ackerman (1963, 1964) presented the idea that a job spends most of its time waiting in queues rather than being processed and that job flow time is therefore highly correlated with the number of operations in a job and not with the job processing time. He used this idea to develop a scheduling procedure which he called "Even Flow" based on scheduling a job by allocating one time period for each job operation starting backwards from the job due date. Ackerman also presented some simulation results which backed his claim of reduced lateness when compared to Random, FIFO, and SPT dispatching rules. However, the comparisons are not strictly valid since the Even Flow system allowed machine overtime in some cases.

Schussel (1968) presents an algorithm directed at work balance and in-process inventory minimization based on a matrix concept with machines and days. The algorithm starts from the due date of any job back, trying to fill in slots of production time. The objective function used is quite complex and could probably be simplified while retaining the main ideas in the article. No application results of this algorithm were presented.

The work by Deane (1972) and the resulting article by Deane and Moodie (1972) bear the closest relationship to this research. Deane develops a Balance Index to be used as the primary measure of performance. This machine work balance index (MWB) measures the deviation of machine utilization from its average every period. Deane then develops what he calls a "flow controlled scheduling methodology." This consists of a periodic search procedure which directly attempts to guide work to under-
loaded machines, that is, jobs that can make large contributions in their next operation to underloaded machines are given high priorities in their present operations. The search procedure is a dynamic one in that any job given a high priority has an effect in the selection of all future jobs.

An additional balance index was developed by Deane. This was the shop Workload Balance Index (SWB) which is based on variations in the utilization of the shop as a whole. The search dispatching rules offered significant improvements in the machine workload balance index, but not on the shop workload balance index. Deane, however, allowed all the jobs to get in the shop as soon as they became available and did not recognize the advantages of maintaining a job pool for providing additional flexibility in the operation of the shop.
CHAPTER III

WORKLOAD BALANCE MEASURES

3.1 General

The two most important considerations regarding the objective of balancing a job shop are the method selected to measure balance and the determination of the effect of "balancing" the shop, if any, on other measures of shop performance. The exploration of the first point is the primary objective of this chapter, while the second one will be briefly discussed below and in a more quantitative basis in Chapters IV and VIII.

The effect of balance on other measures of performance must be investigated because the only obvious objective functions in a shop are minimization of costs or maximization of profits. It is difficult, however, to construct models explicitly in terms of those objectives because many subjective evaluations are required. For this reason, indirect measures of performance are used.

It would be possible, of course, to assign weights and conversion factors to these indirect measures of performance so that total costs could be obtained, but the results would depend heavily on the weights and conversion factors used.

It is usually preferable, however, to establish a logical relationship between the indirect measure and the final objective (cost minimization or profit maximization) and then proceed to devise methods to improve or optimize the indirect measure of performance directly. This
method has been followed in this research.

For example, the ability to meet due dates is among the most common measures of performance used in a job shop. This is justified because of the large penalty cost or opportunity cost resulting from the probable loss of business if due dates are consistently missed. This type of approach is the same one that is used in justifying the importance of shop balancing. The relationship between balancing and the final objectives have been briefly discussed in Chapter I and will be further considered in Chapter IV.

Balancing must be machine oriented or time period oriented. Machine oriented balance measures recognize the fact that shops are designed with a certain product mix in mind and operate most efficiently under those conditions. These measures do not allow an underloaded machine to cancel the effects of an overloaded machine and they also detect the changes of a machine load over time, even when these changes are due to an overall shop condition. Time period oriented balance measures place primary attention to the efficiency improvements that can be achieved when shop productivity and/or loading is predictable over time. These measures do not allow the index to be influenced by overall shop changes from period to period.

It is important to note that the concept of workload balancing necessarily implies the division of the planning horizon into scheduling periods. This, of course, is a very realistic assumption. Most shops work within a definite scheduling period such as a shift, day, week, etc. In practical situations the length of the scheduling period will correspond to the "period of accountability" imposed upon the shop by manage-
management. Management will usually require efficiency or cost statistics for this period.

The length of the time period to be utilized must be given careful thought because a very long one will hide significant fluctuations while a short time period will place too much weight on unavoidable variations.

A scheduling period of eight hours was chosen for the investigations presented in this research. This time period was selected as being reasonable with respect to the other shop parameters that were employed. A longer time period will require that more jobs be loaded in the shop every period so that the amount of work released to the shop per unit time stays fairly constant. The longer scheduling period will also afford less opportunities to correct out of balance conditions existing in the shop. A shorter scheduling period will have the opposite effect, but it will require more computer time.

3.2 Notation

The following notation will be used in developing the balance measures which are presented in the rest of this chapter.

- \( p \): number of scheduling periods in the scheduling horizon
- \( m \): number of machines or machine centers
- \( u_{ij} \): work done by machine \( i \) in period \( j \)
- \( \bar{u}_i \): average work done by machine \( i \) over all periods \( j \)
  \[
  \bar{u}_i = \frac{1}{p} \sum_{j=1}^{p} u_{ij}
  \]
- \( \bar{u}_j \): average work done in period \( j \) over all machines \( i \)
  \[
  \bar{u}_j = \frac{1}{m} \sum_{i=1}^{m} u_{ij}
  \]
average queue size in number of jobs for machine $i$ in period $j$

$\bar{v}_i$ average queue size in number of jobs for machine $i$ over all periods

$$\bar{v}_i = \frac{1}{p} \sum_{j=1}^{p} v_{ij}$$

average queue size in number of jobs in period $j$ over all machines

$\bar{v}_j = \sum_{i=1}^{m} \frac{v_{ij}}{m}$

average queue size (plus work remaining on job being processed) in number of hours of work for machine $i$ in period $j$. This is the average work in process (work to be done) for machine $i$ in period $j$.

$\bar{H}_{ij}$ average aggregate load (in all queues and machines) in hours of work for machine $i$ over all periods $j$.

$\bar{H}_i$ average aggregate load or work in process in period $j$ over all machines $i$.

$\bar{P}_{ij}$ aggregate load for machine $i$, in hours, including jobs that have just been placed in the shop at the beginning of scheduling period $j$.

$\bar{P}_i$ average aggregate load for machine $i$. This aggregate load includes not only the load given by the queue in front of machine $i$, but also the future load for machine $i$ given by jobs in other queues.
\( q_{ij} \) maximum queue size in number of jobs for machine \( i \) in period \( j \).

\( r_i \) desired queue size in number of jobs for machine \( i \).

\( 0_{ij} \) work output by machine \( i \), in hours, performed on jobs leaving the machine during period \( j \). The difference between this variable and \( u_{ij} \) is due to work done on a job during a period in which the job was not completed by machine \( i \).

\( \bar{0}_i \) average output of machine \( i \) over all periods \( j \). As the number of periods increases the percentage difference between \( \bar{0}_i \) and \( \bar{u}_i \) becomes very small,

\[
\lim_{p \to \infty} \frac{u_i - \bar{0}_i}{\bar{0}_i} \leq \varepsilon
\]

where

\[
\bar{0}_i = \frac{1}{p} \sum_{j=1}^{p} 0_{ij}
\]

\( \bar{0}_j \) average output in period \( j \) over all machines \( i \)

\[
\bar{0}_j = \sum_{i=1}^{m} 0_{ij}
\]

\( A_{ij} \) amount of work in hours arriving to machine \( i \) in period \( j \).

\( \bar{A}_i \) average work in hours arriving to machine \( i \) over all periods \( j \).

\( \bar{A}_j \) average work in hours arriving in period \( j \) for all machines.

3.3 Definitions of Shop Balance Measures

Balance in a job shop can be measured in many different ways. A large number of balance measures will be defined in this section, but the ones discussed here are not the only ones.

There is not one best measure of shop balance, but rather each one of the measures given applies best to a specific type of shop, product, or
management structure. Other conditions will certainly be identified in the future that can be measured best in terms of balance statistics not included in this group.

These balance measures are based on work done (or equivalently, machine or shop utilization), work output, queue size, or work arrival. The balance measures presented in paragraphs 3.3.1 and 3.3.2 are due to Deane (1972) and the rest of them are presented here for the first time. Table 1 presents a brief summary of all the balance measures considered.

3.3.1 Machine Work Balance Index (MWB)

The variance in the work done by each machine over all time periods is calculated. The word "variance" is used here to indicate the form of the formula employed and does not imply any statistical meaning.

An overall index is then obtained by averaging over all machines. Let $B_i$ be the machine index for machine $i$.

$$B_i = \sum_{j=1}^{P} \frac{(u_{ij} - \bar{u}_i)^2}{\frac{p}{m} \sum_{i=1}^{m} B_i}$$

$$\text{MWB} = \frac{\sum_{i=1}^{m} B_i}{m}$$

Objective: Minimize MWB

This index can be used when it is important to consider the utilization of individual work centers without allowing a cancelling effect. That is, this index will detect the variations of a machine production over time and will not allow the over production of one machine in a time period to compensate the underutilization of another machine in the
### Table 1. Measures of Shop Balance

<table>
<thead>
<tr>
<th>Paragraph No.</th>
<th>Name</th>
<th>Index Symbol</th>
<th>Unit Symbol</th>
<th>Characteristics, Definition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.1</td>
<td>Machine Work Balance Index</td>
<td>MWB</td>
<td>$n$</td>
<td>Variance of work done per period by each machine</td>
<td>It considers the work done by individual work centers.</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Shop Work Balance Index</td>
<td>SWB</td>
<td>--</td>
<td>Variance of the utilization or work done by the shop as a whole</td>
<td>It measures variability of work done by entire shop; but does not detect variations in individual machines.</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Period Work Balance Index</td>
<td>PWB</td>
<td>$BP_j$</td>
<td>Variance of the work done by all machines for each time period</td>
<td>It measures changes in work done by machines within a period, but ignores differences from period to period.</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Machine Output Balance Index</td>
<td>MOB</td>
<td>$BO_j$</td>
<td>Variance of output per period of each machine</td>
<td>Similar to 3.3.1 but output rather than work done is used. Could be useful when output variability is undesirable.</td>
</tr>
<tr>
<td>3.3.5</td>
<td>Shop Output Balance Index</td>
<td>SOB</td>
<td>--</td>
<td>Variance of the output by the shop as a whole over time</td>
<td>Similar to 3.3.2 but output rather than work done is employed.</td>
</tr>
<tr>
<td>3.3.6</td>
<td>Period Output Balance Index</td>
<td>POB</td>
<td>$PO_j$</td>
<td>Variance of the output by all machines for each time period</td>
<td>Similar to 3.3.3 but output rather than work done is employed.</td>
</tr>
<tr>
<td>3.3.7</td>
<td>Machine Queue Balance Index</td>
<td>QWB</td>
<td>$Q_j$</td>
<td>Variance of queue size in number of jobs per period for each machine</td>
<td>Used when it is desired to keep track of WIP stability at the machine level.</td>
</tr>
<tr>
<td>3.3.8</td>
<td>Shop Queue Balance Index</td>
<td>SQB</td>
<td>--</td>
<td>Variance of the number of jobs in the shop over time</td>
<td>Used when it is desired to keep track of the WIP stability for the shop as a whole.</td>
</tr>
<tr>
<td>3.3.9</td>
<td>Period Queue Balance Index</td>
<td>PQWB</td>
<td>$PO_j$</td>
<td>Variance of the queue size over all machines for each time period</td>
<td>Used in a manner similar to 3.3.7, but ignores WIP variations over time.</td>
</tr>
<tr>
<td>Paragraph No.</td>
<td>Name</td>
<td>Index Symbol</td>
<td>Unit Symbol</td>
<td>Characteristics, Definition</td>
<td>Comments</td>
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<tr>
<td>--------------</td>
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</tr>
<tr>
<td>3.3.10</td>
<td>Measures Related to Hours of Work in Queue</td>
<td>---</td>
<td>---</td>
<td>These measures are similar to 3.3.7, 3.3.8, 3.3.9, but hours of work instead of number of jobs are used</td>
<td></td>
</tr>
<tr>
<td>3.3.11</td>
<td>Machine Work in Process</td>
<td>APWP</td>
<td>SWIP</td>
<td>Variance of the aggregate WIP hours per period for each machine</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The difference with measure 3.3.7 is that the total work in the shop for a machine rather than work in that machine queue only is considered.</td>
<td></td>
</tr>
<tr>
<td>3.3.12</td>
<td>Shop Work in Process</td>
<td>SWIP</td>
<td>---</td>
<td>Variance of the aggregate WIP in the whole shop over time</td>
<td>Similar to 3.3.8.</td>
</tr>
<tr>
<td>3.3.13</td>
<td>Period Work in Process Balance Index</td>
<td>APWP</td>
<td>PNIP</td>
<td>Variance of the aggregate WIP over all machines for each time period</td>
<td>Consideration of variations in the aggregate load could be important as a means of looking beyond immediate period.</td>
</tr>
<tr>
<td>3.3.14</td>
<td>Desired Loading Measure</td>
<td>D</td>
<td>D</td>
<td>Deviation of aggregate shop load for each machine from management target</td>
<td>Useful as an objective function in trying to improve other balance and shop measures.</td>
</tr>
<tr>
<td>3.3.15</td>
<td>Maximum Queue Deviation Index</td>
<td>QD</td>
<td>QD</td>
<td>Maximum excess in queue size over the desired amount set up by management</td>
<td>Could be used in shops where a penalty must be paid if queue lengths exceed some amount.</td>
</tr>
<tr>
<td>3.3.16</td>
<td>Period Idle Time</td>
<td>PIT</td>
<td>IDT</td>
<td>Maximum idle time for any machine in a period</td>
<td>Useful when there is no operator flexibility and operator idleness in a period should not be excessive.</td>
</tr>
<tr>
<td>Paragraph No.</td>
<td>Name</td>
<td>Index Symbol</td>
<td>Unit Symbol</td>
<td>Characteristics, Definition</td>
<td>Comments</td>
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</tr>
<tr>
<td>3.3.17</td>
<td>Machine Idle Time</td>
<td>MIT</td>
<td>IDT</td>
<td>Maximum idle time for a machine over all periods</td>
<td>Useful if machines require adjustments when left unused over a certain length of time.</td>
</tr>
<tr>
<td>3.3.18</td>
<td>Machine Arrival Balance Index</td>
<td>MAB</td>
<td>A_i</td>
<td>Variance of the work arrived per period to each machine</td>
<td>This index is a function of the work arrival pattern, loading mechanism, and dispatching mechanism.</td>
</tr>
<tr>
<td>3.3.19</td>
<td>Shop Arrival Balance Index</td>
<td>SAB</td>
<td>--</td>
<td>Variance of the work arrival to the shop as a whole over time</td>
<td>Similar to 3.3.2 but work arrival rather than work done is employed.</td>
</tr>
<tr>
<td>3.3.20</td>
<td>Period Arrival Balance Index</td>
<td>PAB</td>
<td>D_A</td>
<td>Deviation between actual arrivals to a machine in a period and the machine average</td>
<td>Useful in a situation where relief could be provided to one overloaded machine per period.</td>
</tr>
</tbody>
</table>
same period. A characteristic of those shops where this measure is im-
portant is the existence of several machines in a machine group so that
no labor is wasted by the partial utilization of a machine group, or the
possibility of assigning several tasks or machines to an employee.

3.3.2 Shop Work Balance Index

This is the variance of the utilization of the shop as a whole
taken over time.

\[
SWB = \frac{1}{p} \sum_{j=1}^{p} \left( \sum_{i=1}^{m} u_{ij} - \frac{1}{m} \sum_{i=1}^{m} \bar{u}_i \right)^2
\]

The formula for SWB can be simplified considerably by using the
definition of \( \bar{u}_i \) given in the notation and by defining the average work
per period for the whole shop as follows:

\[
\bar{u} = \sum_{i=1}^{m} \bar{u}_i
\]

Then,

\[
SWB = \frac{1}{p} \sum_{j=1}^{p} (m \bar{u}_j - \bar{u})^2
\]

The objective is: Minimize SWB

This measure is important in those shops where there is flexi-
bility in the type of work that each worker can do. In shops with this
flexibility, a given job can be moved from one machine or operator to
another without incurring a significant penalty. Therefore it is of
primary importance that the total work to be done by the shop be fairly
constant over time so that shop expansion and contraction be reduced, but it is not so important that the work available be distributed exactly according to the nominal machine or operator's capacity.

3.3.3 Period Work Balance Index

This balance index is based on the variance of the work done over all machines for each time period. An index can be calculated then by averaging the variance obtained in each time period. Let $BP_j$ be the index for period $j$.

$$BP_j = \frac{1}{m} \sum_{i=1}^{m} \left( u_{ij} - \bar{u}_j \right)^2 = \frac{1}{m} \left( \sum_{i=1}^{m} u_{ij} \right)^2 - \bar{u}_j^2$$

$$PWB = \sum_{j=1}^{P} \frac{BP_j}{P}$$

Objective: Minimize PWB

This measure is similar to #1 in that it does not recognize any cancelling effects between machines, but in this case it accepts the fact that shop workloads will vary from period to period and looks only at the work balance achieved given the existing work load.

The use of this measure instead of #1 implies great flexibility in expanding or reducing the work force since no penalties are assigned for changes in the work performed in different time periods.

3.3.4 Machine Output Balance Index

This measure and the two that follow are very similar to measures #1-3. The only difference is that work output rather than work done or utilization is used.
The difference is better illustrated by an example. If machine \( i \) in period \( j \) finished job #1 and it spent two hours during the previous period and one hour in period \( j \) working on job #1, finished job #2 which took three hours, and spent three hours on job #3 but couldn't finish it, then the utilization of machine \( i \) in period \( j \) was seven hours while its work output was six hours. The example is represented by Figure 1.

In the case of the machine measures (3.3.4 and 3.3.6), this is a reasonable approach when the job movements are heavily dependent on time periods as would be the case when the machine groups are located in different buildings and trips with vehicles of fixed limited capacity can take place only once per scheduling period.

\[
BO_i = \frac{1}{p} \sum_{j=1}^{p} (O_{ij} - \bar{u}_i)^2
\]

\[
MOB = \frac{1}{m} \sum_{i=1}^{m} BO_i
\]

Objective: Minimize MOB

### 3.3.5 Shop Output Balance Index

\[
SOB = \frac{1}{p} \sum_{j=1}^{p} \left( \sum_{i=1}^{m} O_{ij} - \frac{1}{m} \sum_{i=1}^{m} \bar{u}_i \right)^2
\]

\[
SOB = \frac{1}{p} \sum_{j=1}^{p} (\bar{mO}_j - \bar{u})^2
\]

Objective: Minimize SOB
Machine $i$ utilization in period $j = 1 + 3 + 3 = 7$ hours

Machine $i$ output in period $j = 3 + 3 = 6$ hours

Figure 1. Illustration of Machine Output and Utilization in a Period
3.3.6 Period Output Balance Index

\[ BPO_{ij} = \frac{1}{m} \sum_{i=1}^{m} (O_{ij} - \bar{O}_j)^2 \]

\[ POB = \frac{1}{p} \sum_{j=1}^{P} BPO_{ij} \]

Objective: Minimize POB

3.3.7 Machine Queue Balance Index

This is the variance of queue size in number of jobs for each machine over time. Then an overall index is obtained by averaging over all machines. Let \( Q_{i} \) be the machine queue index for machine \( i \).

\[ Q_{i} = \frac{1}{p} \sum_{j=1}^{P} (V_{ij} - \bar{V}_i)^2 \]

\[ QWB = \frac{1}{m} \sum_{i=1}^{m} Q_{i} \]

Objective: Minimize QWB

This measure is important when there is not much flexibility in the machine assignment for job operations and when furthermore it is desirable to keep the work in process as stable as possible during the scheduling horizon.

3.3.8 Shop Queue Balance Index

This is the variance of the number of jobs in the whole shop taken over time. This is a measure of work in process variability.
The equation for SQB can be simplified by using the definition of \( \bar{V}_j \) given in the notation and by defining the average number of queues in the shop as follows:

\[
\bar{V} = \sum_{i=1}^{m} \bar{V}_i
\]

Then,

\[
SQB = \frac{1}{p} \sum_{j=1}^{P} (m \bar{V}_j - \bar{V})^2
\]

Objective: Minimize SQB

### 3.3.9 Period Queue Balance Index

This is the variance of queue size over all machines for each time period. An index is then calculated by averaging the variance obtained in each time period. Let \( PQ_j \) be the period queue index for period \( j \).

\[
PQ_i = \frac{1}{m} \sum_{i=1}^{m} (V_{ij} - \bar{V}_i)^2
\]

\[
PQWB = \frac{1}{p} \sum_{j=1}^{P} PQ_j
\]

Objective: Minimize PQWB

This measure is similar to #7, but it recognizes that load variations for the entire shop over the scheduling horizon are unavoidable and
attempts to reduce the influence of that kind of variation on the measure of performance.

3.3.10 Measures Related to Hours of Work in the Queue

Indices #7, 8, and 9 measure the variability of work in process using the number of jobs in the queue or the shop as the basis. It is obvious that similar measures can be obtained using the number of hours of work in the queue for the corresponding machines.

3.3.11 Machine Work in Process Balance Index

Measures #11-13 differ from measure group #10 in that before, the hours of work in process at a given queue to be worked by that machine were considered. This time the aggregate work in process for a machine, regardless of the queue where it presently resides, is of interest. Let $MWIP_i$ be the work in process index for machine $i$.

$$MWIP_i = \frac{1}{P} \sum_{j=1}^{P} (P_{ij} - \bar{P}_i)^2$$

$$AMWP = \frac{1}{m} \sum_{i=1}^{m} MWIP_i$$

Objective: Minimize $AMWP$

3.3.12 Shop Work in Process Balance Index

$$SWIP = \sum_{j=1}^{P} \left( \frac{\sum_{i=1}^{m} P_{ij} - \sum_{i=1}^{m} \bar{P}_i}{P} \right)^2$$

Let the average work in process in the shop be given as follows:
Then SWIP can be simplified as shown below:

\[
SWIP = \frac{1}{P} \sum_{j=1}^{P} (m\bar{P}_j - \bar{P})^2
\]

Objective: Minimize SWIP

### 3.3.13 Period Work in Process Balance Index

Let PWIP\_j be the work in process index for period j

\[
PWIP_j = \frac{1}{m} \sum_{i=1}^{m} (P_{ij} - \bar{P}_j)^2
\]

\[
APWP = \sum_{j=1}^{P} \frac{PWIP_j}{P}
\]

Objective: Minimize APWP

### 3.3.14 Desired Loading Measure

This measure identifies the deviation of aggregate shop load for each machine (each period) from a specified target set up by management. The quantity obtained for each machine is then averaged over all periods. Let D\_ij be the deviation of the aggregate load for machine i in period j from the desired amount.

\[
D_{ij} = |P_{ij} - C_i|
\]

(continued)
Objective: Minimize $D$

This measure is important because of its relationship to other shop oriented measures, its intuitive appeal to management and the fact that it attempts to look beyond the immediate conditions at one queue or machine (but without trying to predict or consider the interactions that occur in a job shop as one job moves from one machine to the next).

3.3.15 Maximum Queue Deviation Index

This measure gives for each machine the maximum excess in queue size over the desired queue size (or average) set up by management. The measure can also be used in terms of absolute maximum queue size without referring to any desired quantity.

$$QD_1 = \max \left| q_{ij} - r_i \right|$$

$$QD = \max QD_i$$

or

$$QD = \sum_{i=1}^{m} QD_i$$

Objective: Minimize $QD$
A possible variation is to consider only positive deviations, that is,

\[ QD_i = \max_j (q_{ij} - r_i) \]

This measure could be useful in those shops where a large penalty must be paid when queue lengths at machine \( i \) exceeding \( r_i \) cause a large penalty cost.

### 3.3.16 Period Idle Time

This measure obtains the maximum idle time for any machine in a period.

Then the average of all such maximum period idle times is calculated and the objective is to minimize this average.

Let \( \text{PLEN} \) be the period length.

\( \text{IDT}_{ij} \) is idle time for machine \( i \), period \( j \)

\[ \text{IDT}_{ij} = \text{PLEN} - u_{ij} \]

\[ \text{IDT}_j = \max_i \text{IDT}_{ij} \]

\[ \text{PIT} = \frac{1}{P} \sum_{j=1}^{P} \text{IDT}_j \]

\[ = \frac{1}{P} \sum_{j=1}^{P} \max_j (\text{PLEN} - u_{ij}) \]

**Objective:** Minimize \( \text{PIT} \)
3.3.17 Machine Idle Time

This measure looks at the idle time for a machine over all periods. Then either the maximum, average, or variance of this idle time is calculated and the index is obtained by averaging over all machines.

\[ \text{IDT}_{ij} = \text{PLEN} - u_{ij} \]

\[ \text{IDT}_i = \max_j \text{IDT}_{ij} \]

or

\[ \text{IDT}_i = \frac{1}{p} \sum_{j=1}^{p} \text{IDT}_{ij} \]

or

\[ \text{IDT}_i = \frac{1}{p} \sum_{j=1}^{p} \left( \text{IDT}_i - \frac{1}{p} \sum_{j=1}^{p} \text{IDT}_{ij} \right)^2 \]

\[ \text{MIT} = \frac{1}{m} \sum_{i=1}^{m} \text{IDT}_i \]

Objective: Minimize MIT

The balance index based on the maximum idle time for a machine over all periods can be used when there is a machine that could be "spoiled" or require adjustments if it is left unused over a certain length of time. The index based on the average idle time can be employed when it is necessary to measure the average machine utilization and finally the index based on the variance of the machine idle time could be useful in those cases in which a machine should be used at a steady rate from period to period.
3.3.18 Machine Arrival Balance Index

The variance in the work arrived to each machine over all time periods is calculated. Then an index is obtained by averaging over all machines. Let $A_i$ be the machine index for machine $i$

$$A_i = \frac{1}{p} \sum_{j=1}^{p} (a_{ij} - \bar{a}_i)^2$$

$$MAB = \frac{1}{m} \sum_{i=1}^{m} A_i$$

Objective: Minimize MAB

This index is a function of the work arrival pattern, the loading mechanism, and the dispatching mechanism.

3.3.19 Shop Arrival Balance Index

This measure is similar to the machine arrival balance index, but the shop as a whole is considered.

$$SAB = \frac{1}{p} \sum_{j=1}^{p} \left( \sum_{i=1}^{m} a_{ij} - \sum_{i=1}^{m} \bar{a}_i \right)^2$$

$$= \frac{1}{p} \sum_{j=1}^{p} \left( \bar{a}_{j} - \bar{a} \right)^2$$

3.3.20 Period Arrival Balance Index

Obtain the maximum deviation over all machines between actual arrivals to a machine in a period and the average arrivals to that machine.
The index then consists of the average over all periods

\[ DA_{ij} = a_{ij} - \bar{a}_i \]

\[ DA_j = \max_i DA_{ij} = \max_i (a_{ij} - \bar{a}_i) \]

\[ PAB = \frac{1}{p} \sum_{j=1}^{p} DA_j \]

Objective: Minimize PAB
CHAPTER IV

METHODOLOGY FOR LOADING AND BALANCING THE SHOP

4.1 Shop Balancing, Job Pool Concept, Discrete Job Selection and Loading from the Pool

In general, industrial job shops are designed to operate optimally at certain load levels and outputs for each machine type. Load fluctuations from period to period for a given machine or for the shop, or even deviations from machine to machine within a period, result in costs of idle machinery and labor or overtime premiums.

The need for balancing workloads is beginning to be recognized by some shops and the author is personally aware of two apparel style shops where keeping the shop workload balanced is a primary objective.

The fact remains, however, that most job shop managers do not explicitly mention shop balancing as their primary goal. This has been reported by Panwalkar, Dudek, and Smith (1972). This result is not surprising because maintaining a balanced workload in a shop does not have an obvious payoff or direct penalty, as for example meeting due dates does. Besides, most shops tend to maintain an excessive amount of work in process therefore hiding the effects of poor balancing. Another way in which job shop managers hide the effect of poor balance conditions is by having some job operations performed at other than their normal machines. This, of course, results in increased costs due to poor machine use and/or expensive operator transfers.
Job shops need a certain level of work in process to operate at a given shop utilization percentage. If the work in process is evenly spread over all machines, then a smaller amount of work in process in the shop is needed to maintain the required shop utilization than if the work in process is concentrated in a few machines and not enough work exists for other machines.

The relationship between shop operating costs, work in process levels, and balance conditions in the shop floor has been discussed in the preceding paragraphs, but a direction of causality has not been definitely established. It will be shown during this research, however, that when jobs are loaded in the shop using an algorithm with an objective function which is primarily oriented towards improving one balance measure, then the other balance measures and work in process measures calculated are improved. The variance of the lateness distribution is also improved in some cases. It is therefore anticipated that when shop balance is improved, work in process levels are significantly reduced.

In traditional job shop studies, all jobs are scheduled and sent to their first operation machine as soon as they arrive in the shop. This causes long queues and high work in process as well as shop imbalance according to most balance measures.

Most of the existing dispatching rules are local rules in which only the queue information is used. Expected Work in Next Queue (EWIQ) is the only one of the more common rules mentioned by Conway and others (1967) which is not a local rule or a job dispatching rule since information that is not job related is used in determining job priorities. Deane (1972) considered the use of a shop dispatching methodology to
improve machine workload balancing, but in his study all jobs were released
to the shop as soon as they became available.

Analyzing the methods followed in actual shops in several industries,
it can be seen that the shop is not loaded with every job that becomes
available, that is, not all jobs are released immediately after it becomes
theoretically possible to do so. Rather they are retained in a "suspend
file"; this being nothing more than a notation in a scheduling book or at
most an open purchase order or some unused raw material.

It is wise to keep backlogs off the factory floor. This reduces
the work in process and allows a faster flow of jobs through the actual
shop, even though the total flow time from the moment a job becomes
available might and probably will be increased. Obviously, over a long
period of time the total work arriving at the shop cannot be over 100% of
shop capacity. In fact, as 100% utilization is approached, the queue
sizes begin to move towards infinity. However, over short periods of
time the work content of incoming jobs may exceed shop capacity. In
these cases a temporary overload will exist in the shop. This overload
will consist not only of jobs that have not been started yet, but also of
an excessive quantity of partially completed jobs.

A useful tool to remedy this situation is to let the shop work
behind a pool of jobs not yet released to the shop floor. Additional
benefits can be obtained from the job pool if the job due dates are not
critical so that there is increased flexibility in job selection.

Under the job pool concept the shop consists of a pool of jobs not
yet released to the floor and distinct machine centers with a queue of
jobs in front of each.
Loading consists of the release into the shop of a subset of the pool every scheduling period. The scheduling period can be a shift, a day, a week, etc. If the scheduling period is a day, then new jobs would come into the pool at various times during the day, but a subset of the jobs will be released from the pool to the shop once every day.

The key to the successful use of the job pool is the availability of a good mechanism to select those jobs from the pool that should be moved to the factory floor. This mechanism is in fact the proposed loading algorithm.

The use of the job pool and the loading algorithm provide another useful by-product. This is the concept of "discrete" decision making which is used in practice in many job shops. By this it is meant that decisions in many shops are not made in a continuous fashion, but rather they are made periodically by shop supervisors.

4.2 The Loading Algorithm

The loading algorithm, together with the job pool and the discrete decision making, is an integral part of the proposed loading and balancing methodology. As such, the objectives of the loading algorithm are the same as those of the complete methodology, that is, the improvement of shop balance and work in process measures while still operating under due date constraints. The specific objective function, however, employed by the loading algorithm is the minimization of the deviation from aggregate balance for each machine center in the shop.

Deviation from aggregate balance is interpreted as the difference between a desired total or aggregate load ahead of a machine and the actual
load for each machine. The desired load is set by management and provides control over the shop operation.

It is evident that different objective functions are possible, but the one used concentrates on aggregate scheduling and releasing, as opposed to detailed dispatching, which is in line with the objectives of the research.

The loading algorithm utilizes a mixed integer programming approach with equality constraints based on the current workload assignments at each machine center. The constraints become equalities by the use of positive and negative slack variables giving the excess or lack of work (when compared to desired load) at each machine center. The objective of the program consists then of minimizing the sum of these slack variables, that is, minimizing the absolute deviations from the desired aggregate load for each machine center. An additional term is introduced in the objective function to make jobs in the pool increasingly attractive to be loaded in the shop as their due date approaches. The weight assigned to this term can be easily controlled by the production planner.

The decision variable in the algorithm \(X_i\) is a "0,1" variable. There is one such variable for each job in the pool. A value of "1" for the variable \(X_i\) implies that job \(i\) will be loaded in the shop.

The notation used is explained below:

\[
i = 1, 2, \ldots, n \quad n \text{ is the number of jobs in the pool}
\]

\[
j = 1, 2, \ldots, m \quad m \text{ is the number of machine groups}
\]

\[
X_i = 0 \quad \text{decision variable, job not loaded}
\]

\[
X_i = 1 \quad \text{decision variable, job loaded}
\]
$W_{ij}$ amount of work (standard hours) contributed by job $i$ to machine center $j$

$P_j$ present load in the shop ahead of machine $j$. If $P_j \leq C_j$, then $P_j = C_j$ should be used.

$C_j$ desired aggregate load for machine $j$

$S_{jL}$ amount of work by which the set of jobs loaded plus any existing work in the shop that needs to be done by machine $j$ falls short of the desired load for that machine center $j$

$S_{jH}$ amount of work by which the set of jobs loaded plus existing work exceed the desired load for machine center $j$

$a_{jL}, a_{jH}$ weights used to indicate the seriousness of out of balance conditions in one machine center relative to others. Also used to indicate the different effect of having a machine center underloaded as opposed to having it overloaded.

$f(di)$ a function which increases as the due date $d_i$ of job "$i$" gets closer. This function is a constant, for jobs having the same due date, in any scheduling period. The function used was:

$$f(di) = \frac{K}{[.1 + (di-d)]},$$

where $(di-d)$ is the number of periods away from the due date.
B_j limit desired, if any, on the work loaded for machine j
F_C \pm L upper and lower limits desired on total amount loaded

The mathematical formulation of the algorithm is given as:

Minimize

\[ D = \sum_{j=1}^{m} a_{jL} S_{jL} + \sum_{j=1}^{m} a_{jH} S_{jH} - \sum_{i=1}^{n} f(d_i) X_i \]

subject to:

\[ X_i = 0,1 \]
\[ S_{jL} \geq 0 \]
\[ S_{jH} \geq 0 \]
\[ \sum_{i=1}^{n} W_{ij} X_i + P_j + S_{jL} - S_{jH} = c_j \quad j = 1,2,\ldots,n \]

The first term in the objective function is a measure of the sum of the underload conditions in hours for each machine type. The second term represents the hours of work in excess of the amount desired for those work centers that are overloaded. The work loads being mentioned here are aggregate workloads in the shop and not loads at the individual machine center queues. The third term is the due date adjustment term as given above.

The first term in the constraint function is the work loaded in the shop for one machine by the jobs selected for release by the algorithm. The second term, \( P_j \), is the existing aggregate shop load for machine j
prior to the release of the new jobs. The total load for machine \( j \) given by these two terms falls short or exceeds the desired amount \( C_j \) by the value of the slack variable \( S_{jL} \) or \( S_{jH} \), respectively.

Additional constraints can be imposed to allow only a range on the total work hours loaded in the shop in one scheduling period. That is, they will require that the total work hours moved to the shop every scheduling period will be over \((F_c - L)\) and below \((F_c + U)\). These constraints are:

\[
\sum_{i=1}^{n} \left( \sum_{j=1}^{m} W_{ij} \right) X_i \geq F_c - L
\]

\[
\sum_{i=1}^{n} \left( \sum_{j=1}^{m} W_{ij} \right) X_i \leq F_c + U
\]

Finally, the amount of work loaded in one period for one work center or group of work centers can be restricted. This type of constraint is useful, for example, in a shop where there is a preliminary operation, such as cutting in an apparel shop, through which jobs have to pass before arriving at the true job shop. The equation that follows indicates that the aggregate work loaded in one period for machine center \( j \) is not to exceed \( B_j \).

\[
\sum_{i=1}^{n} W_{ij} X_i \leq B_j \quad \text{for any } j \text{ or group of } j's
\]

This algorithm offers a degree of control on the operation of the shop by the use of different values for the constants \( K \) and \( C_j \). The specific
effect of changes in the $C_j$ will be discussed in Chapter VII.

4.3 The Linear Approximation to the Mixed Integer Programming Loading Algorithm

The above mathematical formulation makes use of a mixed integer program. The simulation program for the job shop uses a linear approximation with bounded variables. The decision to do this was based on the following considerations.

a) Based on tests made with the mathematical programming package OPHELIE from Control Data Corporation, the time required to obtain an integer solution was from 5 to 50 times the linear solution time requirements. This excessive time requirement, even with a fast commercial code, eliminated the possibility of using the mixed integer model in the simulation where the loading algorithm had to be used in 500 periods for each run type and replication.

b) Bounded variable theory shows that the number of non-integer variables in the basis of the LP when a solution is obtained is limited. In a bounded variable problem with $m$ equality constraints and $n$ structural bounded variables the number of structural variables that is between zero and the upper bound is equal to the number of constraints. This is demonstrated by Chung (1963) using the following argument:

If there are $r$ structural variables reaching their respective upper bounds and $s$ variables equal to zero, then the number of structural variables which are positive but below their upper bounds must be $n-(r+s)$. In order to satisfy the upper-bound constraints, this means that there must be $[s+n-(r+s)]$ slack variables in the basis. By assumption we know that there are $[r+n-(r+s)]$ structural variables in the basis; therefore the total is $[r+n-(r+s)] + [s+n-(r+s)] = 2n - (r+s)$. But in a bounded variable problem of this type, the number of basis vectors is $m+n$. Therefore, we have $2n-(r+s) = m+n$, which yields
indicating that the number of structural variables whose values are between 0 and the upper bound is m.

The above argument needs only slight modification to fit the basic equations in the algorithm described in section 4.2. In this case the number of equations is also m, but the number of structural variables with an upper bound is k and there are 2m structural variables without an upper bound. The total number of structural variables is again n where n = k+2m. It is easy to see from the structure of the problem that at least half of the non bounded structural variables (designated as $S_{jL}$ and $S_{jH}$ in the algorithm formulation) will be equal to 0 because for any machine center there will be an overload or underload condition but not both.

Using the same argument employed by Chung, the number of structural bounded variables, $X_1$, and their slacks in the basis is $2k-(r+s)$. The total number of variables in the basis is $m+k$. Now let $t$ be the number of non bounded structural variables in the basis. Then

$$2k-(r+s)+t = m+k$$

$$k-(r+s) = m-t$$

but

$$0 \leq t \leq m$$

therefore

$$0 \leq k-(r+s) \leq m$$

This indicates that the number of structural bounded variables (decision variables for jobs to be loaded in the shop) whose values are larger than
zero but less than one is less than the number of equations, that is, less than the number of machines in the shop.

In actual practical problems the number of fractional variables is considerably smaller than the theoretical limit. For example, in an actual problem with 10 machines and 29 jobs in the job pool, the number of jobs with a fractional $X_i$ value was four while, of course, the theoretical limit was 10. Four problems with 10 machines and between 20 and 30 jobs in the job pool were observed and the number of non-integer job decision variables in the output was between three and five in each case.

c) The results obtained with the job pool and the linear version of the loading algorithm were significantly better than those obtained in an "uncontrolled" shop. The use of the mixed integer version could only improve the results further. This potential improvement, however, is fairly limited because less than a .1% difference has been observed between the values of the objective functions when fractional decision variables are allowed and when the non-integer decision variables are rounded to 0 or 1.

d) There is no guarantee that the optimum will consist of a conversion of the non-integer variables in the solution to 0-1 variables, in fact, most of the time this will not be so. However, the tests performed with the OPHELIE LP system indicated that although a few of the variables changed, the objective value of the rounded solution was only slightly worse than the one given by the mixed integer solution.

e) When the model is used to load an actual shop, the algorithm will be used only once or twice per day while on this research due to the time simulated, the number of replications and the different conditions
tested, it was employed over 20,000 times. It can be seen that the additional computer time required to use the mixed integer version in an actual situation will be fairly insignificant and therefore in that case a detailed study should be made regarding the trade off involved in using the linear approximation.

4.4 Loading Heuristics

The concepts of using a job pool and loading the shop at discrete intervals with jobs in the pool have also been employed with a heuristic loading method as well as the mathematical programming loading algorithm. This does not imply that the loading algorithm is optimal in a general sense, although, of course, it is optimal with respect to its objective function.

The heuristic consisted of loading a job in the shop if the first job operation made a contribution to the queue of a machine that was underloaded. For a given machine, the jobs were selected one at a time with those having the earliest due date selected first until the desired load level for that machine queue was reached or until the job list was exhausted. This was done for every machine.

In addition, an optional feature provided for the loading of additional jobs in the shop if the management desired load for the shop in total had not been reached with jobs loaded in the first part of the algorithm. Again jobs with the earlier due dates were selected first.

In effect, there are two main "factors" in the loading and balancing methodology that may influence the performance criteria. One of these factors is the concept of the job pool itself while the other factor is
the releasing (or loading) methodology employed. The results obtained with the heuristic releasing method have been employed to try to isolate the effects of the two "factors."
CHAPTER V

DESCRIPTION OF THE TESTING VEHICLE

5.1 The Job Shop

The general type of shop with which this research is concerned was presented in Chapter II and its specific characteristics are next described.

No special effort was made to model a specific shop, however, most of the parameters employed are within common ranges for job shops in the apparel "style" and other industries. An exception to this was the selection of ten machines, but this choice was previously explained as a compromise due to computer time requirements. The practice of employing reasonable parameter values, but not values from a specific shop, has been commonly employed in job shop research.

The interarrival times are samples of an exponential distribution with a mean of 1.88 hours and truncated at 40 hours (the true mean is therefore slightly less than 1.88 hours). This arrival rate, together with the other shop parameters used, resulted in a shop utilization between 81% and 83.5%. The shop utilization was determined from statistics accumulated in the simulation runs.

The jobs arriving to the shop were assigned an equal probability of having their first operation performed by any of the machines in the shop. The machine for subsequent operations was then obtained by employing a transition probability matrix. The transition probability matrix used in most of this research was such that a job was assigned an equal
probability of moving to any machine in the shop for their next operation regardless of the machine in which the current operation was performed. The experimental model was thus characteristic of a pure job shop. Some experimental investigations were also performed utilizing a shop with "flow structure".

The processing time per operation was generated using an exponential distribution with a mean of 2.48 hours, but with no operations lasting less than one hour or over nine hours.

The number of operations of an incoming job was generated when the job arrived at the shop using a symmetric unimodal distribution which is shown in Table 2.

A job due date was assigned to each job as it entered the shop using one of two methods. The first method which was used almost exclusively consisted of assigning a due date equal to the current time plus the work content of the job plus a sample from the uniform distribution between 0 and 150. The second method was slightly more complex and it consisted of assigning to 10% of the jobs a due date such that the job had three times its work content in hours to go through the shop. The remaining 90% of the jobs had their work content in hours plus the product of 300 hours times a random number between .1 and 1 to complete all operations. This method is illustrated in Figure 2. Its purpose is to eliminate the existence of jobs with very tight due dates. Only one of the two methods described was used in any given run.

5.2 Dispatching Rules

Four dispatching rules were studied in detail. These rules were
<table>
<thead>
<tr>
<th>Number of Operations</th>
<th>Probability of Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>General Shop</strong></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>0.20</td>
</tr>
<tr>
<td>6</td>
<td>0.30</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
</tr>
<tr>
<td>8</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Shop with Few Interactions</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>0.60</td>
</tr>
<tr>
<td>3</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Figure 2. Method No. 2 of Assigning a Due Date to a Job
used with both an uncontrolled shop model and the controlled loading model with the job pool. The dispatching rules were:

a) **DSOP**, Dynamic Slack per Operation.

The job priority equals the ratio of the slack remaining to the number of operations remaining. The jobs are selected in all cases such that those with the smallest algebraic priority measure value are selected first from the queue.

DSOP was selected because prior studies (Le Grande (1963), Gere (1966), and Conway and others (1967)) have shown that this rule performs well with respect to minimizing the variance of the lateness distribution.

b) **EWIQ**, Expected Work in Next Queue.

The job priority equals the sum of the imminent operation processing times of other jobs in the queue to which the candidate will enter after its current operation. The queue load being added is considered to include jobs now on other machines which will arrive before the job being considered, if it is selected for immediate operation.

This rule was selected because of its "look ahead feature" that is, it is not a local dispatching rule.

c) **SPT**, Shortest Processing Time.

The job priority equals the processing time of the imminent operation. This rule had to be selected. Practically all of the simulation studies that have been mentioned show that it is a very good rule with respect to many measures of performance and at least acceptable with respect to the remaining measures. See, for example, Conway and others (1967).
d) **FIFO**, First In, First Out.

The job priority equals the time the job enters the particular queue. This rule was selected due to its implicit fairness and also due to the fact that it is used quite often in practice.

**5.3 The Simulation Model**

In order to test the effects of the loading and balancing methodology a computer simulation approach was employed. As previously discussed a simulation approach had to be selected for this purpose due to the lack of theoretical queuing results in job shop scheduling research.

The job shop simulator program in this research was written using the GASP II language described by Pritsker and Kiviat (1969). GASP II is a collection of Fortran IV subroutines organized to assist in performing simulation studies. GASP II provides subprograms for handling those simulation tasks that are independent of particular problems. The tasks handled by GASP II are the maintenance of the simulation clock, the handling of independent files and the ranking of elements in those files, the placing and removal of elements from the files, the random variable generation and the maintenance of simulation statistics as well as the production of appropriate summaries.

The user subroutines complement the GASP II program and must be tailored to the specific application. A description of these subroutines as well as flow charts are given in Appendix A.

Figure 3 depicts the operation of the job shop simulator. The Main program reads the user subroutine parameters and starts the simulation by transferring control to the GASP programs. The simulation proceeds
BEGIN

READ PARAMETERS, START SIMULATION (MAIN)

READ ADDITIONAL DATA (GASP, DATAN)

TRANSFER CONTROL TO EVENT SCHEDULED TO OCCUR (EVNTS)

PRELOAD THE JOB SHOP (START)

IF PRELOADING

GENERATE TIME FOR NEXT JOB ARRIVAL AND OBTAIN JOB ATTRIBUTES (ARIVL)

COLLECT END OF PERIOD STATISTICS (COLL)

YES

FINISH PRELOAD

NO

Figure 3. Job Shop Simulator
Figure 3. Concluded
by causing discrete events to occur and calling the right event at the right time is the function of EVNTS. The four events in this simulation are: preloading the shop at time zero (START), obtaining job attributes for new arrivals (ARIVL), moving jobs when a machine operation is finished (ENDSV) and collecting end of period statistics (COLL). The subroutines related to the job loading algorithm are GENMAT, LPI and JOBDEC. Finally, there is a subroutine whose function is to calculate all the statistics at the end of the simulation and print results.

The Fortran IV listing of the user programs are provided in Appendix B. Appendix D contains the description of all attributes, events and optional variables in the GASP programs. The non-GASP variables are described in Appendix E. A variation of the subroutines ENDSV, PTJOB and GENMAT needed for the alternative machine operation feature is given in Appendix K. A sample input set for the simulation program is shown in Appendix F.

The input data provides for reading some decision parameters that are used to change significantly the character of a simulation run. The most important ones are the following:

NRULE Indicates the dispatching rule to be employed in the simulation run.

NLDR Specifies whether a job pool is to be used or not. If a job pool is to be used, it determines which loading method should be employed.

IDUE Specifies which one of two methods of generating due dates is to be used.

NARR Indicates whether the arrival process is strictly Poisson, or whether the interarrival times calculated according to the
exponential distribution are superimposed on a sine curve. This causes the mean interarrival time to fluctuate with respect to time.

MSW Specifies which special loading modification, if any, will be used.

DESLF Specifies the desired shop load level or management load factor when the controlled shop loading approach is utilized.

Using different values for these parameters and others, several special shop conditions were investigated.
CHAPTER VI

DESIGN OF THE EXPERIMENT AND VALIDATION

The approaches toward validation and experimental design of the simulation experiments that have been followed and which are mentioned below are based on the books by Naylor, Balintfy, Burdick and Chu (1966), Schmidt and Taylor (1970), and Tocher (1963); the dissertation by Deane (1972) and the papers by Naylor, Burdick and Sasser (1969), Van Horn (1971) and Conway (1963).

The elements in planning a simulation experiment according to Naylor, Balintfy, Burdick and Chu are the following:

1. Formulations of the problem
2. Collection and processing of real world data
3. Formulations of the mathematical model
4. Estimation of parameters of operating characteristics from real world data
5. Evaluation of the model and parameter estimates
6. Formulations of a computer program
7. Validation
8. Design of the Simulation Experiment
9. Analysis of Simulation Data

Items 1-6 have already been discussed and item 9 will be covered in a subsequent chapter. The purpose of this chapter is to discuss items 7 and 8. Items 7 as listed here includes the steps of verification and
validation given by Fishman and Kiviat (1967). Verification insures that a simulation model behaves as an experimenter intends. Validation tests the agreement between the behavior of the simulation model and a real system.

6.1 The Experiment

The design of simulation experiments must include a random number generator which is truly random, and considerations of start up conditions, run lengths, replications and finally, have the results pass adequate tests of statistical significance. These items will be examined next.

6.1.1 Random Number Generator

The pseudo random number generator used employs a 17 bit multiplicative congruential method. The general formula used is:

\[ N_{i+1} = AN_i \pmod{m} \]

where \( A = 5^7 \) and \( m = 2^{17} \).

The maximum attainable period with this generator is 32,768 and the quantity of random numbers used by a run in this research is close to 30,000.

The random number was tested with a group of seeds some of which were used for the experimental runs. The tests used and the purpose were the following:

a. Goodness of fit, Chi Square test.

The numbers generated were grouped in intervals of .1 from 0 to 1 and a \( \chi^2 \) test was used to check fitness to a uniform distribution.
b. Goodness of fit, Kolmogorov - Smirnov test.

Same purpose as the first test.

c. Serial test, Chi Square.

The purpose of this test was to detect any first order serial correlation. The numbers were truncated so that only the first digit was used and every number was placed in one cell of a ten by ten array as given by the first digit with the columns indicating the previous number obtained and the rows giving the current number. A Chi Square test was then used to test the uniform distribution of the random numbers over the 100 cells.

d. Total Runs, Normal Statistic.

The expected total number of runs was calculated. For samples greater than 20, the distribution of the total number of runs can be approximated by the normal distribution. This fact was used in constructing a two-tailed normal test for checking the number of runs generated.

e. Number of Runs for each Run Length, Chi Square.

A Chi Square test was used to compare the observed vs expected number of runs of run length 1, 2, 3, 4 and greater than 4.

The results of the tests and critical values at the $\alpha = .05$ level for the generator with twelve seeds that passed the test and for a sequence of 10,000 numbers are given on Table 3.

6.1.2 Starting Conditions

Starting conditions are one part of the more general question of equilibrium. According to Tocher (1963), the accepted technique has been to invent starting conditions and to allow the simulation to proceed for
Table 3. Results of Tests on Random Number Generator

<table>
<thead>
<tr>
<th>Seeds</th>
<th>Goodness of Fit $\chi^2$</th>
<th>Goodness of Fit KOLM-Smirnov</th>
<th>Serial Correlation $\chi^2$</th>
<th>Total Number of Runs -- Normal</th>
<th>Number of Runs of Each Length $\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 100933</td>
<td>7.59</td>
<td>.0040</td>
<td>64.7</td>
<td>.34</td>
<td>5.36</td>
</tr>
<tr>
<td>2. 411719</td>
<td>8.12</td>
<td>.0050</td>
<td>64.7</td>
<td>.02</td>
<td>1.32</td>
</tr>
<tr>
<td>3. 297449</td>
<td>9.11</td>
<td>.0080</td>
<td>83.9</td>
<td>.02</td>
<td>3.86</td>
</tr>
<tr>
<td>4. 349387</td>
<td>6.85</td>
<td>.0050</td>
<td>61.9</td>
<td>.07</td>
<td>3.07</td>
</tr>
<tr>
<td>5. 281923</td>
<td>7.22</td>
<td>.0040</td>
<td>64.9</td>
<td>.43</td>
<td>1.18</td>
</tr>
<tr>
<td>6. 154231</td>
<td>4.41</td>
<td>.0060</td>
<td>64.3</td>
<td>1.11</td>
<td>5.30</td>
</tr>
<tr>
<td>7. 329963</td>
<td>7.33</td>
<td>.0060</td>
<td>80.2</td>
<td>.85</td>
<td>1.61</td>
</tr>
<tr>
<td>8. 900131</td>
<td>7.61</td>
<td>.0080</td>
<td>81.8</td>
<td>.24</td>
<td>4.43</td>
</tr>
<tr>
<td>9. 392819</td>
<td>2.55</td>
<td>.0060</td>
<td>61.1</td>
<td>.19</td>
<td>.48</td>
</tr>
<tr>
<td>10. 214753</td>
<td>2.47</td>
<td>.0050</td>
<td>61.2</td>
<td>.17</td>
<td>.35</td>
</tr>
<tr>
<td>11. 200933</td>
<td>6.15</td>
<td>.0050</td>
<td>54.4</td>
<td>.01</td>
<td>2.52</td>
</tr>
<tr>
<td>12. 117341</td>
<td>5.87</td>
<td>.0050</td>
<td>55.8</td>
<td>.00</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Critical Values 16.92 .0136 123.2 1.96 9.49
some time and take the final conditions as the initial conditions of the genuine run. According to Conway (1963), the length of time required to render the state probability distribution independent of the starting conditions must certainly depend upon the starting conditions used. The approach selected in this research was to preload the shop with a number of jobs that would give approximately the same number of hours of work in process in the shop as the hours of work in process that were observed at the end of several trial runs.

Actually, the specific condition selected is not too important since all that must be done is to select a reasonable starting condition. "Reasonableness" according to Conway (1963) should simply be associated with conditions that possess non-zero probability in the equilibrium state probability distribution.

6.1.3 Run in Period

The run in period in a simulation study is the time during which the simulation is allowed to proceed so that operating conditions hopefully reach a "steady" or "representative" state, but not allowing shop statistics accumulated during this time to influence final results. There is not any general method that can be used to determine the length of run-in period. Tocher (1963) flatly states this and Conway (1963) says "there is no single point in the execution of a simulation experiment beyond which the system is in equilibrium."

Regardless of how "good" the initial conditions selected are, there is general acceptance of the idea that a run-in period is needed. Deane (1972) presents a very convincing argument for this. In effect, he argues
that if no run-in period is considered, the first jobs leaving the system will have biased statistics for time spent in the system and due date measures. Also, the initial statistics for work in process performed in the shop will also be biased.

The run-in period selected for this research was 400 hours during which about 175 jobs left the shop and around 1200 operations were performed.

The selection of 400 hours as the run-in period was made after detailed printouts were obtained showing conditions at the end of every 8-hour period. After examining these results, it was clear that there were no easily spottable abnormal conditions in the statistics collected after 30 or 40 periods. However, 50 periods were used in order to stay in the safe side. For example, Figure 4 shows the work in process in operations done for jobs in the shop plotted against time periods for periods 1 through 50 in one of the trial runs made. It can be seen that after the first 25 or 30 periods the initial almost uninterrupted increase in the value of the variable has ceased and a more normal fluctuation is observed. The run-in period selected certainly satisfies the rule of thumb given by Tocher (1963) that the longest cycle in the simulation should have been executed three or four times before abnormal behavior caused by starting conditions can be expected to have died away. Although there are many cycles in a job shop, it was felt that the longest cycle of interest in this research is the time a job spends in the system. This time was from 70-100 hours in the experimental runs, depending on the conditions used.
Figure 4. Work in Process in Operations Done for Jobs in the Shop During the Run In Period
Another rule of thumb that was considered is the following one proposed by Conway (1963): "From pilot runs, truncate a series of measurements until the first of the remaining series is neither the maximum nor the minimum of the remaining set." Conway cautions against examining cumulative statistics for this purpose because they may cause the discarding of too much data. However, if they are used, the error would be on the conservative side. If an average based on a cumulative statistic were used, the last measurement of the truncated series instead of the first of the remaining one must be used. The run-in period used in this research also meets this rule of thumb for the statistics that were printed in detail, whether they are presented on a cumulative basis or not.

6.1.4 Run Length

The variability associated with the measurements of even very simple simulation models is discouragingly large according to Tocher (1963). However, what is desired in most simulation experiments, including this one, is the comparison of alternatives so that relative results are more important than absolute ones.

Another property of simulation experiments that helps keep run lengths and replications to manageable levels is the use of identical event sequences. This procedure insures that any relative differences observed can be attributable to the alternatives and not to random variation.

A trade off in run length still exists since it would be desirable to have very large samples to reduce variability as much as possible, while at the same time run lengths must be kept at reasonable levels to economize computer time.
The time selected for each replication in this simulation experiment was 4000 hours (500, 8-hour periods). In this time about 2,120 jobs left the shop and about 12,720 operations were performed.

Initially, several replications were obtained by using 100 periods after run-in but the variance on the measures of performance was too high. Other run lengths (Tables 4 and 5) were tried until it was decided that 500 periods (4,000 hours) reduced the variance considerably and that additional use of computer time would not be justified. The statistical verification of this run length was made by taking six 4000 hours runs with different seeds and comparing these results with those of a second set with different seeds (Table 5). A standard t-test was then performed to test for equality of means as suggested by Deane (1972). The results on the Shop Balance Measure (SWB) and Average WIP (hours of work in the shop) for each set of runs are shown in Table 5.

The $t_{.975}(10)$ value obtained from the tables is 2.228 while the calculated values were $t_{SWB} = .38$ and $t_{WIP} = 1.39$. Therefore, there are no grounds to reject the hypothesis of equality of means in either case. It is granted that this is not a rigorous justification for the run length selected, but it provides additional assurance.

6.1.5 Replications

One of the first questions faced when deciding the number of runs to be made is whether successive runs shall consist of wholly independent runs started with new random number seeds or whether they should be started using the final calculation of one run as the beginning of the next one.

The advantage of using the first approach is that there is less
Table 4. Runs in an "Uncontrolled" Shop. DSOP Dispatching Rule.
Results with Run Lengths of 800 and 3200 Hours

<table>
<thead>
<tr>
<th></th>
<th>100 Periods (800 Hours)</th>
<th>400 Periods (3200 Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWB WIP (Hours)</td>
<td>SWB WIP (Hours)</td>
<td>SWB WIP (Hours)</td>
</tr>
<tr>
<td></td>
<td>854</td>
<td>670</td>
</tr>
<tr>
<td></td>
<td>616</td>
<td>665</td>
</tr>
<tr>
<td></td>
<td>505</td>
<td>642</td>
</tr>
<tr>
<td></td>
<td>559</td>
<td>613</td>
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<td></td>
<td>565</td>
<td>616</td>
</tr>
<tr>
<td></td>
<td>724</td>
<td>617</td>
</tr>
<tr>
<td>Avg.</td>
<td>.938</td>
<td>.836</td>
</tr>
<tr>
<td>Var.</td>
<td>.1456</td>
<td>.0388</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>.382</td>
<td>.197</td>
</tr>
</tbody>
</table>


Table 5. Two Sets of Runs in an "Uncontrolled" Shop. DSOP Dispatching Rule. Results Used to Test the Adequacy of 4000 Hours Run Length

<table>
<thead>
<tr>
<th>Set 1</th>
<th>Set 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWB</td>
<td>WIP (Hours)</td>
</tr>
<tr>
<td>.753</td>
<td>670</td>
</tr>
<tr>
<td>.715</td>
<td>626</td>
</tr>
<tr>
<td>1.036</td>
<td>625</td>
</tr>
<tr>
<td>.954</td>
<td>619</td>
</tr>
<tr>
<td>.892</td>
<td>623</td>
</tr>
<tr>
<td>.646</td>
<td>635</td>
</tr>
</tbody>
</table>

Avg.    0.833    633    0.868    620
Var.    .0229    352    .0287    170
Std. Dev. .151    18.8    .170    13.1

\[ S^2_{SWB} = 0.0258 \]

\[ S^2_{WIP} = 261 \]

\[ t_{SWB} = 0.38 \]

\[ t_{WIP} = 1.39 \]
risk of running into autocorrelation problems. The second approach insures that satisfactory initial conditions are used in all replications after the first one and also eliminates the need for a run-in period in the second and successive replications.

The first approach has been used in this thesis.

The actual number of replications used is a function of the precision desired in the results and the computer time available. In a case like this one in which it is desired to obtain and compare the values of a group of statistics under different conditions, it is impractical to start from the precision required and arrive at the number of runs needed. Instead, the approach followed was to select the quantity of five replications as an acceptable number from both points of view.

6.1.6 Statistical Design of the Simulation Experiment

The selection of factor levels and combinations of levels and the order of experimentation is often a critical decision in simulation experiments. The number of runs, even with incomplete experimental designs, that might be needed to cover an acceptable range of the factors often gets out of hand. A factorial treatment arrangement was not employed because this arrangement was not necessary to answer the most important question being investigated.

The primary purpose of this study is to explore the effects of loading jobs into a shop from a pool, and to compare the values of some measures of performance using this approach against letting the jobs arrive to the shop directly. It was desired to do this for four different dispatching rules. A paired observation t-test was used to test for
significance in the differences observed between the two loading methods. A total of 40 runs were required for the main portion of the experiment. There were two loading rules to test (an "uncontrolled" shop and shop with a job pool and the loading algorithm) and four dispatching rules to be used with each loading method. Each one of these eight conditions was replicated five times.

An ANOVA has been performed on the four runs with five replications each that do not use the job pool, that is, the conventional uncontrolled loading approach to test for any differences in the means of the measures of performance. Another ANOVA has been used in a similar way for the 20 runs (4 × 5) using the job pool. Statistical tests were also performed to determine the effect of the job pool and loading algorithm on the different dispatching rules.

Several additional items have been explored utilizing the runs mentioned before, but also requiring some additional runs. These runs were made under only one dispatching decision rule, DSOP.

Dynamic Slack per Operation (DSOP) was selected because this is a decision rule which has been shown to give good results with respect to due date measures without showing an extraordinary adverse effect on other measures. A t-test has been used to test for the significance of any differences observed, unless otherwise noted.

The additional shop conditions that have been tested are a. Effect of a variable job arrival rate. The effect of a variable job arrival rate, that is, an arrival distribution with a dynamic mean which has been used throughout in this research is illustrated
by comparing results previously obtained against the results of five additional replications using a fixed arrival rate. The fluctuating arrival rate was obtained by having the interarrival time generation process superimposed on a sine curve such that the mean interarrival time changed from 50% to 150% of its normal value with a period of 16 hours.

b. Effect of the job pool and the loading algorithm when used in a shop with less interactions. This is illustrated with a shop of five machines and an average of two operations/job. Ten additional runs were required here consisting of five replications for each loading condition.

c. Effect of using a heuristic to load the shop from the pool. The purpose of this test is to show the advantages of the loading algorithm over a reasonable heuristic which also utilizes the job pool concept.

d. Effects of variations in the loading algorithm. Several variations of the loading algorithm were explored for various management load factors. The variations consisted of changes in the job releasing mechanism. The results obtained, however, did not justify making the additional computer runs necessary for statistical analysis.

e. Effects of a non-symmetric transition matrix when the machine utilizations remain the same. This experiment requires additional replications (only with DSOP) under loading and no loading conditions. It is desired to investigate the effect of a non-symmetric transition matrix under the uncontrolled loading approach. Also it is desired to check if the improvements produced by the controlled loading methodology
are more significant when the imbalance condition exists. A t-test has been used.

The non-symmetric transition matrix is characteristic of a shop in which special work flow patterns can be identified, that is, when a pure job shop does not exist. The average utilization for each machine and the probability of initial job arrival at each machine was maintained equal between all machines, but the work flow structure used was such that some paths were much more likely than others.

Complete results of all simulation runs are presented in Appendix I. Results are analyzed and summarized in Chapter VII.

6.2 Program Validation

The conditions normally recommended (Naylor, Chu & others; 1966) to insure a satisfactory program validation are:

a. To verify how well the simulated values of the endogenous variables compare with known historical data.

b. To verify how accurate are the simulation models' predictions of the behavior of the real system in future time periods.

It is not possible to satisfy the above conditions in this research because there is no shop data available of the type required to make the comparisons.

Fortunately, however, there have been previous job shop simulation models reported in the literature, some of which have been verified. The verification and validation in this case will consist of comparing results in this research to results reported by Conway (1963) and Deane (1972).
The measures of performance of primary interest in this research are the Shop Balance Measure (SWB) and other measures of balance, the level of work in process calculated in two different ways and a measure of the ability of jobs to meet due dates.

Many of these measures are not available in published research that has been validated and, therefore, it is not possible to use the most interesting measures (balance measures) to validate the program in this thesis. Three measures of performance that were selected for validation are the average flow time, the level of in process inventory and the standard deviation of the lateness distribution. These measures were selected because of their relative interest to this thesis and their availability in published research. The comparisons are shown in Tables 6-8.

The results shown for this thesis are based on average values for the applicable runs (five replications) reported elsewhere on this thesis. The results reported by Deane are based on three runs of about 2100 jobs each and the results of Conway are based on one run of 8700 jobs.

The absolute value of the results reported is not very important due to the difference in parameter values used. The important consideration is the relative performance of the three dispatching rules used. Of course, differences are to be expected even in the relative values shown in the Tables. These differences are caused by "structural" variations in the shops used. For example, the shop used by Conway had nine machines while Deane's and this one had ten machines. Also, the due date generation process used in this thesis is different than the one employed by Deane and the one used by Conway is unknown.
Table 6. Comparison with Conway's Results on Mean Flow Time

<table>
<thead>
<tr>
<th>Rule</th>
<th>Conway's Results (p 232)</th>
<th>Thesis Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual</td>
<td>Percent</td>
</tr>
<tr>
<td>DSOP</td>
<td>74.0</td>
<td>218.</td>
</tr>
<tr>
<td>SPT</td>
<td>34.0</td>
<td>100.</td>
</tr>
</tbody>
</table>
Table 7. Comparison with Conway's and Deane's Results on Standard Deviation of the Lateness Distribution

<table>
<thead>
<tr>
<th>Rule</th>
<th>Conway's Results (p 232)</th>
<th>Deane's Results (p 41)</th>
<th>Thesis Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual</td>
<td>Percent</td>
<td>Actual</td>
</tr>
<tr>
<td>DSOP</td>
<td>4.15</td>
<td>100.</td>
<td>26.9</td>
</tr>
<tr>
<td>SPT</td>
<td>66.5</td>
<td>160.</td>
<td>53.3</td>
</tr>
</tbody>
</table>
Table 8. Comparison with Conway's and Deane's Results on Work-in-Process Levels (Hours)

<table>
<thead>
<tr>
<th>Rule</th>
<th>Conway's Results (p 224)</th>
<th>Deane's Results (p 42)</th>
<th>Thesis Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual</td>
<td>Percent</td>
<td>Actual</td>
</tr>
<tr>
<td>SPT</td>
<td>545</td>
<td>100.</td>
<td>661</td>
</tr>
<tr>
<td>EWIQ</td>
<td>709</td>
<td>130.</td>
<td>720</td>
</tr>
<tr>
<td>FCFS</td>
<td>1078</td>
<td>198.</td>
<td>815</td>
</tr>
</tbody>
</table>
The results shown in Tables 6-8 indicate noticeable differences in the absolute value of the measures of performance for the various shops. The relative differences are smaller, but still significant. The directions of movement for all the measures shown, however, from one dispatching rule to another is the same for Conway's, Deane's and this thesis. It is felt that these results indicate the reasonableness of the shop model used and, therefore, the program can be considered validated.
CHAPTER VII

ANALYSIS OF RESULTS OF THE SIMULATION RUNS

The results of the computer simulation runs are discussed in this chapter. The results of all runs are given in Detail in Appendices I and H. In this chapter, the more significant results have been summarized and presented in tabular form. The chapter is divided in three sections. The first section concentrates on the effects of the management or desired load factor (DESLF) of the job loading algorithm for the control of various measures of performance.

The second section analyzes the effects of the job pool and the loading algorithm when various dispatching rules are used. The improvements obtained in this area were the main objective of the research. The third section analyzes the results obtained under various special shop conditions. The results on these last two sections are based on t tests (Table 53), ANOVA (Table 54) and Duncan Ranking Tests (Table 55).

7.1 Effect of Changes in the Management Load Factor (DESLF)

The effect of changing "DESLF" is equivalent to changing the value of the $C_j$'s in the mathematical formulation of Chapter IV. The results are shown in Table 43 for the DSOP dispatching rule and Table 44 for the SPT dispatching rule. Table 44 illustrates the effects obtained. A reduction in the DESLF parameter causes a reduction in the desired load used in the algorithm since the relation between the two is the following:

\[
\text{Desired Load} = (\text{DESLF}) \times (\text{Scheduling Period})
\]
In this research the scheduling period is eight hours, therefore, for a DESLF of 4.25, the management desired load used is 34 hours. The management desired load is the aggregate shop load that the algorithm attempts to maintain in the shop every scheduling period. As the DESLF decreases, the algorithm attempts to maintain a lower amount of work in the shop, but at the same time attempts to minimize the absolute deviation from desired balance while loading jobs with close due dates. Starting from a relatively high management load factor (DESLF), the following basic effects are observed as the DESLF value is reduced (up to a point):

- Average time spent in the system by a job increases.
- Average time spent in the shop by a job decreases.
- All balance measures improve.
- Average number of jobs in the pool before and after loading increases.
- Average hours of work in process in the shop decrease.
- Average hours of work done for jobs in the shop decrease.
- Variance of the Lateness Distribution decrease.
- There is a very small reducing trend in job tardiness.

The net effect of reducing the management load factor (DESLF) is to keep off the factory floor extra jobs that couldn't be worked on anyway. This condition is illustrated by the progressively shorter shop flow time shown by the jobs as the management load factor (DESLF) decreases. It is fairly obvious that the total hours of work in process in the shop should be reduced as the DESLF is reduced and more jobs are kept in the job pool. It is more interesting, however, to note that the hours of work done for
jobs in the shop also goes down. When the shop is overloaded with jobs, there are many jobs for which one or two operations have been performed, but the jobs still stay in the shop waiting to have the final operations done.

The number of jobs in the pool increases because the algorithm has a smaller requirement from the shop and, therefore, tends to be more selective in loading jobs from the pool. The balance measures improve for the same reason, that is, there are more jobs in the job pool to choose from.

The variance of the lateness distribution is decreased, when the dispatching rule is Shortest Processing Time (SPT), as the Management Load Factor (DESLF) is reduced because this dispatching rule does not explicitly consider due date. Under this condition, the improved shop balance obtained with the smaller DESLF parameter and the due date term in the objective function of the loading algorithm produce a smoother job flow through the shop. This more than offsets the fact that jobs are placed in the shop at a later time. A due date oriented dispatching rule such as Dynamic Slack per Operation (DSOP) does not cause the conditions described in the paragraph above to occur.

The results obtained when the management load factor (DESLF) is reduced do not of course, continue indefinitely. There is a range of values for DESLF where many of the measures of performance start to move in an opposite direction or where the values stay basically constant.

7.2 The Job Pool and the Loading Algorithm with Various Dispatching Rules

The program employing the shop control methodology, that is, with
the job pool and the loading algorithm was replicated five times with different random number seeds. It was desirable to test the effects of the loading algorithm when compared to an "uncontrolled" loading scheme whereby all jobs are released to the shop floor as they are consigned. Thus, five runs were made with the same random seeds for the uncontrolled shop model. The results for the DSOP dispatching rule are shown in Table 9. These results show the average value obtained in the five replications. Similar results for other dispatching rules are shown in Tables 10 to 12.

The detailed discussion and interpretation of results that follow will generally show that very significant improvements were obtained in most balance indices, except the Machine Work Balance Index (MWB) where the results obtained varied depending on the dispatching rule. The Work in Process measures showed consistent improvements and the results with respect to due date measures were mixed.

It can be seen in Table 9 that, when the dispatching rule is DSOP, there is virtually no difference in MWB but there is a 36% improvement in the SWB index. Other balance measure indices showing very significant improvements are QWB with a 39% reduction (improvement) and PQB with a 65% improvement.

The work in process measures were also significantly improved with the job pool and the loading algorithm. The total hours of work in the shop were reduced by 16.5% and the hours of work done for jobs in the shop were reduced by 31.6%. The variance of the lateness distributions on the other hand, was increased by 62% and the average tardiness changed from 2.01 hours to 24.7 hours. A reduction in these last two measures,
Table 9. Comparison of Results Obtained by Using a Job Pool and the Loading Algorithm Against an "Uncontrolled" Shop. Ten Machines. Dispatching Rule is DSOP.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Uncontrolled Shop (From Table 35)</th>
<th>Job Pool, Loading Algorithm (From Table 47)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviations from Balance</td>
<td>157.</td>
<td>120.</td>
</tr>
<tr>
<td>Balance Index, MWB</td>
<td>4.97</td>
<td>5.11</td>
</tr>
<tr>
<td>Balance Index, SWB</td>
<td>.893</td>
<td>.571</td>
</tr>
<tr>
<td>Balance Index, QWB</td>
<td>14.4</td>
<td>8.84</td>
</tr>
<tr>
<td>Balance Index, PWB</td>
<td>4.12</td>
<td>4.58</td>
</tr>
<tr>
<td>Balance Index, PQB</td>
<td>73.1</td>
<td>25.6</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>634</td>
<td>529</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>231</td>
<td>158</td>
</tr>
<tr>
<td>Variance of the lateness dist.</td>
<td>784</td>
<td>1276</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>2.01 hours</td>
<td>24.7 hours</td>
</tr>
<tr>
<td>Measures of Performance</td>
<td>Uncontrolled Shop (From Table 36)</td>
<td>Job Pool, Loading Algorithm (From Table 40)</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>-----------------------------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>153</td>
<td>131.</td>
</tr>
<tr>
<td>Balance Index, MWB</td>
<td>5.19</td>
<td>5.24</td>
</tr>
<tr>
<td>Balance Index, SWB</td>
<td>1.291</td>
<td>1.220</td>
</tr>
<tr>
<td>Balance Index, QWB</td>
<td>9.03</td>
<td>6.47</td>
</tr>
<tr>
<td>Balance Index, PWB</td>
<td>3.94</td>
<td>4.06</td>
</tr>
<tr>
<td>Balance Index, PQB</td>
<td>61.9</td>
<td>47.6</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>553</td>
<td>495</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>258</td>
<td>228</td>
</tr>
<tr>
<td>Variance of the lateness dist.</td>
<td>4296</td>
<td>3629</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>13.4</td>
<td>12.1</td>
</tr>
</tbody>
</table>
Table 11. Comparison of Results Obtained by Using a Job Pool and the Loading Algorithm Against an "Uncontrolled" Shop. Ten Machines. Dispatching Rule is SPT.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Uncontrolled Shop (From Table 45)</th>
<th>Job Pool, Loading Algorithm (From Table 46)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>156.</td>
<td>84.4</td>
</tr>
<tr>
<td>Balance Index, MWB</td>
<td>5.15</td>
<td>4.69</td>
</tr>
<tr>
<td>Balance Index, SWB</td>
<td>1.16</td>
<td>.442</td>
</tr>
<tr>
<td>Balance Index, QWB</td>
<td>3.65</td>
<td>2.07</td>
</tr>
<tr>
<td>Balance Index, PWB</td>
<td>4.04</td>
<td>4.28</td>
</tr>
<tr>
<td>Balance Index, PQB</td>
<td>17.3</td>
<td>4.85</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>471</td>
<td>366</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>Variance of the lateness dist.</td>
<td>3218</td>
<td>2217</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>6.89</td>
<td>13.1</td>
</tr>
</tbody>
</table>
Table 12. Comparison of Results Obtained by Using a Job Pool and the Loading Algorithm Against an "Uncontrolled" Shop. Ten Machines. Dispatching Rule is FCFS.

<table>
<thead>
<tr>
<th>Measure of Performance</th>
<th>Uncontrolled Shop (From Table 38)</th>
<th>Job Pool, Loading Algorithm (From Table 42)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>153.</td>
<td>94.8</td>
</tr>
<tr>
<td>Balance Index, MWB</td>
<td>5.00</td>
<td>4.99</td>
</tr>
<tr>
<td>Balance Index, SWB</td>
<td>.781</td>
<td>.684</td>
</tr>
<tr>
<td>Balance Index, QWB</td>
<td>15.3</td>
<td>8.67</td>
</tr>
<tr>
<td>Balance Index, PWB</td>
<td>4.26</td>
<td>4.34</td>
</tr>
<tr>
<td>Balance Index, PQB</td>
<td>130.</td>
<td>40.</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>657</td>
<td>540</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>249</td>
<td>201</td>
</tr>
<tr>
<td>Variance of the lateness dist.</td>
<td>2967</td>
<td>2670</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>14.9</td>
<td>16.4</td>
</tr>
</tbody>
</table>
usually involving some tradeoff with the balance and WIP measures could be accomplished by changing the weighting factor in the due date term of the loading algorithm or by forcing the jobs from the pool to the shop sooner. This second approach is illustrated in Table 50. Also Tables 51 and 52 illustrate the insignificance of the tardiness measure in either case when the jobs have looser due dates.

A t test for paired observations (Ostle, 1963) has been used to test for the equality of pairs of means. Results of these tests are given in Table 53.

A computed t value of 10.9 for SWB is greater than the $t_{.99} (4)$ table value of 3.747. The job pool and loading algorithm have thus improved significantly the SWB index. Other statistically significant improvements in measures of performance consisted of the QWB balance index and the hours of work done for jobs in the shop.

Even more dramatic improvements are observed when the SPT dispatching rule is employed.

In this case the improvement in the MWB index is a respectable 9% while the SWB index is reduced by 62%. The Period Queue Balance Index is reduced from 17.3 to 4.85, an improvement of 72%.

The work in process measures, total hours of work in the shop and hours of work done for jobs in the shop, are reduced by 22.3% and 20%, respectively.

Finally, the average tardiness is increased from 6.9 hours to 13.1 hours, but there is a reduction in this case (as opposed to the increase with DSOP) on the variance of the lateness distribution from 3218 to 2217 for a 34.1% improvement. The results obtained in the SWB and QWB indices and in the Work in Process measures are significant at the 99% level,
while the improvements in the MWB index and the variance of the lateness distribution are significant at the 99% level. The increase in average tardiness is also significant at the 99% level.

The results obtained with dispatching rules EWIQ and FCFS are of a similar nature to the ones already described, although in these cases no experimental search was made for the best range for DESLF. These results are given in Tables 10 and 12.

An analysis of variance was performed utilizing the results of Tables 35 to 38 to test the differences in the effects of the four dispatching rules. The calculated F values are given on Table 54. It can be seen that the MWB index does not change significantly for the various dispatching rules. However, SWB, QWB, PWB, the work in process measures and the timeliness measures show significant differences when the four dispatching rules are used. For example, the calculated F value for average hours of work in process is 75.15 which greatly exceeds the $F_{.99}(3,16)$ value of 5.29. This is not a new result since it has been reported before by Conway and others (1967) and also in many other works.

Another analysis of variance was performed using the results of Tables 40, 42, 46 and 47 to determine the effect, if any, of various dispatching rules on the measures of performance studied when a job pool and the loading algorithm were used. The calculated ANOVA values are given on Table 54. The results are basically the same as in the ANOVA described in the preceding paragraph, except that the conclusion that there is some difference in the four dispatching rules with respect to the average tardiness can not be reached this time. In addition to the ANOVA, Duncan
Ranking Tests as described by Hicks (1964) were also performed to identify the dispatching rules with significant differences in the measures of performance. These results are presented in Table 55.

7.3 Other Results Obtained

7.3.1 Variations in Shop Arrival Patterns

One of the arrival patterns used assumed Poisson arrivals, while the other arrival pattern as was explained in Chapter VI was obtained by superimposing the exponential interarrival times on a sine curve. This created a fluctuating or dynamic mean interarrival time. The results for each condition are shown in Table 13. The Shop Balance Index increases by 50% when fluctuating arrivals are introduced. The reason for this is that some of the variability of the arrival rate filters through the shop and is seen also in the departure rate. The other measures where significant differences at the 99% level are detected are WIP (hours), PWB and PQB. The difference for the WIP (hours) was only a 4.1% increase in the hours for the case with fluctuating arrivals, but this became significant due to the small variability observed over the various replications.

The conclusion in this case is that a fluctuating arrival rate of the magnitude used here causes most measures of performance to have a less favorable value than when a flat arrival rate (pure Poisson arrivals) is employed. The variance of the lateness distribution is the notable exception, but the results in this case are not significant at the 99% level.
Table 13. Comparison of Results in an "Uncontrolled" Shop Obtained when Arrivals Are Generated by a Distribution with a Static Mean vs Results when a Dynamic Mean Was Employed. Dispatching Rule is DSOP.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Flat Arrivals (From Table 29)</th>
<th>Fluctuating Arrivals (From Table 35)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>138</td>
<td>157</td>
</tr>
<tr>
<td>Machine Balance, MWB</td>
<td>4.83</td>
<td>4.97</td>
</tr>
<tr>
<td>Shop Balance, SWB</td>
<td>.595</td>
<td>.893</td>
</tr>
<tr>
<td>Queue Workload Balance, QWB</td>
<td>13.5</td>
<td>14.4</td>
</tr>
<tr>
<td>Period Workload Balance, PWB</td>
<td>4.27</td>
<td>4.12</td>
</tr>
<tr>
<td>Period Queue Balance, PQB</td>
<td>109</td>
<td>73.1</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>609</td>
<td>634</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>227</td>
<td>231</td>
</tr>
<tr>
<td>Variance of Lateness Dist.</td>
<td>894</td>
<td>784</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>2.05</td>
<td>2.01</td>
</tr>
</tbody>
</table>

Note: The results shown are the average of 5 runs.
7.3.2 Shop with Few Interactions

The effects produced by the job shop control methodology in a shop with few interactions are illustrated by simulations performed in a shop with five machines and where the average number of operations per job is only two. The comparison of these results with results obtained in the same shop while operating under "controlled" conditions are shown in Table 14. They are of the same type as those obtained for the larger shop when the same dispatching rule (DSOP) was used, except that the percentage improvements obtained by the job pool and the loading algorithm are even more dramatic here. The balance indices are reduced as follows:

- MWB - 16%
- SWB - 46%
- OWB - 42%
- PWB - .5%
- POB - 83%

The work in process measures are reduced by 43% (total hours in the shop) and 65% for hours of work done for jobs in the shop. The variance of the lateness distribution shows a 12.5% increase and the average tardiness increased from .2 to 6.5 hours. The results where the improvement was statistically significant at the .99 level were the deviation from balance, the MWB, SWB, QWB indices, and the work in process measures.

The other measures were not shown to be statistically significant using the paired observation t test due to the large variance in the observed samples. There is no question, however, that the percentage improvements obtained do have practical significance.
Table 14. Comparison of Results Obtained by Using a Job Pool and the Loading Algorithm Against an "Uncontrolled" Shop. Small Shop (5 Machines) with Few Interactions. Dispatching Rule is DSOP.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Uncontrolled Shop (From Table 31)</th>
<th>Job Pool, Loading Algorithm (From Table 32)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>41.6</td>
<td>26.5</td>
</tr>
<tr>
<td>Machine Workload Balance, MWB</td>
<td>5.67</td>
<td>4.76</td>
</tr>
<tr>
<td>Shop Workload Balance, SWB</td>
<td>1.54</td>
<td>.831</td>
</tr>
<tr>
<td>Queue Workload Balance, QWB</td>
<td>28.5</td>
<td>16.3</td>
</tr>
<tr>
<td>Period Workload Balance, PWB</td>
<td>4.19</td>
<td>3.99</td>
</tr>
<tr>
<td>Period Queue Balance, PQB</td>
<td>166</td>
<td>27.5</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>161</td>
<td>91.7</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>38.5</td>
<td>13.6</td>
</tr>
<tr>
<td>Variance of the Lateness Dist.</td>
<td>1158</td>
<td>1303</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>.21</td>
<td>6.50</td>
</tr>
</tbody>
</table>
The reason why the job pool and the loading algorithm cause an even greater improvement in this case is because the balancing features of the model have a greater effect on the jobs since they remain in the shop for an average of two operations only. In this form, the shop interactions have a much smaller chance of disrupting the work done at loading time.

### 7.3.3 Special Loading Modifications

It was desired to investigate the effect of several variations of the releasing of jobs provided by the loading algorithm.

The loading provided by the algorithm is done normally once every scheduling period. It is apparent that in practical situations a shop should be flexible enough to expedite jobs to idle machines if the need arises. It was desirable to test this feature as a modification or extension of the basic loading algorithm.

**Modification 1**

This condition consists of putting a job directly in the shop, without passing through the pool, if the machine which is to perform the job's first operation is idle at the time the job arrives in the shop.

**Modification 2**

This option is put into use when a job is finished by a machine and that machine queue is empty. Under this condition, the pool is then searched to see if any job from the pool uses the machine in question for its first operation.

**Modification 3**

This option provides a modification of conditions 1 and 2. It allows conditions 1 and 2 to take place only if the machine in question
has not yet performed its average amount of work in the scheduling period.

Modification 4

This option operates as follows: after loading from the pool using the loading algorithm, a check is made to see if a match is found between an idle machine and the first operation number of a job in the pool. If this match is found, the job is loaded immediately. Condition 4 can be used by itself or with options 1, 2, and 3. It should not be used with options 1 and 2 alone because it would be redundant in that case.

The results obtained with these special loading conditions are shown in Tables 26 to 28. These special loading modifications were investigated to test the shop control methodology under various shop conditions. It was observed that the improvements obtained for most balance measures and for work in process levels were maintained. No significant improvement was obtained in the MWB index, however, and it must, therefore, be concluded that to obtain changes in this index, it is necessary to get into the shop and "direct traffic" from machine to machine.

7.3.4 Results Obtained with a Loading Heuristic

The loading heuristic utilized was explained in Chapter IV and briefly consisted of loading a job in the shop if the first job operation made a contribution to the queue of a machine that was underloaded at the time. The complete list of jobs in the pool was examined every period but no attention was paid to the contribution of the second and succeeding operations. The results obtained with this heuristic method are compared to those obtained with the loading algorithm (both using the job pool) and they are shown in Table 15.
Table 15. Comparison of Results Obtained by Using the Job Loading Algorithm and a Loading Heuristic. Job Pool is Used. Dispatching Rule is DSOP.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Job Loading Algorithm (From Table 39)</th>
<th>Loading Heuristic (From Table 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>95.7</td>
<td>130 hours</td>
</tr>
<tr>
<td>Machine Workload Balance, MWB</td>
<td>5.04</td>
<td>5.09</td>
</tr>
<tr>
<td>Shop Workload Balance, SWB</td>
<td>0.674</td>
<td>0.830</td>
</tr>
<tr>
<td>Queue Workload Balance, QWB</td>
<td>9.51</td>
<td>11.4</td>
</tr>
<tr>
<td>Period Workload Balance, PWB</td>
<td>4.40</td>
<td>4.30</td>
</tr>
<tr>
<td>Period Queue Balance, PQB</td>
<td>32.8</td>
<td>43.6</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>550 hours</td>
<td>588 hours</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>181 hours</td>
<td>210 hours</td>
</tr>
<tr>
<td>Variance of Lateness Dist.</td>
<td>1029</td>
<td>854</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>14.6 hours</td>
<td>5.44 hours</td>
</tr>
</tbody>
</table>
The results obtained with the loading algorithm are better in most areas except in the variance of the lateness distribution and the average tardiness. The improvements are significant at the 99% level in the cases of the SWB and QWB indices as well as with the work in process measures. Some improvement is obtained, however, by the loading heuristic in some of the measures when results are compared to those obtained when the shop operates under "uncontrolled" loading conditions. It must be concluded, therefore, that the improvements reported elsewhere in this research have been produced jointly by the use of the job pool concept and the loading algorithm.

7.3.5 Shop with a Non-Symmetric Transition Matrix

A shop with a non-symmetric transition matrix is one in which special work flow patterns can be identified. The matrix used is shown in Figure 5. The comparison of results obtained in a shop with specific job flow structure when the shop control methodology is used and those obtained for the same shop under "uncontrolled" shop loading conditions are illustrated in Table 16.

It can be seen that sizable improvements were obtained for SWB, QWB, and PQB as well as the work in process measures. These are the same type of results obtained for the pure job shop when the same dispatching rule used here, Dynamic Slack per Operation, is employed.

7.3.6 Shops with Alternate Selections of Machines in a Machine Pair

This feature allows for some alternative routing characteristics in the shop. Specifically, the shop is treated as if it consisted of pairs of machine groups with the odd numbered machine group and the even numbered group immediately following it making up a pair. Thus each machine
<table>
<thead>
<tr>
<th>from machine</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>.16</td>
<td>.01</td>
<td>.20</td>
<td>.01</td>
<td>.01</td>
<td>.30</td>
<td>.01</td>
<td>.10</td>
<td>.20</td>
</tr>
<tr>
<td>2</td>
<td>.26</td>
<td></td>
<td>.01</td>
<td>.01</td>
<td>.30</td>
<td>.10</td>
<td>.20</td>
<td>.10</td>
<td>.01</td>
<td>.01</td>
</tr>
<tr>
<td>3</td>
<td>.20</td>
<td>.01</td>
<td></td>
<td>.01</td>
<td>.09</td>
<td>.26</td>
<td>.01</td>
<td>.40</td>
<td>.01</td>
<td>.01</td>
</tr>
<tr>
<td>4</td>
<td>.01</td>
<td>.10</td>
<td>.36</td>
<td></td>
<td>.01</td>
<td>.01</td>
<td>.01</td>
<td>.01</td>
<td>.20</td>
<td>.29</td>
</tr>
<tr>
<td>5</td>
<td>.01</td>
<td>.20</td>
<td>.30</td>
<td>.01</td>
<td></td>
<td>.10</td>
<td>.07</td>
<td>.10</td>
<td>.20</td>
<td>.01</td>
</tr>
<tr>
<td>6</td>
<td>.10</td>
<td>.01</td>
<td>.01</td>
<td>.35</td>
<td>.01</td>
<td></td>
<td>.11</td>
<td>.01</td>
<td>.20</td>
<td>.20</td>
</tr>
<tr>
<td>7</td>
<td>.20</td>
<td>.01</td>
<td>.01</td>
<td>.20</td>
<td>.27</td>
<td>.10</td>
<td></td>
<td>.10</td>
<td>.01</td>
<td>.10</td>
</tr>
<tr>
<td>8</td>
<td>.02</td>
<td>.30</td>
<td>.10</td>
<td>.20</td>
<td>.01</td>
<td>.10</td>
<td>.10</td>
<td></td>
<td>.10</td>
<td>.07</td>
</tr>
<tr>
<td>9</td>
<td>.10</td>
<td>.20</td>
<td>.10</td>
<td>.01</td>
<td>.10</td>
<td>.02</td>
<td>.10</td>
<td>.26</td>
<td></td>
<td>.11</td>
</tr>
<tr>
<td>10</td>
<td>.10</td>
<td>.01</td>
<td>.10</td>
<td>.01</td>
<td>.20</td>
<td>.30</td>
<td>.10</td>
<td>.01</td>
<td>.17</td>
<td></td>
</tr>
</tbody>
</table>

Example of a likely 6 operation path - 1,7,5,3,8,2

Example of an unlikely 6 operation path - 1,3,2,4,7,9

Figure 5. Non-Symmetric Transition Matrix
Table 16. Comparison of Results Obtained by Using a Job Pool and the Loading Algorithm Against an "Uncontrolled" Shop. Shop with a Non-Symmetric Transition Matrix. Dispatching Rule is DSOP.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Uncontrolled Shop (From Table 33)</th>
<th>Job Pool, Loading Algorithm (From Table 34)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>164</td>
<td>86.2</td>
</tr>
<tr>
<td>Machine Workload Balance, MWB</td>
<td>5.03</td>
<td>5.11</td>
</tr>
<tr>
<td>Shop Workload Balance, SWB</td>
<td>0.806</td>
<td>0.546</td>
</tr>
<tr>
<td>Queue Workload Balance, QB</td>
<td>14.0</td>
<td>9.09</td>
</tr>
<tr>
<td>Period Workload Balance, PWB</td>
<td>4.25</td>
<td>4.59</td>
</tr>
<tr>
<td>Period Queue Balance, PQB</td>
<td>40.9</td>
<td>18.5</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>647</td>
<td>545</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>230</td>
<td>185</td>
</tr>
<tr>
<td>Variance of the Lateness Dist.</td>
<td>727</td>
<td>934</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>2.06</td>
<td>11.3</td>
</tr>
</tbody>
</table>
in the shop has a companion machine. Both machines do the same type of work such that jobs can be interchanged on the two machines. The shop operates in its normal way except that when a given machine becomes idle, the queue of its companion machine is checked to see if there are any jobs in it so that it can be transferred to the idle machine. Also when a job is first placed in a machine queue, the status of the companion machine is checked to verify that it is not idle. The purposes in using this feature were to investigate the effect on shop balance measures in general of having a shop with this additional flexibility and also to check on the usefulness of the pool concept and the loading algorithm under these conditions.

A group of simulation runs for shops in which the alternate selection of machines in a machine pair was allowed were performed. The DSOP dispatching rule was used in all cases.

Table 17 compares the results in a traditional shop with those in which the alternate routing feature was allowed. These runs did not utilize the loading algorithm. The hours of work in process were reduced by the use of the alternate machine feature by 32.3% and the hours of work done for jobs in the shop were reduced by 25.6%. The calculated t statistic for these measures were 50.4 and 21.7 respectively, while the tabulated value for $t_{0.99} (4)$ is 3.747. It can, therefore, be said that the work in process measures are improved by the use of the alternate machine feature. This result is not surprising since improvements in work in process measures and mean flow times (the improvement in average time in the shop in this research was close to 40%) when some sort of alternate machine
Table 17. Comparison of Results in a Traditional Shop with a Shop Where Alternate Routing is Allowed. Shop is "Uncontrolled". Dispatching Rule is DSOP.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Traditional Shop (From Table 35)</th>
<th>Alternate Routing (From Table 48)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>157</td>
<td>280.</td>
</tr>
<tr>
<td>Machine Workload Balance, MWB</td>
<td>4.97</td>
<td>4.61</td>
</tr>
<tr>
<td>Shop Workload Balance, SWB</td>
<td>.893</td>
<td>1.58</td>
</tr>
<tr>
<td>Queue Workload Balance, QWB</td>
<td>14.4</td>
<td>7.04</td>
</tr>
<tr>
<td>Period Workload Balance, PWB</td>
<td>4.12</td>
<td>3.05</td>
</tr>
<tr>
<td>Period Queue Balance, PQB</td>
<td>73.1</td>
<td>49.7</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>634 hours</td>
<td>429 hours</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>231</td>
<td>172</td>
</tr>
<tr>
<td>Variance of the Lateness Dist.</td>
<td>784</td>
<td>1288</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>2.01</td>
<td>.46</td>
</tr>
</tbody>
</table>
scheme is used has already been reported by Conway and others (1967).

The main purpose, however, of investigating the alternate machine feature in this research was in relation to its effect on shop balance measures. The MWB, QWB, PWB and PQB indices show improvements of 7.2%, 51%, 26%, and 32% respectively with the improvements in the MWB, and PWB shown to be significant at the 99% level by the paired observation t test.

The surprising result is that the SWB index and the variance of the lateness distribution show a significant increase when the alternate machine feature is used. The calculated t values are 9.07 and 16.4 while $t_{.99} (4)$ is 3.747.

A possible explanation for this shop behavior is that the alternate machine feature causes greater fluctuation in shop output by pushing out a lot of work in some periods which can not be maintained over the long run. Table 18 illustrates the same type of comparison as Table 17, but in this case the job pool and loading algorithm are used.

The direction of the improvements observed in this case are similar to the ones observed when the job pool was not used except that the magnitude of the improvements obtained by the use of the alternate machine feature are somewhat larger this time. The SWB index shows again an increase, but the variance of the lateness distribution does not experience a significant change this time.

Finally Table 19 deals with a shop in which the alternate routing feature is used and the dispatching rule is DSOP. The Table shows a comparison of a shop with a job pool and the loading algorithm against one operating under "uncontrolled" loading conditions. Very significant
Table 18. Comparison of Results in a Traditional Shop with a Shop Where Alternate Routing is Allowed. Dispatching Rule is DSOP; a Job Pool and the Loading Algorithm Are Used.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Traditional Shop (From Table 47)</th>
<th>Alternate Routing (From Table 49)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>120.</td>
<td>260.</td>
</tr>
<tr>
<td>Machine Workload Balance, MWB</td>
<td>5.11</td>
<td>4.24</td>
</tr>
<tr>
<td>Shop Workload Balance, SWB</td>
<td>.571</td>
<td>.767</td>
</tr>
<tr>
<td>Queue Workload Balance, QWB</td>
<td>8.84</td>
<td>2.81</td>
</tr>
<tr>
<td>Period Workload Balance, PWB</td>
<td>4.58</td>
<td>3.48</td>
</tr>
<tr>
<td>Period Queue Balance, PQB</td>
<td>25.6</td>
<td>3.84</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>529</td>
<td>311</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>158</td>
<td>97.8</td>
</tr>
<tr>
<td>Variance of the Lateness Dist.</td>
<td>1276</td>
<td>1199</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>24.7</td>
<td>9.36</td>
</tr>
</tbody>
</table>
Table 19. Comparison of Results Obtained by Using a Job Pool and the Loading Algorithm Against an "Uncontrolled" Shop. Shop with 10 Machines and Where Alternate Routing is Allowed. Dispatching Rule is DSOP.

<table>
<thead>
<tr>
<th>Measures of Performance</th>
<th>Uncontrolled Shop (From Table 48)</th>
<th>Job Pool, Loading Algorithm (From Table 49)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate Deviation from Balance</td>
<td>280.</td>
<td>260.</td>
</tr>
<tr>
<td>Machine Workload Balance, MWB</td>
<td>4.61</td>
<td>4.24</td>
</tr>
<tr>
<td>Shop Workload Balance, SWB</td>
<td>1.58</td>
<td>.767</td>
</tr>
<tr>
<td>Queue Workload Balance, QWB</td>
<td>7.04</td>
<td>2.81</td>
</tr>
<tr>
<td>Period Workload Balance, PWB</td>
<td>3.05</td>
<td>3.48</td>
</tr>
<tr>
<td>Period Queue Balance, PQB</td>
<td>49.7</td>
<td>3.84</td>
</tr>
<tr>
<td>Work in Process, hours</td>
<td>429</td>
<td>311</td>
</tr>
<tr>
<td>Work done for jobs in shop</td>
<td>172</td>
<td>97.8</td>
</tr>
<tr>
<td>Variance of the Lateness Dist.</td>
<td>1288</td>
<td>1199</td>
</tr>
<tr>
<td>Average Tardiness</td>
<td>.46</td>
<td>9.36</td>
</tr>
</tbody>
</table>
improvements are also obtained this time. For example, the SWB and QWB indices are reduced by 51% and 60%. The hours of work in process are reduced by 27.5% and the hours of work done for jobs in the shop by 43%. All four of these measures showed a significant improvement at the 99% level. The average tardiness had an increase from .46 to 9.36 hours and the variance of the lateness distribution showed a small, but non-significant improvement when the job pool was used. This is somewhat surprising since the variance of the lateness distribution increased when the shop control methodology was employed under the DSOP dispatching rule and the alternate machine feature was not used (see Table 9).
CHAPTER VIII

EXTENSIONS OF THE BASIC LOADING METHODOLOGY

The extensions that follow were developed during the course of the research for this dissertation. They are not a necessary part of the central research theme and therefore have not been used. They are presented here, however, so that they can serve as possible starting points for future research.

The basic idea of loading and of the loading algorithm are extended below to the area of dispatching and then a model is proposed to use the operations to be performed in a given period while jobs are selected from the pool. Finally the desirability of combining the research presented here and the work of Deane (1972) into a single methodology is discussed.

8.1 A Dispatching Model Using the Same Concepts Employed by the Loading Model

The concept presented here consists of treating each machine queue as a "job pool" and giving priority at that machine to that subset of jobs which minimizes the deviation from balance for the rest of the shop as a whole. Conventional dispatching rules (SPT, DSOP, FCFS, etc.) can then be used to rank the subset selected.

This extension, while considering the loading or releasing problem, looks at the dispatching problem in a way similar to that used by Deane (1972).
The differences are that Deane used an elimination scheme to arrive at the subset of eligible jobs and then a repeated search to obtain the actual jobs to be worked on. Here the loading idea is added and a mathematical programming approach is used to select the subset of eligible jobs.

The objective function minimizes the deviation between actual and desired (management goals) aggregate loads for each machine. Deviation values are obtained both from the pool loading constraints and the queue loading constraints. The due date term employed in the loading algorithm in Chapter IV is also used here.

A modification of the objective function is also needed to assign some weight to those jobs with large in process inventory value. It is assumed that this can be determined from the number of work hours already spent on the job. The formulation requires $m^2$ constraints where $m$ is the number of machines.

**Notation**

- $i(o)$: job index for jobs in the pool
- $j$: machine index (m machines)
- $N_0$: number of jobs in the pool
- $i(j)$: job index for jobs in the queue at machine $j$ (also including the job being worked on)
- $X_{i(o)} = 0$: job pool decision variable -- job not selected
- $X_{i(o)} = 1$: job pool decision variable -- job selected
- $X_{i(j)} = 0$: job queue decision variable -- job not selected
- $X_{i(j)} = 1$: job queue decision variable -- job selected
- $W_{ij}$: amount of work contributed by job $i$ to machine center $j$
(work not yet performed on job i)

\[ V_{ij} \]

same as \( W_{ij} \), but this time referring to work already performed on job i

\[ P_j \]
present load in the shop (not in the pool) ahead of machine j

\[
P_j = \sum_{k=1}^{m} \sum_{i(k)=0}^{n_k} W_{i(k)j}
\]

\[ B_{jL} \]
present load in the shop (not in the pool) ahead of machine j, but not including the work in the queue of machine \( L \)

\[
B_j = \sum_{k=1}^{m} \sum_{i(k)=0, i(k) \neq L}^{n_k} W_{i(k)j}
\]

\[ Q_j \]
present load in the shop for machine j loaded in the queue at machine j

\[
Q_j = \sum_{i(j)=1}^{n_j} W_{i(j)j}
\]

\[ P_{o(j)} \]
present load in the pool for machine j

\[
P_{o(j)} = \sum_{i(o)=1}^{n_o}
\]

\[ C_j \]
desired load in the shop for machine j

\[ F_j \]
desired load in the queue for machine j

\[ S_{jL}, S_{jH} \]
deviation from desired aggregate load in the shop (except queue of machine \( k \)) for machine j after loading jobs for machine \( k \)
The formulation then consists of the following:

**Pool Loading Constraint for Machine j:**

\[
\sum_{i(o)=1}^{n_o} W_{i(o)}X_{i(o)} + P_j + S_{jL} - S_{jH} = C_j \quad j=1,2,\ldots,n
\]

These constraints indicate that the contribution of jobs selected from the pool to the aggregate shop load for machine j plus the existing aggregate load in the shop for machine j plus (minus) any shortage load (any excessive load) released must equal the total desired aggregate load in the shop established by management.

**Queue Loading Constraint for Machine j when Loading Jobs at Machine k:**

\[
\sum_{i=1}^{n_k} W_{i(k)}X_{i(k)} + P_{jk} + q_{jkL} - q_{jkH} = \frac{m-1}{m} C_j
\]

for \( j=1,2,\ldots,k-1,k+1,\ldots,m \)

for \( k=1,2,\ldots,m \)

The queue loading constraint for machine j when loading jobs at machine k considers the shop as if the jobs at machine k were in a job pool outside the shop. This constraint then indicates that the aggregate workload for machine j contributed by those jobs given priority at machine k plus the present load in the shop (not in the pool) ahead of machine j without including the jobs in the queue of machine k plus or minus any deficiency or excess of work equals the amount desired by management. It must be noted that, due to the constraint structure, at least one of the two slack variables in the equation will be equal to zero.
Non Negativity and Integer Constraints:

Objective Function

\[ D = \sum_{j=1}^{m} a_{jL} S_{jL} + \sum_{j=1}^{m} a_{jH} S_{jH} + \sum_{j=1}^{m} \sum_{k=1}^{m} (q_{jkL} + q_{jkH}) \]

\[ - \sum_{j=0}^{m} \sum_{i=1}^{n_j} f(d_i) X_i(j) - K_2 \sum_{j=1}^{m} \sum_{i=1}^{n_j} V_i(j) X_i(j) \]

The objective function minimizes the sum of the deviations from desired loading from the job pool and the individual machine centers. It also includes a term to make jobs increasingly attractive loading candidates as their due date approaches and as the investment on a job, given by the work already performed on it, increases.

8.2 The Aggregate Loading Problem Using Multiple Operations in the Horizon

In aggregate scheduling problems, the number of time periods to be planned is called the planning horizon. Generally, the length of the planning horizon should be such that the addition of one more period to the planning horizon would have little effect on the production rate decisions in the early periods.

For example, according to Holt, Modigliani, Muth, and Simon (1960), since each period's decision has cost implications that extend over an appreciable length of time, this cost function must span sufficient time to include virtually all of the cost implications of the decision.
The formulation that follows does not employ time periods or scheduling periods (although a loading decision is made every scheduling period). The formulation uses "operation in a machine" as the planning period. This is based on the argument that the critical time element in a job shop is the number of operations to be accomplished, Ackerman (1963). Along the line of the RMS argument, the penalty function will have to span sufficient operations into the future to include virtually all of the shop balancing implications of the decision.

Notation (n jobs, m machines)

\[ W_{ijt} \] amount of work contributed by job i to machine center j on their immediately next plus \( t \)th operation

\[ \sum W_{ijt} = W_{ij} \] amount of work contributed by job i to machine center j

\[ P_{jt} \] present load in the shop for machine j, \( t \) operations away from machine j

\[ P_{jo} \] load in the queue for machine j

\[ \sum_{t} P_{jt} = P_{j} \] present load in the shop ahead of machine j

\[ C_{jt} \] desired load in the shop for machine j, \( t \) operations away from machine j

\[ C_{jo} \] desired load in the queue for machine j

\[ \sum_{t} C_{jt} = C_{j} \] desired load for machine j in the shop

The following should hold among the \( C_{j} \)'s and make the job of developing them easier

If \[ k_1 C_{10} = k_2 C_{20} = k_3 C_{30} = \ldots = k_m C_{m0} \]

Then \[ k_1 C_{1t} = k_2 C_{2t} = k_3 C_{3t} = \ldots = k_m C_{mt} \] for \( t = 1, 2, 3, \ldots \)
Of course this in no way implies that

\[ C_{jo} = C_{jt} \quad \text{for any } t \]

since the absolute values of the \( C_j \)'s with respect to the \( C_{jo} \) must recognize the additional loading that the pool will effect during future scheduling periods.

weighting factors to be used in the objective function to attach different penalties to the deviations from balance right now at the queue, in the entire shop, 1 operation away, etc.

**Formulation**

\[
\text{Min } D = a_t \sum_{j=1}^{m} (S_{jL.} + S_{jH.}) + \sum_{t=1}^{t^*} a_t \left[ \sum_{j=1}^{m} (S_{jLt} + S_{jHt}) \right]
\]

subject to:

\[ X_i = 0,1 \]

\[ S_{jL.} \geq 0, S_{jH.} \geq 0 \]

\[ S_{jLt} \geq 0, S_{jHt} \geq 0 \]

\[
\sum_{i=1}^{n} W_{ij} X_i + P_j + S_{jL.} - S_{jH.} = C_j \quad j = 1,2,\ldots,m
\]

\[
\sum_{i=1}^{n} W_{ijt} X_i + P_{jt} + S_{jLt} - S_{jHt} = C_{jt} \quad j = 1,2,\ldots,m \quad t = 0,1,2,\ldots,t^*
\]

where \( t^* \) is the operations horizon
The objective function is the deviation in work hours from a desirable and pre-established shop condition. The constraints contain positive and negative slack variables to indicate the excessive or deficient work loaded for a machine group. One of the two slack variables will be zero in each constraint, and the other is used in the objective function. There is a constraint for the aggregate shop load for each machine center and also constraints for the work 1, 2, 3, etc. operations removed from each machine center.

If the future periods are handled on a "time" basis rather than an "operation" basis, then it is not possible to present a "loading only" model since the loading decisions required for balancing "t" periods into the future are going to depend also on the dispatching decisions made during that time. Such a loading and dispatching model with a planning horizon should not be too difficult although the notation required will be cumbersome.

8.3 Combination of Dispatching and Loading Algorithms

The model in the first section of this chapter attacked the problems of dispatching and loading on an integral basis by looking at the dispatching problem as if it were a loading problem. However, it was observed that the number of resulting constraints is large and the model is rather awkward.

On the other hand, it has been shown by this research that the loading methodology presented here improves the shop workload balance measure (SWB) and other balance measures as well as work in process measures considerably. However, the results obtained with the machine work-
load balance measure (MWB) have been mixed. Modest improvements were obtained with some dispatching rules (SPT) and no improvement at all with some others (DSOP). The reason for this is that the job goes through too many operations in the shop without any "balance" control after being loaded from the pool. The results obtained by Deane (1972) with his dispatching method give practically the opposite results and job control is maintained at every operation in the shop. The combination of the loading methodology presented in this research and the dispatching approach introduced by Deane is, therefore, a logical step which should be investigated by future researchers.
CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

The objective of this research has been to develop a loading and balancing methodology for job shop control. This objective has been accomplished by the introduction of the job pool concept and the development of the job loading algorithm to select jobs from the pool.

In addition, a large number of shop balance measures have been identified and their applicability to different kinds of shops has been discussed. The validity and relevance of the shop balance concept as a measure of performance has been presented.

Significant improvements were obtained through the use of the job pool and the loading algorithm in most balance measures tested as well as in work in process measures related to both total work in the shop and to work performed for jobs in the shop. The results dealing with balance measures and work in process levels are closely related.

In fact, it can be argued that the reduction of work in process levels is a consequence of the better "balanced" shop because under the improved balance condition there is less interference in the shop and, therefore, a lower in process level is needed to maintain a certain work throughput level.

These results were not achieved without paying a price, however. The use of the loading and balancing methodology resulted in increases in the average job tardiness and the variance of the lateness distribution
the dispatching rule was Dynamic Slack per Operation. On the other hand, the variance of the lateness distribution was reduced by the use of the loading algorithm when the dispatching rule was shortest processing time. It has also been observed that the results obtained with the job pool and the loading algorithm are highly dependent on the desired load level (management load factor) used in the algorithm. This parameter greatly influences the average number of jobs in the job pool and the loading methodology needs a reasonable number of jobs in the pool so that it can have flexibility in selecting the jobs to be loaded in the shop.

The work performed in this dissertation can result in significant practical applications and it also provides a good starting point for additional research. Among the important areas where additional research could be done are:

a) Testing the results obtained by incorporating into a single model the dispatching approach introduced by Deane (1972) and the loading ideas developed in this research. The combination of these two approaches was discussed in Chapter VIII. This combined model should offer the benefits of a shop with better overall balance provided by the shop control methodology and the ability to react to specific out-of-balance conditions that develop on the shop floor as provided by the "search" dispatching approach.

b) Extending and testing the algorithms presented in Chapter VIII. The first one consists of a dispatching model which utilizes the same concepts employed by the loading model. The second one is a loading model which considers the shop load not only in an aggregate basis but also takes
into account the "timing" of work availability to the various machines. The testing required will consist of programming the algorithms and employing them in a job shop simulator to investigate their effect on various measures of shop performance.

c) Performing sensitivity analysis on the loading algorithm with respect to both the management load factor and the due date function. The performance of the algorithm is dependent on the desired aggregate load in the shop and also on the weight assigned to the due date term in the objective function. As the management load factor is increased, the aggregate load in the shop increases and the average job pool size decreases. This condition hurts the balance and work in process measures but improves the average tardiness.

An increase in the weight assigned to the due date term forces jobs into the shop earlier, at the expense of balance and work in process measures. The effect of changes in values of these two parameters is highly interrelated and the performance of detailed sensitivity analysis on them will add new understanding to the job shop behavior.

d) Investigating the sensitivity of the results obtained with respect to the scheduling period. The value of the management load factor that should be used is closely related to the scheduling period employed because as the scheduling period gets longer, more work hours should be loaded in the shop every period. The reason for this is that the times between job releases to the shop will be longer.

e) Investigating "loading" algorithms that control the job pool size in a more direct way than the algorithm presented in this research.
The loading algorithm exercises an indirect effect in the size of the job pool through the management load factor and the weight of the due date term. The results of the simulation have shown a high correlation between the size of the job pool and the value of most of the measures of performance related to shop balance. A new algorithm that recognizes this fact and makes use of it explicitly could possibly result in additional significant improvements for several shop measures of performance.
APPENDIX A

DESCRIPTION AND FLOW DIAGRAM
OF SIMULATION PROGRAMS
Table 20. Description of Simulation Subroutines

**MAIN.** This is the main program and its functions are to read in the parameters describing the simulation, initialize the non-GASP variables, and to call subroutine GASP which turns over control to the GASP II language.

**EVNTS.** This subroutine calls one of the four event subroutines (ENDSV, ARIVL, COLL, START).

**START.** It sets the simulation clock to zero and generates new arrivals to preload the shop. The new arrivals are placed in the job pool if a pool is being used and if the initial number of jobs desired in the pool has not been reached yet. Otherwise the new jobs are placed directly in the proper machine queues. New arrivals continue to be generated until the total number of jobs to be preloaded is reached.

**ARIVL.** The subroutine ARIVL generates the simulation clock time for the next job arrival to the shop and this time is set up as an arrival event in the GASP event file. It then generates the job attributes for the job that just came in, starting with the number of operations, and then the machine number and time for the first operation, other machine numbers from the job transition matrix and their times, and finally the job due date. The subroutine then assigns a file location to the job and moves it to the job pool or shop. It also contains options to handle the special loading conditions #1,3 described in Chapter VII.
**ENDSV.** This subroutine is used every time a job finishes an operation at a machine. It must then collect shop statistics and depending on whether the job is leaving the shop at this time or not it must collect the terminal job statistic or update the job attributes and place it in the next queue.

The next task for this subroutine is to select from the queue of the machine that just finished an operation the next job to be processed. If the queue contains one or more jobs, statistics on job waiting times as well as shop workload must be calculated. On the other hand if the queue is empty, machine utilization statistics must be updated. This subroutine also contains instructions to handle the special loading conditions #2,3 given in Chapter VII.

**COLL.** COLL is a subroutine called only at the end of every scheduling period. Its main functions are to calculate and update statistics which are kept on a scheduling period basis and, if a pool is used, to call the matrix generator subprogram. In addition, this subroutine tests for the end of run-in period and end of simulation conditions and takes appropriate action if these conditions have occurred.

**CLEAR.** This subroutine is used only at the end of the run in period to clear and reset the arrays which keep the accumulated statistics. The shop status, of course, is left undisturbed.
Table 20. (Continued)

**PTJOB.** Subroutine PTJOB is responsible for placing a job in the job pool or in a machine queue or in the machine itself. Which one of these actions is taken depends on whether the shop is still being preloaded, on whether the job is a new arrival or not, whether a job pool is being used, and on the status of the machine itself. In addition to the above, statistics are collected on interarrival times to the pool and each machine. Once it has been decided to put a job in a machine, the workload in the machine status is changed and the time for the completion event is set if the machine was idle.

**GENMAT.** Subroutine GENMAT generates the matrix required by the loading algorithm to select those jobs that will be moved from the job pool to the shop. The matrix is generated by using job attributes contained in the job pool file. This subroutine is by-passed if the job pool is not being used and it calls the proper loading routine, either the loading heuristic or the mathematical programming loading algorithm if the job pool is being used.

**LPI.** LPI is basically a simple linear programming code with the bounded variable feature. It then calls JOBDEC and transmits the values of the job decision variables to it.

**JOBDEC.** The function of JOBDEC is to decide which jobs will be moved from the job pool to the machine queues based on the value of the job decision variables given by LPI.
| ENSIN. | This subroutine is called at the end of the simulation to print simulation results. In addition it has an option to start other simulation runs with a different dispatching rule and if this option is used, ENSIM must reinitialize the non-GASP variables and call GASP to begin the new run. |
| POOLHE. | This is the loading heuristic subroutine and was already explained in Chapter IV. |
Figure 6. Job Shop Simulator
Figure 6. Concluded
START

GENERATE TIME FOR NEXT ARRIVAL TO THE SHOP

GENERATE THE NUMBER OF OPERATIONS FOR NEW JOB

GENERATE MACHINE NUMBER AND TIME FOR FIRST OPERATION WITH EACH MACHINE HAVING EQUAL CHANCE OF BEING CHOSEN

GENERATE MACHINE NUMBER AND TIME FOR EACH SUCCEEDING OPERATION ACCORDING TO JOB TRANSITION MATRIX

DETERMINE JOB DUE DATE AND ASSIGN JOB ATTRIBUTES

ASSIGN THE NEW JOB A NUMBER AND MARK ITS LOCATION. PROGRAM LOOKS FOR FIRST JOB NUMBER WITHOUT A COLUMN LOCATION

MOVE JOB INTO THE SHOP (CALL PTJOB)

RETURN

Figure 7. Subroutine ARIVL
CLEAR AND RESET THE GASP ARRAYS SUMA, SSUMA, AND JCELS

RESET NON-GASP VARIABLES

SET INDICATOR NRST TO INDICATE NO RESET DESIRED IN THE FUTURE

RETURN

Figure 8. Subroutine CLEAR
START

SCHEDULE NEXT DATA COLLECTION AT THE END OF THE NEXT SCHEDULING PERIOD

UPDATE TIME INTEGRATED STATISTICS ON FACILITY UTILIZATION

COMPUTE AND COLLECT STATISTICS ON SHOP UTILIZATION FOR PERIOD

IS A POOL USED?

YES

1

NO

2

Figure 9. Subroutine COLL
ADJUST AGGREGATE SHOP LOAD FOR EACH MACHINE AND QUEUE LOAD FOR PARTIALLY COMPLETED JOBS (QUEUE LOADS & AGGREGATE SHOP LOADS ARE REDUCED IN ENDSV AND PTJOB AS SOON AS A JOB STARTS TO BE WORKED ON BY A MACHINE)

CALL GENMAT
CALL LPI
CALL JOBDEC
CALL PTJOB

Figure 9. Concluded
START

COLLECT AND UPDATE DYNAMIC SHOP STATISTICS TMST 13, 14

IS JOB LEAVING SHOP?

YES

COLLECT TERMINAL STATISTICS ON THE JOB, INCLUDING TIME SPENT IN SYSTEM, POOL, AND SHOP

NO

60

UPDATE JOB ATTRIBUTES
CALL PTJOB (2, NSET)

80

DOES MACHINE HAVE ADDIT JOBS IN QUEUE?

NO

UPDATE DYNAMIC AND STATIC SHOP STATISTICS
COLLECT STATIC SHOP STATISTICS (WORK AND OPERATIONS IN SHOP)

YES

100

COLLECT MACHINE STATISTICS

1

2

Figure 10. Subroutine ENDSV
Figure 10. Continued
START

PRINT SIMULATION RESULTS

INCREASE NRULE BY ONE

SET GASP RANKING INDICATORS FOR NEW RULE

REINITIALIZE NON-GASP VARIABLES

SET INDICATOR FOR GASP SUMMARY REPORT

RETURN

Figure 11. Subroutine ENSIM
Figure 12. Subroutine EVNTS
Figure 13. Subroutine GENMAT
Figure 13. Concluded
START

OBTAIN JOB DECISION VARIABLES FROM LPI OR POOLHE OUTPUT MATRICES

IN OBTAINING VALUE FOR XJOB CONSIDER WHETHER VALUE IS GIVEN BY UPPER BOUND, BASIC VARIABLE, OR UPPER BOUND MINUS BASIC VARIABLE

SEARCH JOB POOL FOR JOBS WITH DECISION VARIABLE \geq .75

REMOVE THOSE JOBS FROM POOL PILE (CALL RMOVE) MOVE THOSE JOBS INTO THE PROPER MACHINE (CALL PTJOB) UPDATE SHOP LOAD

WAS POOLHE USED?

YES

NO

1

2

Figure 14. Subroutine JOBDEC
GET FROM JOB POOL FILE
NEXT JOB WITH DECISION
VARIABLE BETWEEN .3 AND
.75

NO MORE JOBS WITH DEC.
VARIABLE BETWEEN
.3 AND .75

WORK-SHOP LOAD
GREATER THAN
DESIRED
LOAD?

REMOVE JOB FROM POOL FILE
CALL PTJOB TO PUT JOB IN
THE SHOP
UPDATE SHOP LOAD

RETURN

Figure 14. Continued
INCREASE NO. OF ITERATIONS BY 1

SET PARAMETERS AND INITIALIZE

START

INCOL = 0?

INCREASE NO. OF ITERATIONS BY 1

OPTIMAL SOLUTION OBTAINED?

SET PARAMETERS AND INITIALIZE

CALL JOBDEC

RETURN

COLUMN COMING TO THE BASIS HAS BEEN SELECTED
- PICK ROW TO PIVOT ON
- USE ISUB TO DENOTE THE FOLLOWING:
  0 STANDARD PIVOT
  1 PIVOT AND UPPER SUBSTITUTE
  2 UPPER SUBSTITUTE

Figure 15. Subroutine LPI
Any row candidate found? 

Yes: $301$ 

No: 

Any auxiliary variable in the basis? 

Yes: 

Solution infeasible 

No: 

Unbounded solution 

ISUB value = ? 

0 

ISUB value = ? 

1 

Update matrix, $C$ vector, and KBV 

- Change $C$(INCOL) sign 
- Adjust value of RHS column to account for variables at upper bound 
- Change upper bound switch for this column 

ISUB value = ? 

0 

GO TO 200 

1 

Figure 15. Concluded
START

READ IN PARAMETERS DESCRIBING SIMULATION

INITIALIZE NON-GASP VARIABLES

CALL GASP

END

Figure 16. MAIN Program
SET TO ZERO \( A(NRROW+2,J) \)
TEMPAG

START WORKING WITH A MACHINE TEMPOL = 0.0

\( NTEST = MBEST = 0 \)

ADDITIONAL LOADING REQUIRED IN QUEUE FOR THIS MACHINE

LOOK AT FIRST JOB IN THE POOL

PUT JOBS IN QUEUE UNTIL QUEUE QUANTITIES ADD UP TO DESIRED AMOUNTS. THEN DEPENDING ON FEATURE SELECTED, PUT MORE JOBS IN THE SHOP UNTIL THE TOTAL DESIRED LOAD FOR THE SHOP IS REACHED.

Figure 17. Subroutine POOLHE
FIRST OPERATION OF JOB IS FOR THIS MACHINE?

YES

HAS THIS JOB BEEN SELECTED ALREADY?

NO

DOES THIS JOB HAVE AN EARLIER DUE DATE THAN ANY PREVIOUSLY NON SELECTED JOB FOR THIS MACHINE?

YES

RESET MBEST MTEST

10

YES

LOOK AT NEXT JOB

NO

IS THIS THE LAST JOB IN THE POOL?

YES

RESET A(NOROW+2,J) = -1.0 FOR SELECTED JOB J. ALSO INCREASE QUEUE LOAD AND AGGREGATE LOAD.
Figure 17. Concluded
Figure 18. Subroutine PTJOB
COLLECT STATISTICS ON INTERARRIVAL TIME TO THE POOL

MSW(1)?

YES

T_NOW < .0001

NO

FIRST OPERATION MACHINE BUSY?

YES

PUT JOB IN POOL

NO

RETURN

HAS THIS MACHINE DONE ENOUGH WORK THIS PERIOD ALREADY?

YES

RESET LOADING SWITCH TO NORMAL

NO

MSW(3)?

PUT JOB IN SHOP BY GOING TO STATEMENT 20

Figure 13. Continued
COLLECT STATISTICS ON INTERARRIVAL TIMES TO THE CURRENT MACHINE

IS MACHINE BUSY?

YES

CHANGE MACHINE STATUS. UPDATE STAT. ON MACH. UTILIZATION, REDUCE AGGREGATE LOAD IN SHOP FOR THIS MACHINE

NO

60

INITIALIZE PROCESSING OF THE JOB BY MACHINE. SET TIME FOR COMPLETION EVENT TO OCCUR

50

PUT JOB IN MACHINE QUEUE

INCREASE WORKLOAD IN MACHINE QUEUE

Figure 18. Concluded
START

SET PRESENT TIME TO 0 AND POOL SWITCH (NSTSW) TO 0 (USE POOL)

GENERATE A NEW ARRIVAL (CALL ARVL) TO PRELOAD THE SHOP

HAS JOB POOL BEEN PRELOADED?

SET NSTSW TO 1 (BYPASS POOL)

ARE ALL JOBS PRELOADED?

RETURN

Figure 19. Subroutine START
APPENDIX B

FORTRAN IV LISTING OF SIMULATION PROGRAMS
- FOR IS SUBLOADING ARRIVAL

**SUBROUTINE ARRIVAL (GSEP)**

*** SUBROUTINE CALLED WHEN A NEW ARRIVAL COMES
*** INTO THE SHOP

**DIMENSION ASET (35,1)**

COMMON /OPL:AD/ OPLS, OPLC, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:PR/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:OL/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:TP/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:PM/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:MT/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:ST/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:HF/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:GH/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:GL/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:SM/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:SS/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:AG/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:GU/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:MG/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:SG/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:PM/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:PM/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:PM/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:PM/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:PM/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ
COMMON /OPL:PM/ OPLE, OPLD, OPLP, OPLR, OPLT, OPLU, OPLV, OPLW, OPLX, OPLY, OPLZ

*** GENERATE THE TIME FOR THE NEXT ARRIVAL
*** TO OCCUR

K=O (AND (K=0))
ATRIL(1)=CALL Y(1,1,1,1)
ATRIL(2)=O
CALL FILL (1,1,1,1)

*** SPECIAL ENTRY POINT FOR JOBS TO PRELAD
*** THE SHOP

ENTRY ARRIVAL (GSEP)

*** GENERATE THE NUMBER OF OPERATIONS FOR THE
*** JOB THAT JUST CAME IN

K=O (AND (K=0))
NOP=O (AND (NOP=0))
ATRIL(1)=O
ATRIL(2)=O
K=O (AND (K=0))
ATRIL(1)=O
ATRIL(2)=O

*** CHOOSE THE FIRST OPERATION OF THE JOB EVENTS
DO 10 J=1,IM
  XJ=J
  IF (R.GT.XJ/FLOAT(NJ)) GO TO 10
  R=DRAND(U,E)
  M=J
  ATRIB(11)=Y
  A1=TIME(R)
  CALL COLCT (A1,65,NSET)
  ATRIB(12)=A1*TIME(M)
  AKTM=ATRIB(12)*(8*CAPX(M))
  X(J)=X(J)+ATRIB(12)
  GO TO 20
10 CONTINUE

*** PICK EACH SUCCEEDING OPERATION ON THE ROUTE
*** ACCORDING TO THE JOB TRANSITION MATRIX

20 DO 60 I=2,NOP
  R=DRAND(U,E)
  DO 40 II=1,NJ
    IF (R.GT.X(I,II)) GO TO 40
    MAC=II
    IF (MAC.EQ.M) GO TO 30
    GO TO 50
  40 CONTINUE
  50 M=MAC
     R=DRAND(U,E)
     ATRIB(2*I+9)=MAC
     A1=TIME(R)
    CALL COLCT (A1,65,NSET)
     ATRIB(2*I+13)=A1*TIME(MAC)
     AKTM=AKTM+A1*TIME(MAC)*(8*CAPX(MAC))
60 ATRIB(MAC)=ATRIB(MAC)+ATRIB(2*I+10)

*** SET UP OTHER ATTRIBUTE VALUES

ATRIB(32)=U
MNEXT=ATRIB(11)+MNNN+1
ATRIB(9)=U
NNN=10+2*NOP
DO 70 I=12,NNN,2
70 ATRIB(I)=ATRIB(I)+ATRIB(I)
ATRIB(3)=TNOW
WORK=ATRIB(9)
ATRIB(4)=DUEL(AKTIM,1,DE)+TNOW
ATRIB(6)=ATRIB(4)-AKTM
IF (NRULE.LE.3) ATRIB(6)=ATRIB(5)
ATRIB(7)=ATRIB(6)/ATRIB(5)
*** GIVE THE NEW JOB A NUMBER AND MARK ITS LOCATION.
*** PROG LOOKS FOR FIRST JOB NO. WITH NO COLUMN LOC.

DO 60 I=1,200
L=LCCT(I)
IF (L.EQ.0) GO TO 90
60 CONTINUE
CALL ERROR (2,0,NSET)

A=1
IF (A.GT.MAX) MAX=I

*** MOVE THE JOB INTO THE SHOP

CALL PTJOB (1,NSET)
RETURN
END

SUBROUTINE CLEAR (NSET)

*** CLEAR THE STATISTICAL STORAGE AREAS
*** AFTER NRSET PERIODS

DIMENSION NSET(35,1)
COMMON ID,I,J,INIT,JEVI,T,XX,XX2,XXC,XXCLCT,
INHIST,NOG,repeat,PRINT,PROG,PRUN,PRUN,STAT,OUT,SCALE,
2 SEED,NOX,TEG,FIN,XX,PRINT,NOCT,REP,NOCLC(25),
3ΚΟΗ,ΚΟΞ,ΚΟΟ,ΑΤΡΙΟ(33),ΕΜΙ(25),ΗΜΙ(25),ΗΚΕΛΣ(22,32),
4ΚΤΑΧ(25),JCLR,MAXUC(25),NFE(25),NLG(25),NLG(25),
5 NCLLS(25),NG(25),PARC(40,4),ULG(25),SSUGA(20,3)
6 SUBIA(75,5),NAME(6),NPROC,10,11DAY'S,12,

COMMON PLEN,ATPOS,ATPOS,XX,XXS,XXY,XXZ,XXZ,XX,
1 TYPE,NEXT,REN,RLV,IIELD,AB(10),OB(10),XXM(10),13,
2 BUS(10),NRSET,FRULE,NOAX,STAT,ENDS,CHR,5,
3 XXM(10),SEED,ARATE,LOC(20),MAX,ARAT(11),

COMMON NPREL,NPREP,DESL,DESL,DESL,DESL,DESL,
1 LOC(10),DESCI,DESCI,DESCI,DESCI,DESCI,DESCI,DESCI,
2 RSTS,NDP0,MAP,SHOPLD(10)
IF (LCCT(I)) 44,45,16
10 DO 20 I=1,NCLCT
   DO 10 J=1,3
20 SUM(10)=.
   SUM(10)=1..L20
10 DO 70 I=1,.L.
40 IF (.NOT.A) 8,8,8,8
50 DO 70 I=1,.L.

\begin{verbatim}
SSUMAT(I,1)=TNOA
DO 60 J=2,3
60 SSUMAT(I,J)=0.0
SSUMAT(I,4)=1.0E20
70 SSUMAT(I,5)=-1.0E20
80 IF (NHIST) 110,110,90
90 DO 100 K=1,NHIST
   DO 100 L=1,XC
100 JCELS(K,L)=0
110 DO 120 I=1,NC,
   WBU(I)=0.0
   WBU(I)=0.0
120 WBU(I)=0.0
   DO 130 K=1,NG3,
   VNO(K)=0.0
   ENU(K)=0.0
130 MAXV(K)=NNO(K)
   NRST=9999999
   TBEG=TNOA
   NEN=0
   NLV=J
   RETURN
END

FOR IS SHOPLADING COLL
SUBROUTINE COLL (NSET)
C
C *** EVENT SUBROUTINE TO COLLECT STATISTICS AT
C *** THE END OF EVERY SCHEDULING PERIOD AND TO
C *** CALL THE LOADING ROUTINE
C
DIMENSION NSET(35,1),SCHLD2(15),SCLAD2(15)
COMMON 10,1,INIT,LEVAT,INIT,FAT,STOP,YX,4X,CCLC,1
NHIST,NG3,APRT,PHR,PRE,S,RHUN,REJS,STATS,SCALE,2
KSEL,TDH,TBEL,TFIN,XX,ARPT,TCOR,MEP,VXN(25),3
KLST,KL,ATRI(33),LAM(25),ISEC(25),JCELS(25,32),4
KAXK(25),JCLK,MAXK(25),VFE(25),LC(25),VLT(25),5
NG3S(25),AMT(25),PAD(4),TIE(25),SSUMA(25,5),6
JUM(75,5),JAM(0),NPCS,CLNY,XX
COMMON KLE1,KL0KJ,SHLD1,XXX,ARXSY,XXX,11
;NPSX,EXT1,EXT2,SHLD2(1),X2(15),X(15,15),2
BUS(12),IRRT,APLE,ORLST,ETST,ERSO,CLPL,L
2,AM2(10),SEL2,ARAT,LC(25),MAX(11)
COMMON KF1P,PREP,IFNLS,DLCL,CAP(10),DEL(10),10
JL(10),JDFSL,DFSL,SCLAD(15),XCPY,X,KS,TIEF(10),2
2NSTA,1NLDF,MAIN,SHOPLD(15)
\end{verbatim}
*** SCHEDULE THE NEXT DATA COLLECTION POINT

ATRIb(2) = 3.0
ATRIb(1) = TNO+k+PLEN
CALL FILEEX (1, NSET)
NTPDS = NTPDS + 1
ISCALE = SCALE + 0.00001
NTP = NTPDS - 1
TS = U.T
TOT = V.T

*** UPDATE TIME INTEGRATED STATISTICS ON MACHINES
*** AND COMPUTE STATISTICS ON FACILITY UTILIZATION
*** DURING THE PERIOD

AP = U.T
BP = 0.T
DO 10, 1 = 1, N:
CALL TAST (BUS(I), TNO, I, NSET)
UT = SSUMA(I, 3) / PLEN * 100.T
b(I) = b(I) / PLEN * 100.T
TS = TS + SSUMA(I, 3)
SSUMA(I, 3) = SSUMA(I, 3) * SSUMA(I, 3)
TOT = TOT + a(I)
AWW(I) = aWW(I) + SSUMA(I, 3) * SSUMA(I, 3)
10  SSUMA(I, 3) = 0.T
AP = AP + SSUMA(I, 3)
BP = BP + SSUMA(I, 3) * SSUMA(I, 3)
b(I) = 0.T
SSUMA(I, 3) = 0.T
AP = AP / FLOAT(NM)
BP = BP / FLOAT(NM)
rp = rP - AP ** 7
CALL COLCT (OP, 7, NSET)
CP = 0.T
DP = 0.T
NM1 = NM + 1
DO 12, 1 = 2, N-
11 = 1 - 1
XV = XN0(1)
XC = (EN(1) + XN0 * (TNO - CTIME(I)))
IF (TNO < LEQ0.01) XV(II) = 0.T
AVG = (XC - XAVL(II)) / PLEN.
CP = CP + AVG.
DP = DP + AVG ** 2
12  XAVL(II) = XC
CP = CP / FLOAT ( )
DP = DP / FLOAT ( )
DP = DP - CP * 2
CALL COLCT ( DP, 71, NSET )
ATS = TS / FLOAT ( )
ATOT = TOT / FLOAT ( )
CALL COLCT ( ATS, 14, NSET )
CALL HISTO ( ATS, J, 5..5, 3, NSET )
AT = ATOT
CALL HISTO ( AT, 6..6, 4, NSET )

C
C *** CHECK IF A JOB POOL IS BEING USED
C
R66 = NC ( 12 )
CALL COLCT ( R66, 66, NSET )
IF ( NLDR = 66 ) GO TO 39

C
C *** POOL IS BEING USED ** CALL SUBROUTINES TO LOAD THE
C *** SHOP
C
IF ( NL ( 12 ) = 0 ) GO TO 39
CALL GL ( MSLT )

C
C *** ADJUST AGGREGATE SHOP LOAD FOR EACH MACHINE AND
C *** QUEUE LOAD FOR PARTIALLY COMPLETED JOBS
C
39 R67 = NC ( 12 )
CALL COLCT ( R67, 67, NSET )
IF ( AT = 4 ) GO TO 40
IF ( NL ( 12 ) = 1 ) GO TO 40
J = 0
N1 = MFE ( 12 )
15 J = J + 1
NFRST = FLOAT ( NSET ( 11, N1 ) ) / SCALE + 0.001
IF ( BUSE ( NFRST ) ) 25, 25, 25
20 N1 = NSET ( X, N1 )
IF ( N1 N1 = 7777 ) GO TO 15
GO TO 40
25 N2 = NSET ( X, N1 )
CALL RMOV ( N2, 12, NSET )
CALL COLCT ( J, 65, NSET )
NEX = AT + AT ( 11 ) + 0.001
CALL PTOJ ( 2, NSET )
N1 = N2
IF ( 11 = 7777 ) GO TO 15
40 N1 = MFE ( 1 )
45 IF ( AT = 2 1 ) / SCALE + 1..2 ) GO TO 60
T1 = T1 + AT ( 11, 1 ) / SCALE + 0.01
T1 = FLOAT ( NSET ( 11, N1 ) ) / SCALE + 1.11
SCPLU2('1') = SMCPLU('1') + (TILEFT*CAP('1'))/B.5
LOAD2('1') = CLADL('1') + (TILEFT*CAP('1'))/B.5

60 IF (I1.N.E.1777) GO TO 45

*** CALCULATE DEVIATIONS FROM BALANCE

DBALD = 0.0
DO 75 J=1,N
DBALD = D30(J) - SCPLD2(J)
D53 = J + 3
DBALD = DBALD + D53
CALL COLCT (D30, 53, NSET)
D30AB = AB5(D30)
75 DBALD = DBALD + D53
CALL COLCT (DBALD, 53, NSET)

*** CALCULATE ADDITIONAL DEVIATIONS FROM BALANCE

IF (H.E.777) GO TO 45

CALL ENSIM (NSET)
RETURN
END
SUBROUTINE DYNAM (MDEST, NSET)

*** SUBROUTINE USED WITH DYNAMIC SLAC.

*** DISPATCHING RULES

DIMENSION NSET(35,1)

COMMON ID, INIT, JEVNT, JCVNT, NFA, NST, MX, YY, C, CLC, INT, NIP, NCPRT, NOP, NCF, NCFN, NSTAT, UNT, SCALE,
2, SEED, TOP, TEG, TFX, XX, NPRT, NCDF, NCR, X, Y, YW, E, YW, (25),
3, KOF, KLE, KAT, DTR, (33), END, (25), 1*/ (25), JCEL5 (20, 32),
4, KRA(25), JCLK, XA, X(E, 25), XL (25), XLE (25),
5, XCEL5 (20), XG (25), PARA (4, 4), TITM (25), SSSA, (12, 5),
6, SPM (75, 5), NAVE (6), NPX, XPD, XDAY, YX

COMMON FLE, TPUS, STOTPD, IX, SYS, XX, SY, XE,
1, TYPE, NEXT, MEM, RELV, HELD, (10), N (10) * X (10), 10,
2, BUS (10), NSET, RULE, NOWN, NEST, NDEC, NKL, 11,
3, NEX (10), SELD, ARATE, LCC (20), XAX, X (10),
4, COMMON NPREL, P'REP, NSEL, NUL, CAPA, (10), DES (10),
5, DGL (10), DSLF, DLF, SLOA (10), XOPS, XXKs, TIEF (10),
6, NSTD, NLD, MRR, SHOPLD (10),

XX=1, XE+20

X1=XOW+1

MEXIT=0

MXT= "FE" (VAL)

IF (MXT) 1, 10, 2

1 CALL ERROR (201, NSET)

2 IF = NSET (4, NXT) - NSET (5, NMT)

DS = DIF / SCALE - THU.

DS = DS / (FLOAT (NSET (5, NMT)) / SCALE)

NSET (7, MXD) = DS * SCALE + .0001

IF (RULE.EQ.2) GO TO 3.

IF (DS.LT.XY) MEXIT = "XT

IF (DS.LT.XX) XX = DS

GO TO 4.

3 IF (DS.LT.XY) MEXIT = "XT

IF (DS.LT.XY) XY = DS

GO TO 4.

4 IF (MXT = "SET" (XY, NMT))

IF (NMT - 7777) 3, 6, 5

5 RETURN

END
SUBROUTINE ENDSV (NSET)

*** EVENT SUBROUTINE CALLED WHEN AN END OF SERVICE HAS OCCURRED FOR A JOB OPERATION

DIMENSION NSET(35,1)
COMMON ID, INIT, JEVT, JINIT, TFA, TSTOP, MX, YMC, NCLCT,
1INHIST, NW, IEND, JRT, NPRINT, KRUN, MSR, NSTOUT, SCAL,
2ISEED, NOV, TEG, TM, VX, XPRNT, MCR, MORE, VP, VH(25),
3KOF, KLE, KCL, ATRI(33), ENS(25), IIN(25), JCELS(25,32),
4KANK(25), JCLR, MAXY(25), APL(25), LCL(25), VLE(25),
5 NCELS(25), NL(25), PARA(40,4,1), TIME(25), SSUMA(25,5),
6, SUMA(75,5), NAME(6), MPRT, MINT, DAY, CYK,
COMMON PLEN, TPOD, TLOT, XYS, XY, KSY, TOU,
1IT, TYPE, MNEXT, TENV, VM, INHOLD, T3(10), HM4(10), X(10,10),
2BUS(10), NSET, MRRU, XMD, IRT, XENDS, INOL, XRL,
3WWW(10), SELD, RATE, LOC(25,5), MAX, AR(11),
COMMON NPREL, MPRT, MPRTD, MDEL, CDEL, CAP(10), ESL(10),
1DQL(10), DESL, DSEL, SEL, SLOAD(10), XOPS, XYS, TIMEF(10),
2NSTSW, XLP, NARR, SHOPLO(10),
COMMON A(25,100), KEO(35), C(100), FACOD,
COMMON ICOUNT, JCOUNT, SINDEX, MSE(10), AVGLD9
AADD=ATRI(11)+CJUSCIC1
MNEXT=ATRI(13)+AADD+1
CALL TAST (XOPS, TOUT, 13, NSET)
XOPS=XOPS+1
CALL TAST (XKYS, TOUT, 14, NSET)
XKYS=XKYS+ATRI(12)
ATRI(32)=ATRI(32)+ATRI(12)
ATRI(5)=ATRI(5)+1
IF (ATRI(5)) 10, 10, 6

*** COLLECT STATISTICS ON THE JOB LEAVING THE SYSTEM

TISYS=TNOV-ATRI(3)
CALL COLCT (TISYS, 11, NSET)
NOP=ATRI(10)+AADD
NP23=NOP+22
CALL COLCT (TISYS, NP23, 12, NSET)
XISYS=XISYS-1
CALL TAST (XKYS, TOUT, 11, NSET)
XKYS=XKYS+ATRI(9)
ADD=ATRI(TNOV-ATRI(4))
CALL COLCT (ADD, 13, NSET)
TLATE=TNOV-ATRI(+)
CALL COLCT (TLATE, 12, NSET)
CALL HISTO (TLATE-1, 20, 1, NSET)
TARDY = TLATE
IF (TLATE.LT.0.0) TARDY = 0.0
CALL COLCT (TARDY, 13, NSET)
TSYNPL = TSYNPL - ATRIB(33)
CALL COLCT (TSYNPL, 42, NSET)
NP40 = NP + 39
CALL COLCT (TSYNPL, NP40, NSET)
TIPool = ATRIB(33) - ATRIB(3)
CALL COLCT (TIPool, 48, NSET)
PERPOL = TIPool / PLEN + 0.5
NPEPOL = PERPOL
CALL COLCT (NPEPOL, NP40, NSET)
NP46 = NP + 45
CALL COLCT (TIPool, NP46, NSET)
D = FLOAT(NTPCS - 1) * PLEN
O DUE = ATRIB(4)
IF (O DUE.LT.0) GO TO 30
IF (O DUE.LT.TNOA) GO TO 20
LP = (TNCW - O DUE / PLEN) - 9999999
GO TO 40
20 LP = 0
GO TO 40
30 LP = (O - O DUE) / PLEN + 9999999
40 XP = LP
CALL HISTO (XP, -10, 9, 1, 16, NSET)
XOPS = XOPS - ATRIB(10)
XWKS = XWKS - ATRIB(9)
NLV = NLV + 1
JOB = ATRIB(3) + 101
LOC(JOB) = 0
IF (JOB .NE. MAX) GO TO 50
50 MAX = MAX + 1
JOB = JOB - 1
IF (LOC(JOB) .LE. 0) GO TO 50
GO TO 80
C
C *** THE JOB IS NOT LEAVING THE SYSTEM
C *** UPDATE THE JOB ATTRIBUTES
C
60 IF (NRULE.LT.3) ATRIB(5) = ATRIB(5) - ATRIB(12)
LR = ATRIB(5) + 101
LR = 2 * LR + 9
DO 70 I = 11, LR + 2
ATRIB(I) = ATRIB(I + 2)
70 ATRIB(I + 1) = ATRIB(I + 3)
ATRIB(LR + 2) = ...
ATRIB(LR + 3) = ...
CALL PTJOB (2, NSET)
*** Check machine queue for any jobs available for processing

IF (NO(MNO*1)) 90, 90, 160

*** There are no jobs in the queue

CALL TST (BUS(MNO*1), THO(MNO*1), NSET)
BUS(MNO*) = J
IF (MS(2) .LE. 0) GO TO 93
IF (NLDR .GE. 0) GO TO 93
CALL COLCT (1*1, 68*1, NSET)
IF (NO(12) .LT. 1) GO TO 93
IF (MS(3) .GE. 0) GO TO 88
IF (SSUMA(MNO*3) .GE. AVGLD9) GO TO 93

*** Try to move job from pool to empty machine

J = 0
N1 = MFE(12)
J = J + 1
NFIRST = FLOAT(NSET(11, N1)) / SCALE + .001
IF (NFIRST .EQ. MNO*1) GO TO 92
N1 = NSET(MX, N1)
IF (N1 .NE. 7777) GO TO 91

*** No job was found that could help idle machine

GO TO 93

*** Put job from pool in idle machine

CALL RMOVE (N1, 12*1, NSET)
CALL COLCT (1*1, 69*1, NSET)
MNEXT = ATRIO(11) + .0001
CALL PTOB (3*1, NSET)
RETURN

*** More than one job is available. Compute
*** priorities and bring in the job with the
*** highest priority from the queue.

160 N1 = NOX + 1
IF (NRULE*1 .EQ. 1) GO TO 120
IF (NRULE .EQ. 0 .AND. NRULE .GT. 3) GO TO 120
IF (NRULE .GT. 2) GO TO 110
CALL DYNAT (BEST*1, NSET)
CALL RMOVE (BEST*1, NSET)
GO TO 130
110 CALL AWING (NSET,NSET)
   IF (MSET.EQ.0) GO TO 120
   CALL RMOVE (MBLI,MN1,NSET)
   GO TO 130
120 CALL RMOVE (MFE (MN1),MN1,NSET)
C
   *** COMPUTE THE WAITING TIME FOR THE JOB AND
   *** DECREASE THE WORKLOAD IN THE MACHINE QUEUE.
C
   130 ..T=TNOW-ATRIB(8)
   MN15=MNOW+15
   CALL COLCT (.T,MN15,NSET)
   QLOAD (MNOW)=QLOAD (MNOW)-ATRIB(12)
   SHOPLD (MNOW)=SHOPLD (MNOW)-ATRIB(12)
   TIMEVT=ATRIB(12) *(8.-/CAP/(MN1))
   ATRIB(1)=TNOW+TIMEVT
   ATRIB(2)=1.0
   JOB=ATRIB(30)+.001
   LOC (JOB)=MFA
   CALL FILEM(1,NSET)
   RETURN
END

-FOR IS SHOPLOADING-ENSIM
SUBROUTINE ENSIM (NSET)
C
   *** SUBROUTINE USED TO PRINT SIMULATION RESULTS
C
   DIMENSION NSET (35,1)
   COMMON ID , IR, INIT, IENV, JANIT, MFA, NSTOP, MX, XC, NCLET, 1
   INHIST, NOG, NORT, NNPRT, NRUNS, NSTAT, OUT, SCAL,
   2ISEED, INOA, IBEG, IFIN, XXX, NPRNT, NCRDR, NEN, NCI (25),
   3KOF, KLE, KCL, ATRIB(33), ENJ(25), INJ(25), JCELS(25,32), 4
   4KANK(25), JCLK, MAXMN(25), MFE(25), "LC(25), "LE(25),
   5 NCELS(25), NL(25), PARAM(40,4), TIME(25), SUMA(20,5)
   6 SUMA(75,5), NAME(6), NPROJ, NDAY, NVR
   COMMON PLEN, IPTOS, NTOTPO, NXL, LYS, XRSY, IDEL,
   11 TYPE, NEXXT, REN, AVL, VHLD, JBL(10), "BL(10), "X(10),10,
   2 BUS(10), ARSET, ARULE, RACK, ARST, REUS, RCHL, KAL,
   3 RAX(10), SEED, ARATE, LOC(200), MAX, ART(11)
   COMMON NPREL, NPREP, NDES, NDL, NEN, CAP"(10), DESL(10),
   10 DL(10), DESL, UMLE, QLOAD(10), XCP, YX, KS, TIMEF(10),
   2NST, SLD, NSM, SHOPLD(10)
   COMMON A(25,100), KBV(15), C(100), FACMOD
   COMMON ICOUNT, INCOUNT, SINPER, NSY(10), AVGLOD
   PRINT 160, NLDR, NRULE
CALL T MST (XKSY, TNOW, 11, NSET)
CALL T MST (XSYS, TNOW, 12, NSET)
CALL T MST (XOPS, TNOW, 13, NSET)
CALL T MST (XK5, TNOW, 14, NSET)
DO 10 I = 1, NM
10 CALL T MST (BUS(I), TNOW, 1, NSET)
NTPDS = NTPDS - NRSET
NNTP = NNTP - NRSET
WRITE (6, 170) NM, NRSET, NNTP, PLEN
WRITE (6, 171) MSW(J), J = 1, 10
IF MSW(5) > J GO TO 13
WRITE (6, 172)
XN = NTPDS
DO 12 I = 1, NM
J30 = 30 + I
XM1 = SUMA(J30, 1)/FLOAT(NTPDS)
J53 = 53 + I
XM2 = SUMA(J53, 1)/FLOAT(NTPDS)
12 WRITE (6, 173) I, XM1, XM2
13 CONTINUE
XM3 = SUMA(41, 1)
XM4 = SUMA(64, 1)
X3 = SUMA(41, 3)
X4 = SUMA(64, 3)
XS3 = SUMA(41, 2)
XS4 = SUMA(64, 2)
AVG3 = XM3/XN3
AVG4 = XM4/XN4
VAR3 = (((XN3*XS3) - (XM3*XM3))/(XN3*(XN3-1.0)))
VAR4 = (((XN4*XS4) - (XM4*XM4))/(XN4*(XN4-1.0)))
WRITE (6, 174)
WRITE (6, 175) AVG3, VAR3
WRITE (6, 176)
WRITE (6, 175) AVG4, VAR4
J = 11
DO 16 I = 1, 3
X5 = SUMA(J, 1)
XS5 = SUMA(J, 2)
X5 = SUMA(J, 3)
AVG5 = X5/15
VAR5 = (((X5*XS5) - (X5*X5))/(X5*(XN3-1.0)))
IF (1ST = 1) GO TO 14
WRITE (6, 177)
J = 48
GO TO 16
14 IF (1ST = 2) GO TO 15
WRITE (6, 176)
J = 42
GO TO 16
15 WRITE (6,179)
16 WRITE (6,175) AVG5,VAR5
   XM7=SUMA(66,1)
   XM7=SUMA(66,3)
   XM7=SUMA(66,2)
   AVG7=XM7/XM7
   VAR7=(((XM7*XM7)-(XM7*XN7))/((XM7*(XM7 1.0))))
   STD=SQRT(ABS(VAR7))
   WRITE (6,185) AVG7,STD
   XN7=SUMA(67,1)
   XN7=SUMA(67,3)
   XN7=SUMA(67,2)
   AVG7=XN7/XN7
   VAR7=(((XN7*XN7)-(XN7*XN7))/((XN7*(XN7 1.0))))
   STD=SQRT(ABS(VAR7))
   WRITE (6,186) AVG7,STD
   IF MSW(5) .GT. 0 GO TO 17
   WRITE (6,187)
17 CONTINUE
   XM=NTPDS
   DO 20 I=1,N
      AB=SUMA(I,1)/FLOAT(NTPDS)
      WW(I)=(AB/1)/FLOAT(NTPDS)
      WB(I)=(WBM(I)*XN-SUMA(I,2)*2)/(XN-(XN-1.0))
      IF MSW(5) .GT. 0 GO TO 20
      WRITE (6,197) I,AB,OBN(I)
20 CONTINUE
   TT=SUMA(1,1)
   TT=SUMA(1,2)
   TT=SUMA(1,3)
   AVG=XS/XT
   VAR=(((XN*XS)-(XS-XS))/(XN 1.0))
   IF (I.EQ.12) PRINT 21,, AVG,G,VAR
   IF (I.EQ.13) PRINT 22,, AVG,G,VAR
   IF (I.EQ.14) PRINT 23,, AVG
40 CONTINUE
   DO 50 I=1,14
      XT=SUMA(I,1)-TDBG
      XS=SUMA(I,2)
      XSS=SUMA(I,3)
      AVGX=XS/XT
      STD=(XS/XT-AVGX*AUX)
STD = SIGN SQRT (ABS (STD)) * STD
IF (I.EQ.11) PRINT 240, AVGG, STD
IF (I.EQ.12) PRINT 250, AVGG, STD
IF (I.EQ.13) PRINT 252, AVGG, STD
IF (I.EQ.14) PRINT 254, AVGG, STD
50 CONTINUE
TIME = FLOAT (NTPDS) * MLE
PRINT 260, NTPDS, TIME
IF MSW (5) .GT. 0) GO TO 51
PRINT 270, (I, WWW (I), I = 1, NM)
51 CONTINUE
WRITE (6, 361)
WRITE (6, 362)
WRITE (6, 363)
QWB = 0
MAXQ = 0
XX = 0
NM1 = NM + 1
DO 53 I = 2, NM1
XNQ = NQ (I)
XE = (ENQ (I) + XNQ * (NOW - QTIME (I)) / (NOW - TBEG))
VARE = ((VNQ (I) + XNQ * XNQ * (NOW - QTIME (I)) / (NOW - TBEG)) - XF * XE)
IF (MAXNQ (I) .GT. MAXQ) MAXQ = MAXNQ (I)
IF MSW (5) .GT. 0) GO TO 52
11 = I - 1
WRITE (6, 364) I 1, XE, VARE, MAXNQ (I)
52 CONTINUE
XX = XX + XE
QWB = QWB + VARE
XX = XX / FLOAT (NM)
QWB = QWB / FLOAT (NM)
WRITE (6, 365) XX, QWB, MAXQ
PWB = SUMA (70, 1) / SUMA (70, 3)
WRITE (6, 367) PWB
PQB = SUMA (71, 1) / SUMA (71, 3)
WRITE (6, 368) PQB
IF NRUN .GT. 1) GO TO 69
IF MSW (5) .GT. 0) GO TO 69
PRINT 280
DO 60 I = 1, NM
WRITE (6, 290) (X (I, J), J = 1, NM)
WRITE (6, 300)
WRITE (6, 310) IDOL, ITYPE, 5F EE, IS-ED, NLDR
WRITE (6, 320) RRATE
WRITE (6, 321) RRATL
XN6 = SUMA (65, 3)
AVG6 = X6 / XN6
C *** SET UP FOR NEXT RUN. CHANGE DISPATCHING RULE.
C *** INITIALIZE STATUS VARIABLES.

NRULE = NRULE + 1

*** IT IS DESIRED TO SKIP RULE 5 (DUE DATE)
IF (NRULE.GE.5) NRULE = 6
IF (NRULE.LE.4) GO TO 120
IF (NRULE.GT.5) GO TO 80

DO 70 I = 2, 11
   KRAK(I) = A
   GO TO 120
C 70 IF (NRULE.GT.6) GO TO 150

DO 90 I = 2, 11
   KRAK(I) = B
   GO TO 120

120 CONTINUE

DO 130 I = 1, NM
   PAK(I) = 0.0
   NAK(I) = 0.0
   BAK(I) = 0.0
   WAK(I) = 0.0
   DAK(I) = 0.0
   SFOPL(I) = 0.0

130   LOAD(I) = 0.0
   MAX = 0
   DO 140 I = 1, 2, 6

140   LOAD(I) = 0
   AR(I) = 0.0
   CPR = 0.0
   XFR = 0.0
   ASY = 0.0
   ASY = 0.0
VARIOUS APPROACHES FOR JOB SHOP LOAD
1.37 SCHEDULING USING DIFFERENT DISPATCHING RULES.
2.21 SCHEDULING APPROACH NUMBER 15, 24 X 15, 10.
4.9 THE NUMBER 14/11.
1.6 BALANCE, 21X, 14-AGGREGATE LOAD, 14X, 1 QUEUE LOAD.
1.7 FORMAT (5X, 16, 10X, 34X, F12.3).
1.8 FORMAT (5X, 37, DEVIATION FROM BALANCE, AGGREGATE LOAD).
1.9 FORMAT (5X, 5, 7, AVERAGE, 2X, F10.3, VARIANCE, 5X, F10.3).
1.10 FORMAT (5X, 33, DEVIATION FROM BALANCE, QUEUE LOAD).
1.11 FORMAT (5X, 24, TIME SPENT IN THE SYSTEM).
1.12 FORMAT (5X, 26, TIME SPENT IN THE JOB POOL).
1.13 FORMAT (5X, 38, TIME SPENT IN THE SYSTEM).
1.15 FORMAT (1X, 37, HOURS IN THE SHOP).
1.16 FORMAT (5X, 16, 10X, 34X, F12.3).
1.17 FORMAT (1X, 45, HOURS IN THE SHOP).
1.18 FORMAT (1H, 5X, 16, SPECIAL FEATURES).
1.19 FORMAT (1H, 7X, 7, MACHINE, 16, UTILIZATION BALANCE MEASURE).
1.20 FORMAT (1H, 37, HOURS IN THE POOL BEFORE LOADING AVG =, F7.2).
1.21 FORMAT (1H, 37, HOURS IN THE POOL AFTER LOADING AVG =, F7.2).
1.22 FORMAT (5X, 16, F12.3, F14.3).
1.23 FORMAT (1H, 10X, 25, MACHINE BALANCE MEASURE =, F12.3).
1.24 FORMAT (1H, 22, HOURS BALANCE MEASURE =, F12.3).
1.25 FORMAT (23, NUMBER OF JOBS ENTERING SHOP =, 17, 10X).
1.26 FORMAT (32, NUMBER OF JOBS LEAVING SHOP =, 17).
1.27 FORMAT (1X, 29, AVERAGE JOB LATENESS =, 10X, 2).
1.28 FORMAT (1X, 23, AVERAGE JOB COMPLETION VARIANCE =, 10X, 2).
1.29 FORMAT (5X, 28, AVERAGE JOB COMPLETION VARIANCE =, 10X, 2).
1.30 FORMAT (1X, 28, AVERAGE SHOP UTILIZATION =, F12.3).
1.31 FORMAT (1X, 34, AVERAGE JOB LATENESS =, 10X, 2).
1.32 FORMAT (1X, 28, AVERAGE JOB COMPLETION VARIANCE =, 10X, 2).
1.33 FORMAT (1X, 34, AVERAGE JOB LATENESS =, 10X, 2).
1.34 FORMAT (1X, 29, LENGTH OF SIMULATION RUN WAS =, 10X).
-FOR J W SHOPLOADING.EVNTS

SUBROUTINE EVNTS (IX,NSET)

C
C *** DIRECTS THE PROGRAM TO THE
C *** PROPER EVENT SUBROUTINE
C
DIMENSION NSET(35,1)
COMMON ID,IF,JN_IT,JEVT,JUNIT,IFU,STOP,XX,XXM,NCCLT,
1 HIST,NO,NOT,INPS,TRN,FLS,STAT,OUT,SCALE,
2 SEED,IND,TSBS,THIN,XX,APRNT,ACB,LD,WNLXI (25),
3KOF,KLE,KLX,ALRI (33),ERQ (25),MAJ (25),SCLS (25,32),
SUBROUTINE GENMAT (NSET)

C *** THIS SUBROUTINE PLACES THE PARAMETERS FOR THE JOBS
C *** IN THE JOB POOL IN THE FORM REQUIRED BY LP
C
DIMENSION ASET(35,1),JUDEP(5,J),KPOP(10,7,J),RAUX(5)
COMMON ID,IP,JINIT,JENV,JUNIT,FH,STOP,AX,WC,,NCLCT,
1,HIST,ACCD,SCRPT,NAT,APRS,KRUN,KRJS,STAT,OUT,SCALE,
2,SEED,IND,TOLE,TFIN,MAX,XPRAT,KCMDR,REP,VECH(25),
3,KOF,KLE,KEL,ATRIL(33),END(25),INN(25),JCELS(25,32),
4,KANK(25),JCLR,MAX(25),SFE(25),MLE(25),LE(25),
5,JCELS(25),ACT(25),PARAM(4,4),TIME(25),SSTM(25,5),
6,SUAM(75,5),NARE(6),APROJ,MONDAY,TYR
COMMON PLEN,TPOS,TPTR,MAX,TSYS,XKEY,IDPE,
1,ITYPE,NEXT,LEN,LEV,TEL(10),V(10),X(10,10),
2,BOU(1),INSET,KRULE,CMY,AST,NTD,NTD,MLC,,MLE,
3,SELM(10),SELD,SMART,LOC(200),MAX,MA(11)
COMMON INP,APEL,APRP,GENL,EL,CAP(10),JEL(10),
1,DESL(10),DESF,DELF,LOAD(10),XCPD,XKST,TIMEF(10),
2,STX,NDAY,WAR,SHOPLO(10)
COMMON A(25,100),KEY(15),C(100),FAC900

CALL ENDSV (NSET)
RETURN

CALL ARRVL (NSET)
RETURN

CALL COLL (NSET)
RETURN

CALL START (NSET)
RETURN

END

FOR IS SHOPLOADING...GENMAT

** Obtain list of jobs in pool and initialize matrices
NPCOL=NJ(12)
NROA=25
NCOL=66
NROA=N4
NCOL=NPOOL+2*NM
INDEX=J
DO 3 I=1,5
3 KUX(I)=J
DO 1 I=1,NM
DO 1 J=1,NPOOL
WOP(I,J)=0.0
1 CONTINUE
DO 2 I=1,NM
DO 2 J=1,NCOL
2 A(I,J)=0.0
J=J
N1=MFE(12)

*** OBTAIN LP MATRIX ENTRIES FOR EACH JOB

DO 30 J=1,NP00L
WOP=0.0
NO1=FLOAT(NSET(1,J,N1))/SCALE+0.00001
DO 35 I=1,NO1
NON1=9+2*I
NON2=FLOAT(NSET(NON1+1,I))/SCALE+0.00001
NON3=NON1+1
WOL=FLOAT(NSET(NON1+1,J))/SCALE
AT(NON2,J)=WOL
AKT1M=AKT1M+WOL*(8.0/CAP(1,NON2))
35 CONTINUE

*** OBTAIN NEXT JOB IN THE POOL, IF THERE IS ANY

N1=NSET(4,J,N1)
IF (N1.NE.7777) GO TO 30

*** SET UP MATRICES REQUIRED BY LPI

IF (NLDR.NE.2.OR.NLDR.NE.3) GO TO 35
IF (N1.NE.11) GO TO 35
WOP=FLOAT(NSET(4,J,N1))/SCALE+0.00001
ARK=FLOAT(NSET(9,J,N1))/SCALE+0.00001
DUDSLK=TIMDUE-TNDW-AKT1M
IF (DUDSLK.LE.0.0) DUDSLK=0.0
DUFT(J)=FACDUD/(DUDSLK+0.1)
DO 51 I=1,NGROW
DO 52 J=1,NOCOL
IF (J.LE.(NPGOL+I)) A(I,J)=1.
IF (J.EQ.(NPGOL+NM+I)) A(I,J)=-1.
52 CONTINUE
A(I,NOCOL+1)=DESL(I)-SHOPLD(I)
AA=A(I,NOCOL+1)
OBJIN=OBJIN+ABS(AA)
KBV(I)=NPOOL+I
IF (AA.GE.0.0) GO TO 51
A(I,NOCOL+1)=-AA
KBV(I)=NPOOL+NM+I
DO 54 J=1,NOCOL
54 A(I,J)=-A(I,J)
51 CONTINUE
GO TO 71
C
C *** MATRIX PREPARATION WHEN NEXT QUEUE RULE IS USED
C
60 DO 61 I=1,NGROW
DO 62 J=1,NOCOL
IF (J.LE. NPGCL) A(I,J)=OPU(J)
IF (J.EQ.(NPGCL+I)) A(I,J)=1.
IF (J.EQ.(NPGCL+NM+I)) A(I,J)=-1.
62 CONTINUE
A(I,NOCOL+1)=UGL(I)-QLOAD(I)
AA=A(I,NOCOL+1)
OBJIN=OBJIN+ABS(AA)
KBV(I)=NPOOL+I
IF (AA.GE.0.0) GO TO 61
A(I,NOCOL+1)=-AA
KBV(I)=NPGCL+NM+I
DO 64 J=1,NOCOL
64 A(I,J)=-A(I,J)
61 CONTINUE
GO TO 71
C(NOCOL+1)=-OBJIN
A(NOROW+1,NOCOL+1)=0.0
DO 76 J=1,NOCOL
C(J)=0.0
IF (J.GT.NPOCL) GO TO 77
C(J)=-DUDFT(J)
A(NOROW+1,J)=1.0
A(NOROW+2,J)=1.0
GO TO 76
77 C(J)=1.0
A(NOROW+1,J)=-1.0
A(NOROW+2,J)=1.0
76 CONTINUE
C(NOCOL+1)=-OBJIN
A(NOROW+1,NOCOL+1)=0.0
A(NOROW+2,NOCOL+1) = 0.0
DO 88 I=1,NOROW
  DO 88 J=1,NOCOL
    C(I,J) = C(J) - A(I,J)
    CONTINUE
  IF (NLDR.GE.4) GO TO 91
  CALL LP1 (NSET,NOROW,NOCOL,NROW,NCOL,INDEX,AUX)
  GO TO 92
91 CALL POOLHE (NSET,NOROW,NOCOL)
92 RETURN
END

-FOR IS SHOPLOADING

FUNCTION GNARV(RNUM)
C *** COMPUTES TIME FOR THE NEXT JOB ARRIVAL
COMMON ID,IP,INIT,JEVT,NUMIT,PA,STOP,MX,XC,CLCT,
1 INHIST,NSCH,NCAPK,NOT,NSHS,NNUS,NSST,OUT,SCALE,
2 ISEED,TKDG,TSEG,TFIN,XXX,SNPRN,NSNR,NSST,OUT,SCALE,
3 KUF,KLE,KOL,ATRD(33),ENQ(25),IRN(25),JCELS(20,32),
4 XHAK(25),JCLR,HAXG(25),HFE(25),HLC(25),YLE(25),
5 JCELS(20),NC(25),PARAK(40,4),TIME(25),SUMA(20,5).
6, SUMA(75,5), NAME(6), NPREL, NPREP, NDESR, NDWL,
7 COMMON PLEN, ATPTS, NTPDS, NNT0T, XSYS, XSYS, IDUE,
8 ITYPE, INEXT, RNEN, XNLV, SHLD, XE(10), XB(10), X(10,10),
9 BUS(10), NSET, NRULE, XG, KRST, ENDS, NGCL, VL,
10 XDB(10), SEED, ARATE, LOC(20), MAX, ART(11),
11 COMMON NPREL, NPREP, NDES, NDML, CAP(110), DESL(10),
12 NQL(10), DESL, VAL, GLOAD(10), XOPS, XKS, TIMEF(10),
13 NST(10), SL, NSTD, SHLR, SHPL(10),
14 COMMON A(25,10), X3V(15), C(10,10), FACODU,
15 COMMON ICOUNT, NCOUNT, SPIPER
IF (NARR.GT.1) GO TO 10
GNARV = -T•0/ARATE*ALOG(RNUM)
IF (GNARV.GT.40.0) GNARV = 40.0
GO TO 20
10 IF (ICOUNT.LE.5) GO TO 15
  ICOUNT = 0
15 ICOUNT = ICOUNT + 1
  AI = -1.0/ARATE*ALOG(RNUM)
  AZ = (6.28*ICOUNT)/S•PI•EK
  IF (AI.GT.49.0) AI = 49.0
  S = SIN(A2)
  GNARV = AI*(1.0+S53)
20 RETURN
END
**FOR SHOPLOADING.JOBDEC**

**SUBROUTINE JOBDEC (INSET, NROA, NOCOL)**

**C**

*** THIS SUBROUTINE USES THE LP RESULTS TO MAKE THE
*** FINAL SELECTION REGARDING THE JOBS THAT SHOULD
*** BE LOADED IN THE SHOP

**C**

DIMENSION NSET(35,1), XJOB(100)

COMMON IDC, INC, JDIR, JUNIT, JUNIT, "FA", "STOP", "X", "XC", "XCLC.

INHIST, NrO, NRPT, R, NFRS, NCDRNS, NSTAT, JOUT, SCLL.


3KOF, KLC, KCL, KATR, IACD(33), "EN"(25), "IN"(25), "JCPPS"(25,32),


5 JCELS(20), "A"(25), "PARA"(40,4), "TIME"(25), SSUMA(25,5).

6, SUMA(75,5), NAME(6), NPROJ, NCRN, NDAY, NVR.

COMMON PRED, NTPDS, NTO, NTD, NS, XSYS, XSY, IDUE,


3WAA(10), "SEED", "ARATE", LOC(200), MAX, "AR"(11).

COMMON NPRED, NPREL, NRED, NRED, NRED, NRED, NRED, NRED, NRED,


2NLDS, NS, "NDS", "NDS", "NDS", "NDS", "NDS", "NDS", "NDS", "NDS",

COMMON A(25,100), KBV(15), C(150), FACDUD

NPOOL = NR(12)

DO 1 J=1, NPROJ

XJOB(J) = 0.0

AA1 = A(NR0 + 2, J) - 0.01

IA = I IF (AA1)

1 IF (IA .EQ. -1) XJOB(J) = 1.0

IF (NLDR .GE. 4) GO TO 20

DO 2 I=1, NHR

JJ = KBV(I)

XJOB(JJ) = A(I, NROA+1)

2 CONTINUE

*** VARIABLES IN BASIS AND WITH UPPER BOUND INDICATOR
*** DO NOT NEED TO BE CALCULATED DIFFERENTLY

AA1 = A(NR0 + 2, JJ) - 0.01

IA = I IF (AA1)

IF (IA .NE. -1) GO TO 2

XJOB(JJ) = A(NR0 + 1, JJ) - A(I, NROA+1)

2 CONTINUE

*** SEARCH JOB POOL FILE AND LOAD IN THE SHOP THOSE
*** JOBS WITH DECISION VARIABLE .GE. .75

J=.0

N1 = !EF(12)

WKSHP1 =.0
TDES1=0.0
DO 25 I=1,NM
TDES1=TDES1+DFSL(I)
25 WKSHP1=WKSHP1+SHOPL(I)
J=J+1
XJBN=XJOB(J)
IF (XJBN.LT.0.75) GO TO 40
N2=NSET(MX,N1)
CALL RMOVE(N1,12,NSET)
WKSHP1=WKSHP1+ATRIB(9)
MNEXT=ATRIB(11)+.0001
CALL PTJOB(3,NSET)
N1=N2
GO TO 41
40 N1=NSET(MX,N1)
41 CONTINUE
IF (N1.NE.7777) GO TO 30
C
C *** SEARCH JOB POOL FILE AND LOAD JOBS WITH DECISION
C *** VARIABLES BETWEEN 0.3 AND 0.75 IF TOTAL SHOP LOAD
C *** IS LESS THAN DESIRED
C
J=0
IF (NO(12).EQ.0) GO TO 70
N1=MFE(12)
50 IF (WKSHP1.GE.TDES1) GO TO 70
J=J+1
IF (J.GT.NPOOL) GO TO 70
XJBN=XJOB(J)
IF (XJBN.GE.0.75) GO TO 55
IF (XJBN.LT.0.3) GO TO 65
N2=NSET(MX,N1)
CALL RMOVE(N1,12,NSET)
WKSHP1=WKSHP1+ATRIB(9)
MNEXT=ATRIB(11)+.0001
CALL PTJOB(3,NSET)
N1=N2
GO TO 66
65 N1=NSET(MX,N1)
66 CONTINUE
IF (N1.NE.7777) GO TO 50
70 CONTINUE
RETURN
END
SUBROUTINE LPI (NSET, NOK, NUCOL, NOKN, MCOL, INDEX, KAX)

*** THIS SUBROUTINE CALCULATES DECISION VARIABLES USED
*** FOR LOADING JOBS INTO THE SH.

DIMENSION NSET(35,1), KAX(5), COLIN(10), LOMAN(10)
COMMON ID, I', INIT, JEVNT, JINIT, JFA', JSTOP, AX', YX', XC', NCOL,
JHST, NO', KORPT, NOT, NPRR', NKRUN', NOKN', STATUT, NIT, SCALE,
21seed, TNO', TDEL, TFIM, XX', NPRRT, NCDM', NER, Vnu(25),
3KOF, KLE', KOL, ATIP(33), Enw(25), Sn(25), CELS(20,32),
4KAXK(25), JCLP', MAXNO(25), VFE(25), MLC(25), XLE(25),
5NCOLS(26), XG(25), PARA'(4), 4, QTIE(25), SSHA(25,5),
6, SUXA(25,5), NAME(6), NPROJ, MON', NDAY, NYK
COMMON PLE', NTPDS, NTOTPD, N', XSYS, YPRK', 1NUE,
11TYPE', N', NEXT', HN', N', HL', X'(10), N', (10) X'(10,10),
2', BUS(10), NRSET, NRULE, HN', J', V', ENDS', XHOL', OHL,
3', X', (10), SEED', VARATE, LOC(20), MAX, AK(11),
COMMON NPRED, ANPRE', INDELS, MPDL, CAP(10), DESL(10),
10GL(10), DESE', DXLE', XLOAD(10), XUPS, WXORS, TMEF(10),
2NSTS', NLDL, N', X', SHUR', S', COL(10)
COMMON A(25,100), KBV(15), C(100), FACDUD
DO 51 1 = 1, 10
51 COLIN(I) = 0,
EPS = 1000001
'MAXCOL = MAXCOL - 1
'MAXRO = MAXRO + 1
'NOK = NOK + 1
'NOKN + 1
IF (COLIN(I) .GT. MAXRO .OR. MAXCOL .GT. MAXCOL ) GO TO 910
50 ITER = 1
INCOL = 1

*** BEGIN MAIN ITERATION LOOP

200 ITER = 'ITER' + 1
625 CONTINUE

*** CHECK OPTIMALITY AND-OR FIND INCOMING COLUMN

250 IF (INCOL .EQ. 0 ) GO TO 920
50 INCOL = INCOL + 1
CHI = EPS
GO TO 260
260 IF (INCOL .EQ. 1 ) INCOL = INCOL + 1
IF (INCOL .EQ. 1 ) INCOL = INCOL + 1
260 CONTINUE
IF(INCOL .LE. 0) GO TO 900

C
C *** PICK ROW TO PIVOT ON
C *** ISUB=0 IMPLIES STANDARD PIVOT
C *** ISUB=1 IMPLIES PIVOT AND UPPER SUBSTITUTE
C *** ISUB=2 IMPLIES UPPER SUBSTITUTE

INROW=0
RATMIN=999999.:b
DO 282 NR=1,NROW
IF(A(NR,INCCL) .LE.FPS) Go Tu 2S0
RATIO=A(NR,NRHS)/A(NR,INCCL)
IF(RATIO.GE.RATMIN) Go To 283
RATMIN=RATIO
INROW=NR
ISUB=0
280 IF(A(NR,INCCL) .GE.-EPS) Go To 282
NDX=KBV(NR)
IF(A(NUPPER,INDEX) .LE.-EPS) Go To 282
RATIO=A(A(NK,NRHS)-A(NUPPER,INDEX))/A(NK,INCCL)
IF(RATIO.GE.RATMIN) Go To 282
RATMIN=RATIO
INROW=NR
ISUB=1
282 CONTINUE
IF(A(NUPPER,INCCL) .LE.-EPS) Go To 281
IF(A(NUPPER,INCCL) .GE.RATMIN) Go To 281
RATMIN=A(NUPPER,INCCL)
INROW=NUPPER
ISUB=2
281 IF(INROW .NE. 0) Go To 301

C
C *** CHECK FOR AUXILIARY VARIABLES IN BASIS
C
IF(INDEX .LE. 0) Go Tu 420
IT=1
DO 421 1=1,NROW
DO 422 J=1,INDEX
IF(KBV(I),NE,KCAUX(J)) Go Tu 422
IDONE(IT)=KBV(I)
IT=IT+1
GO TO 421
422 CONTINUE
421 CONTINUE
IF(IT.GT.1) Go To 423

C
C *** UNBOUNDED SOLUTION
WRITE(6,285) INCOL
285 FORMAT(1H,3H SOLUTION UNBOUNDED--ADDING COL.15)
GO TO 625
C
C *** PIVOT
C
301 IF(ISUO.LT.2) GO TO 304
302 C(NCRHS)=C(NCRHS)-C(INCOL)*A(NUPPER,INCOL)
C(INCOL)=-C(INCOL)
RATMIN=A(NUPPER,INCOL)
DO 303 NC=1,NOROW
A(NC,NORHS)=A(NC,NORHS)-A(NC,INCOL)*A(NUPPER,INCOL)
A(NC,INCOL)=-A(NC,INCOL)
303 CONTINUE
A(NUPSW,INCOL)=-A(NUPSW,INCOL)
GO TO 200
304 NCROW=KBV(INROW)
KBV(INROW)=INCOL
DO 305 NR=1,NOROW
305 COLIN(NR)=A(NR,INCOL)
CSTIN=C(INCOL)
COEF=A(INROW,INCOL)
DO 330 NC=1,NORHS
A(INROW,NC)=A(INROW,NC)/COEF
CORR=A(INROW,NC)
DO 310 NR=1,ROW
IF(NR.EQ.INROW) GO TO 310
A(NR,NC)=A(NR,NC)-COLIN(NR)*CORR
310 CONTINUE
C(NC)=C(NC)-CSTIN*CORR
330 CONTINUE
IF(ISUU.LT.1) GO TO 200
INCOL=NCROW
GO TO 302
C
C *** END MAIN ITERATION LOOP
C
C *** OPTIMAL SOLUTION
C
995 CONTINUE
GO TO 998
423 WRITE(6,193)
193 FORMAT(1H,4H SOLUTION INFEASIBLE, AUXILIARY VARIABLE 14:HAVE A:1D, 23H VALUE GREATER THAN ZERO)
GO TO 998
910 WRITE(6,911)
911 FORMAT(1H,25H MANY ROWS OR COLUMNS)
995 WRITE(6,996)
996 FORMAT(1H,25H *** STOP LOADING ABORTED)
GO TO 998
CALL JOBDEC(NSET,NORO,NOCOL)
CONTINUE
RETURN
END

*** READ IN SIMULATION PARAMETERS

READ(5,40) NM, NTOTPD, NSET, PLEN, ISeed
XXS = RAND (ISeed)
READ(5,50) ITYPE, RULE, IDUE, FLDR
READ(5,50) (ISU(J), J=1,10)
READ(5,60) ARATE, DAMAGE, FACDUD, SINPER
AVGLD = (ARATE*8.5*2.48)/FLOAT(NM)
AVGLD =AVGLD -1.24
IF (ARATE.LT.1.0) NSET = 0
NTOTPD = NTOTPD + NSET
NSET = NSET
IF (NSET.EQ.0) NSET = 0.00001

*** READ IN TRANSITION MATRIX

DC 1. 1=1,10
READ(5,70) (X(I,J), J=1,10)
READ(5,50) NPREL, NREP, DESEL, FLEF, NL, OLF
READ (5,7) (TIME(J),J=1,N)
READ (5,9) (CAP(J),J=1,N)
IF (INDELS.EQ.0) GO TO 12
READ (5,3) (DESL(J),J=1,N)
GO TO 16
12 DO 13 J=1,N
13 DESL(J)=DESL*CAP(J)
IF (INDELS.EQ.0) GO TO 16
READ (5,9) (BCL(J),J=1,N)
GO TO 18
16 DO 17 J=1,N
17 BCL(J)=DESL*CAP(J)
18 CONTINUE

*** INITIALIZE THE STATUS VARIABLES

DO 20 I=1,N
WB(I)=0.0
WBW(I)=0.0
AR(I)=0.0
WWW(I)=0.0
BOS(I)=0.0
SHOPLD(I)=0.0
20 CONTINUE

GO TO (1,20)

*** LOAD THE DEPARTMENTS

CALL SNDPL(SNDP)
}
50 FORMAT (15E14.6)
55 FORMAT (11E11.6)
60 FORMAT (15E15.6)
70 FORMAT (1E7.4)
80 FORMAT (15E14.6)
90 FORMAT (15E17.2)
END
-FOR, IS SHOPLOADING. FOP

FUNCTION MOP(R)

C *** COMPUTES NUMBER OF OPERATIONS FOR AN INCOMING JOB

MOP=4
IF (R .GT. 0.15) MOP=5
IF (R .GT. 0.35) MOP=6
IF (R .GT. 0.65) MOP=7
IF (R .GT. 0.85) MOP=8
RETURN
END

-FOR, IS SHOPLOADING. OTPUT

SUBROUTINE OTPUT (NSET)
RETURN
END

-FOR, IS SHOPLOADING. POOLHE

SUBROUTINE POOLHE (NSET, NROW, NCOL)

C

C *** THIS SR LOADS THE JOBS FROM THE POOL BY ATTEMPTING
C *** TO KEEP THE QUEUES AT A CERTAIN LEVEL

DIMENSION NSET(35,1)
COMMON ID,IM,INIT,JENVT,JENVIT,XFA,NSTOP,XX,MYC,NCLCT,
1 INIT,NOQ,INBTC,NOT,MRMMS,MRUN,MRUNMS,NSTAT,OUT,SCALF,
2 INESD,INQ,TM,TFIN,UM,MRAPP,NCRC,R,NEP,VM(25),
3 KOF, KLE, KCL, ATNB(33), ENQ(25), INM(25), JCELS(25,32),
4 KKRAK(25), JCLA, MAXJU(25), JFE(25), MLC(25), MFE(25),
5 NCELS(25), AN(25), Parm(40,4), QIF(25), SSA(25,3)
6 SUMA(75,5), NAME(6), MPX, MONDAY, NYR

COMMON PLEN, NIPDS, NTOPDO, W, XSYS, XSYS_CT, ECTU,
1 TYPE, NEXT, GEN, XG, R, X(10), X(10,10),
2 BUS(10), NRSET, NRULE, NNOX, NAST, NNOX, NCOL, NKL,
3 WAXX(10), SEED, ARAA, LOC(2,10), MAX, AR(11)

COMMON XPRES, NPRES, NRDES, NO.1, CAP(10), DESL(10),
1 DLG(10), DESL, XG, XG, XG, XG, XG, XG, XG, XG, XG,
2 NSTS, NLR, NOS, USPE, SLPE(10)

COMMON A(25,10), B(10,10), C(10,10), F, CUPD

COMMON ICOUNT, MCOUNT, STPER, KS, (10), AVGLOD

JJ1=NU(12)
DO 1 J=1, JJ1
1 A(MX, KJ+2, J)=..0
TEMPAG=..0
DO 20 I=1,MAX

TEMPGL= .0
5 MTEST=0
MBEST=0
DIF=DGL (I) - LOAD (I) - TEMPGL
IF (DIF .LE. 0.) GO TO 26
N2=:FE(12)
DO 10 J=1, J1
N1=N2
IF (A(NORG + 2, J) .LT. 0.) GO TO 10
IF (A(I, J) .LT. 0.) GO TO 10
IF (C(J) .GE. MTEST) GO TO 10
MBEST=J
MTEST=C(J)
10 N2=NSET(YX, N1)
IF (MBEST .NE. J) A(NORG + 2, MBEST) = -1.
TEMPGL=A(I, MBEST) + TEMPGL
TEMPAG = TEMPAG + NSET(Y, N1) / SCALE
IF (MTEST .EQ. 0.) GO TO 26
GO TO 5
20 CONTINUE
IF (NDR .LE. 0.) GO TO 50
TOTLD=0.0
ACTL0=0.0
DO 30 I=1, N1
TOTLD=TOTLD + DESL(I)
30 ACTL0 = ACTL0 + GNOPLD(I)
ACTL0 = ACTL0 + TERPAG
TEMPPL = .0
36 MTEST=0
MBEST=0
DIF = TOTLD - ACTL0 - TEMPLP
IF (DIF .LE. 0.) GO TO 50
N2=:FE(12)
DO 40 J=1, J1
N1=N2
IF (A(NORG + 2, J) .LT. 0.) GO TO 40
IF (C(J) .GE. MTEST) GO TO 40
MBEST=J
MTEST=C(J)
40 N2=NSET(YX, N1)
IF (MBEST .NE. J) A(NORG + 2, MBEST) = -1.
TEMPPL = TEMPLP + NSET(Y, N1) / SCALE
IF (MTEST) 50, 50, 33
50 CONTINUE
CALL JOULEC(NSET, NORG, NCOL)
RETURN
**FOR, IS SHOPLOADING, PTJOB**

C

**SUBROUTINE PTJOB (INP, NSET)**

C

*** SUBROUTINE WHICH MOVES JOB TO NEXT MACHINE
C

*** CENTER

C

DIMENSION NSET(35,1)

COMMON ID, INIT, JEVT, JANIT, MFA, MSTOP, MX, MXC, NCLCT,
 INHIST, NOG, NORPT, NOT, NPK'S, XRUN, NRUNS, NSTAT, OUT, SCALE,
  INSEED, TNOW, TFG, TFIN, TXX, XPRNT, NCRDR, NRP, XQ(25),
  KOF, KLE, KIL, ATRID(33), ENC(25), INA(25), JCELS(20,32),
  KRAK(25), JCLR, MAXNO(25), FFE(25), PLC(25), BLE(25),
  NCELS(25), ENC(25), PARAP(40,4), TIME(25), SSUMA(20,5)

6, SUMA(75,5), NAME(6), NPROJ, MON, NDAY, MABM,
 COMM. PLEN, ATUS, NTCTPD, NA, XSYS, XX, XSY, IDLE,
 ITYPE, INEXT, HENV, VHELD, WBI(10), XGM(10), X(10,10),
  BUS(10), ARSET, HRULE, XNOW, NRES, THOL, KRL,
  XWW(10), SEV, VDATE, LOC(20), MAX, AR(11)

COMMON NPREL, NPREP, NDES, NDL, CATP(10), DESL(10),
  IDGL(10), DESL, DHLF, GLOAD(10), XOPS, XXS, TIMEF(10),
  2NSTX, NLD, NARR, SHOPLD(10)

COMMON A(25), IDOL(10), KBV(15), C(10), FACDUD

COMMON ICOUNT, NCOUNT, SINPER, MS'A, (10), AVGLOD

C

*** CHECK IF JOB IS A NEW ARRIVAL

IF (INP.NE.1) GO TO 10
ATRID(3)=TNOW
NEN=NEN+1

C

*** NEW ARRIVAL. CHECK IF A JOB POOL IS BEING USED

IF (NLDR.EQ.0.5) GO TO 20

C

*** CHECK IF SHOP IS BEING PRELOADED AND JOB POOL
C

*** HAS BEEN COMPLETED

IF (NSTS.EQ.1) GO TO 20

C

*** PUT ARRIVING JOB IN THE POOL IF CP. 1 MACH IS NOT IDLE

ATRID(8)=TNOW
JOB=ATRID(3)+JND-1
LOC(JOB)=TFA

C

*** COLLECT STATISTICS ON INTERARRIVAL TIMES TO
C

*** THE JOB POOL

O=TNOW-AR(11)
CALL HISTO (D,0.5,0.5,15,NSET)
AR(11)=TNOW
NFIRST=ATRIB(11)+JOOO1
IF (MSW(1).EQ.0) GO TO 4
IF (TNOW.LE.JOOO1) GO TO 4
IF (BJS(NFIRST)) 5,5,4
4 CALL FICLEN(12,NSE)
GO TO 7

C *** IF FIRST OPERATION MACHINE IS IDLE, CONSIDER THE
C *** JOB AS COMING FROM POOL AND PUT IN THE SHOP
C
5 CONTINUE
IF (MSW(3).EQ.0) GO TO 6
IF (SSUMA(NFIRST,3).GE.AVGLD91) GO TO 4
5 =NEX
C CALL COLCT (1,0,69,NSET)
GO TO 20

C *** JOB IS NOT A NEW ARRIVAL. CHECK IF IT IS COMING
C *** FROM THE POOL
C
6 IF (INP.EQ.2) GO TO 4
C *** JOB IS COMING FROM THE POOL.
C *** ALSO NEW JOBS WHEN A POOL IS NOT USED ARRIVE
C *** AT THIS POINT
C *** UPDATE STATUS OF WORK IN SHOP AND ALSO UPDATE
C *** AGGREGATE LOAD IN SHOP QUEUES FOR EACH MACHINE.
C
20 CALL TMST (XSYS,TNOW,12,NSET)
CALL TMST (XKSYS,TNOW,11,NSET)
XSYS=XSYS+1.0
XKSYS=XSYS+A
ATRIB(33)=TNOW
NNN=NNN+1
DO 37 I=11,NNN,2
J=ATRIB(I)
37 SHOPLD(J)=SHOPLD(J)+ATRIB(I+1)
C *** JOB IS NOT GOING INTO THE POOL. COLLECT STATISTICS
C *** ON INTERARRIVAL TIMES TO THE CURRENT MACHINE
C
40 D=TNOW-AR(MNEXT)
NN4=MNEXT+4
CALL HISTO (D,0.5,0.5,NN4,NSET)
AR(MNEXT)=TNOW
C *** CHECK ON THE STATUS OF MACHINE FOR NEXT
*** JOB OPERATION

IF (BUS(MNEXT)) 60, 60, 50

*** NEXT MACHINE IS BUSY. JOB CAN NOT BE PUT ON MACHINE

ATRIB(8) = TNOW
MX1 = MNEXT + 1
JOB = ATRIB(30) + 0.001
LOC(JOB) = MFA
GLOAD(MNEXT) = GLOAD(MNEXT) + ATRIB(12)
CALL FILEM(MX1, NSET)
GO TO 70

*** NEXT MACHINE IS NOT BUSY.
*** JOB MAY BE PUT ON MACHINE

CALL TMST(BUS(MNEXT), TNOW, MNEXT, NSET)
BUS(MNEXT) = 1.0
WT = U.0
MX15 = MNEXT + 15
CALL COLCT(WT, MX15, NSET)
TIMEVT = ATRIB(12) * (8.0 / CAPR(MNEXT))
ATRIB(1) = TNOW + TIMEVT
ATRIB(2) = 1.0
J = ATRIB(11)
SHOPLD(J) = SHOPLD(J) - ATRIB(12)
JOB = ATRIB(30) + 0.001
LOC(JOB) = MFA
CALL FILEM(1, NSET)
70 NSTAT = 0
RETURN
END
**FOR IS SHOPLOADING START**

SUBROUTINE START (NSET)

*** GENERATES INITIAL JOBSET IN THE SHOP AT TIME ZERO ***

*** AND ESTABLISHES THE JOB POOL IF REQUIRED ***

DIMENSION NSET (35, 1)
COMMON ID, IOUT, IUNIT, JUNIT, JEREAL, STOP, XI, XM, NCLCT,
IWAIT, INOUT, JOUT, NOT, KPRNT, NRUN, NRUNS, NSTAT, OUT, SCALE,
SEED, TBEG, TFIN, MMX, NPRINT, NCRBR, NCRF, VNO (25),
KOF, KLE, KCL, ATRIO (33), ETH (25), IMIN (25), JCELS (25, 32),
KRAKE (25), JCLK, MAXREF (25), MFR (25), NLC (25), NLE (25),
NCELS (25), NCL (25), PARAX (40, 4), STIME (25), SSUMA (25, 5)

DIMENSION NSET (35, 1), NNAME (6), NPREL, NDAY, NYSK
COMMON PLEN, MNAME, TOTPD, TR, XSYS, XSYSX, IDJE,
NNAME (10), NNAME, NCL, ATRIO, ETH (10), IOM (10), X (10, 10),
BUS (10), NSET, NREF, NOX, PVNAME, MNAME, INCL, ATR,
NNAME (10), NNAME, NCL, ATRIO, ETH (10), IOM (10), X (10, 10),
BUS (10), NSET, NREF, NOX, PVNAME, MNAME, INCL, ATR,

TNO = 0.0
TBE = TNOW
NSTSW = 0
DO 10 1 = 1, NPREL

*** DO NOT SET SWITCH IF POOL IS STILL BEING LOADED ***

IF (I .LE. NPREP) GO TO 7
NSTS = 1
7 CALL ARVL (NSET)
10 CONTINUE
RETURN
END

**FOR IS SHOPLOADING TIME**

FUNCTION TIME (NRM)

*** COMPUTES TIME FOR A JOB OPERATION ***

TIME = 2.46 * ALOG (NRM)
IF (TIME .LT. 1.00) TIME = 1.00
IF (TIME .GT. 9.00) TIME = 9.00
RETURN
END
FOR IS SHOPLOADING.WKING

SUBROUTINE WKING (MBEST, NSET)

*** SUBROUTINE USED WITH WORK IN NEXT QUEUE
*** DISPATCHING RULE

DIMENSION NSET(35,1)
COMMON ID,IMIT,JENVT,JMNIT,MBEST,NSET(1,35),NCLCT,
INHIST,NOG,NOCP,TOT,NPRMS,NRUS,NSAT,OUT,SCALE,
21SEED,TNOW,TFIN,MXX,IMPRT,NCRR,NEP,WN(25),
3KOF,KLE,KATRIO(33),END(25),NNI(25),JCELS(20,32),
4KRONK(25),JCLR,MAXM(25),MFE(25),MCL(25),MLE(25),
5NCELS(20),MCR(25),PARAM(40,4),CTIME(25),SSUMA(20,5)
6, SUMA(75,5),MAVE(6),NPROJ, lHIIJDAY, NYP
COMMON PLEN,NTPDS,NNTPD,NT,NX,ISYS,X,KSY,IDUE,
11TYPE, MNEXT, MAX, THLD, WB(10), xM(10), x(10,10),
2BUS(10), MSET, NPUTE, WB, NSGU,NSIG,NHOL,HAL,
3WMW(10), SEED, ARATL, LOC(250), MAX, AR(11)
COMMON NPREL, NPREL, DESL, NDEL, CAM(10), DESL(10),
1NDEL(10), NDLF, DELF, QLOAD(10), QCPS, XYZ, TMEF(10),
2NSTS, NCTRL, NARR, SHOPT, LOAD(10)

*** CHECK JOBS IN QUEUE FOR THIS MACHINE

XX=1.0E+20
MBEST=0
MN1=MNOW+1
MXT=MFE(MN1)
10 NM=M FLOAT(NSET(13,MXT))/SCALE+.000001

*** CHECK IF THIS JOB HAS A NEXT OPERATION

IF (NM .EQ. 0) GO TO 50
TMK=QLOAD(NM)
TM=TNOW+FM(NSET(12,MXT))/SCALE
N1=MFE(11)

*** CHECK IF NEXT EVENT IS AN END OF SERVICE

20 IF (FLOAT(NSET(2,M1))/SCALE.GT.1.0) GO TO 40

*** FIND MACHINE CENTER WHERE END OF SERVICE EVENT
*** IS GOING NEXT

MN=FLOAT(NSET(13,M1))/SCALE+.000001
IF (MN .NE. NM) GO TO 40

*** CHECK IF EVENT IS GOING TO HAVE AN EFFECT ON WK
*** AT NEXT QUEUE WITH RESPECT TO THE JOB WE ARE
**CONSIDERING**

```
** CONSIDERING **
   IF (FLOAT(NSET(1,N1))/SCALE-(Tm)) 30,40,40
30 Twk=Twk+FLOAT(NSET(14,N1))/SCALE
40 N1=NSET(MX,N1)
   IF (N1.NE.7777) GO TO 20
```

**CHECK IF MEASURE IS OPTIMAL SO FAR**

```
** CHECK IF MEASURE IS OPTIMAL SO FAR **
   IF (Twk.LT.Xx) Xxest=Xxt
   IF (Twk.LT.Xx) Xx=Twk
```

**GET NEXT JOB IN QUEUE FOR THIS MACHINE**

```
** GET NEXT JOB IN QUEUE FOR THIS MACHINE **
50 Mxt=NSET(Xx,Xxt)
   IF (Mxt.NE.7777) GO TO 10
RETURN
END
```
APPENDIX C

FORTRAN IV LISTING OF THE RANDOM NUMBER GENERATOR TEST PROGRAM
C *** PROGRAM MAIN

DIMENSION NMAT(11,11),NRUN(10),NLIN(10),ER(10)
READ (5,10) ISEED,INUM

10 FORMAT (16,2X,15)

DO 20 I=1,10
NRUN(I)=0
NLIN(I)=0
DO 20 J=1,10
20 NMAT(I,J)=0

NRUNTO=0
NRUNLE=0
KA=ISEED
KB=5**7
KD=KA
DO 100 I=1, INUM
KA=KD
KC=KA*KB
KD=MOD(KC,2**17)
D=KD
X=D/(2.0**17)
XX=X*10.
IX=XX
IX=IX+1
IF (I.EQ.1) GO TO 99

IF (I.EQ.1) GO TO 99
NMAT(I1,IX)=NMAT(I1,IX) +1

IX=X*1000000.
IX1=X*1000000.
IF (IX.EQ.IX1) GO TO 900
IF (IDIP.EQ.1.AND.X.GT.X1) GO TO 30
IF (IDIR.EQ.2.AND.X.LT.X1) GO TO 30
NRUNTO=NRUNTO+1
IF (NRUNLE.GE.5) NRUNLE=5
NRUN(NRUNLE)=NRUN(NRUNLE)+1
NRUNLE=0
30 IF (X.GT.X1) IDIR=1
IF (X.LT.X1) IDIR=2
NRUNLE=NRUNLE+1
99 X1=X
IX1=IX
100 CONTINUE

NRUNTO=NRUNTO+1
IF (NRUNLE.GE.5) NRUNLE=5
NRUN(NRUNLE)=NRUN(NRUNLE) +1
WRITE(6,201)
201 FORMAT (IH1,24HRANDOM NO GENERATOR TEST//)
WRITE (6,203)
203 FORMAT (IH ,32HFREQUENCY COUNTS AT .1 INTERVALS)
DO 207 J=1,10
DO 205 I=1,10
205 NLIN(J)=NLIN(J)*NMAT(I,J)
WRITE(6,209) J,NLIN(J)
207 CONTINUE
209 FORMAT (IH ,3X,I2,3X,16)
WRITE (6,221)
221 FORMAT (//IH , 13HMATRIX COUNTS)
DO 223 I=1,10
223 WRITE (6,225) (NMAT(I,J),J=1,10)
225 FORMAT (IH ,1016)
WRITE (6,231)
231 FORMAT (//IH ,10HRUN COUNTS)
WRITE (6,233) (NRUN(I),I=1,5)
233 FORMAT (1016)
WRITE (6,235) NRUNTO
235 FORMAT (/IH ,20HTOTAL NUMBER OF RUNS,5X,I6)
C *** CHI-SQUARE GOODNESS OF FIT
CHISQ=0.0
EXP=FLOAT(INUM-1)/10.
DO 301 I=1,10
Y=(NLLN(I)-EXP)**2
Y=Y/EXP
301 CHISQ=CHISQ+Y
WRITE (6,303) CHISQ
303 FORMAT (//IH ,33HCHISQUARE GOODNESS OF FIT(9DOF) ,F9.3)
C *** KOLMO GOROV-SMIRNOV GOODNESS OF FIT
D=0.0
Y1=0.0
EXP1=0.0
EXP=EXP/FLOAT(INUM-1)
DO 321 I=1,10
Y=FLOAT(NLIN(I))/FLOAT(INUM-1)
Y1=Y1+Y
EXP1=EXP1+EXP
DIF=ABS(Y1-EXP1)
IF (DIF.GT.D) D=DIF
321 CONTINUE
WRITE(6,323) D
323 FORMAT (//IH ,34HKOLM-SMIRNOV GOODNESS OF FIT(9DOF),F9.3)
C *** SERIAL TEST
CHISQ=0.0
EXP=FLOAT(INUM-1)/100.0
DO 331 I=1,10
DO 331 J=1,10
Y=(NMAT(I,J)-EXP)**2
Y=Y/EXP
331 CHISQ=CHISQ+Y
WRITE (6,333) CHISQ
333 FORMAT (/1H ,27HCHI-SQ SERIAL TEST(99DOF) ,F9.3)
C *** RUN TESTS(TOTAL RUNS)
   RNUM=NRUNTO-(2.0*FLOAT(INUM)-1.0)/3.0
   RDEN=(16.0*FLOAT(INUM)-29.0/90.0
   RDEN=RDEN**0.5
   Z=RNUM/RDEN
   WRITE (6,341) Z
341 FORMAT(/1H ,28HTOTAL RUN NORMAL STATISTIC ,F9.4)
C *** RUN TESTS(RUN LENGTHS)
   FINUM=FLOAT(INUM)
   ERT=((2.*FINUM)-1.)/3.
   ER(1)=((5.*FINUM)+1.)/12.
   ER(2)=((11.*FINUM)-14.)/60.
   ER(3)=((19.*FINUM)-47.)/360.
   ER(4)=((29.*FINUM)-105.)/2520.
   ER(5)=ERT-ER(1)-ER(2)-ER(3)-ER(4)
   CHISQ=0.0
   DO 351 I=1,5
   FNRUN=FLOAT(NRUN(I))
   Y=(FNRUN-ER(I)**2
   Y=Y/ER(I)
351 CHISQ=CHISQ+Y
WRITE (6,353) CHISQ
353 FORMAT (/1H ,26HCHISQ RUN LENGTHS(4DOF) ,F9.3)
   GO TO 951
900 WRITE (6,901) I
901 FORMAT(11H ,34HERROR CONDITION, 2 EQUAL NO. ITER ,15)
951 CONTINUE
END
RANDOM NO GENERATOR TEST
FREQUENCY COUNTS AT .1 INTERVALS

1  983
2  1011
3  978
4  994
5  1049
6  1032
7  976
8  973
9  1017
10 986

MATRIX COUNTS

87  100  89  102  110  107  104  98  102  83
96  102  111  102  89  100  100  98  110  103
90  109  95  85  107  104  89  108  89  102
94  96  106  101  106  111  95  89  94  102
114 113  104  102  109  95  101  105  109  98
104 109  95  109  111  101  103  101  99  100
92  87  102  87  102  96  102  90  103  115
98  91  85  99  106  113  95  87  106  93
101 101  94  106  102  105  98  105  104  101
107 103  97  101  107  103  89  92  101  89

RUN COUNTS

4147 1872  503  121  22

TOTAL NUMBER OF RUNS  6666

CHISQUARE GOODNESS OF FIT (9DOF)  6.146

KOLM-SMIRNOV GOODNESS OF FIT (9DOF)  .005

CHI-SQ SERIAL TEST (99DOF)  54.435

TOTAL RUN NORMAL STATISTIC  -.0079

CHISQ RUN LENGTHS (4DOF)  2.515

END  1469 MLSEC
APPENDIX D

DESCRIPTION OF ATTRIBUTES, EVENTS, AND OPTIONAL VARIABLES IN THE GASP PROGRAM
Events

1- End of service (ENDSV)
2- Arrival of a job to the system (ARIVL)
3- Completion of a scheduling period (COLL)
4- Beginning of the simulation (START)

Other events which are not called by EVNTS are:
   End of run in period (CLEAR)
   End of simulation (ENSIM)

User Subroutines

MAIN

EVNTS

ENDSV This is used when a job operation has been completed on a machine.
ARIVL Called when a new arrival comes into the system.
COLL Collects statistics on machine and shop utilization at the end of every scheduling period.
START Called at the beginning of the simulation to preload jobs in the shop.
CLEAR Used to clear statistical areas after the run in period.
DYNAM This is used to calculate priorities for dynamic rules (DSOP).
WKINQ Used with the expected work in next queue rule.
PTJOB Takes an available job from ARIVL, ENDSV, or JOBDEC and moves it to the machine center required.
GENMAT Called by COLL to put the shop loading information in the mathematical programming model when this form of loading is being used.
LPM  The linear program model used to decide which jobs should be moved from the job pool into the shop.

JOBDEC  Program used to interpret the results of LPM and to call PTJOB as required.

ENSIM  End of simulation.

POOLHE  Program used to load jobs in the shop with a heuristic algorithm instead of the linear program algorithm.

**Function Subprograms**

DUED  Computes a due date for each incoming job.

MOP  Computes the number of job operations for each incoming job.

TIME  Computes a processing time for each of the job operations on the routing.

GNARV  Computes the time before the next arrival is due.

**Files**

#1  Events

#2-11  Machine queues (jobs in the queue) for machines #1-10

#12  Jobs in the job pool

**Attributes**

1- Time the event is going to take place

2- Event code

3- Time at which the job came into the system

4- Due date for the job (including TNOW)

5- Number of operations left

6- Slack time (including TNOW) (for static rules); work remaining (for dynamic rules)
7- Slack or work remaining/operation
8- Time at which job arrived at its current queue
9- Total work time
10- Total number of operations
11- First or actual operation (machine) number
12- Time required for the operation in attribute 11, that is, for the operation in the machine where the job is presently located.
13-26 Similar to #11,12
27-29 Not used
30- Job number
31- Not used
32- Amount of work already performed on this job (hours)
33- Time at which the job came out of the pool

Statistics Collected

COLCT (SUMA array) : 64 statistics

No Var.
1-10 UT Percent of time busy in a period for machine I
11 TISYS Time spent in the system
12 TLATE Time value of job lateness
13 TARDY Time value of job tardiness
14 ATS Average time busy in a period per machine
15 DDD Time value (absolute) of job lateness
16-25 WT Waiting time for jobs at queue of machine "I"
26-30 TYSYS Time spent in the system for jobs with 4-8 operations
31-40 DBAL Deviation from balance for machine J
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<thead>
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<tr>
<td>41</td>
<td>DBALT</td>
<td>Deviation from balance for entire shop</td>
</tr>
<tr>
<td>42</td>
<td>Time spent in system w/o counting pool time</td>
<td></td>
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<tr>
<td>43-47</td>
<td>Time spent in the system w/o counting the pool time for jobs with 4-8 operations</td>
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<tr>
<td>48</td>
<td>Time spent in the pool</td>
<td></td>
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<tr>
<td>49-53</td>
<td>Time spent in the pool for jobs with 4-8 operations</td>
<td></td>
</tr>
<tr>
<td>54-53</td>
<td>DBALQ</td>
<td>Deviation from balance in queue for machine &quot;J&quot;</td>
</tr>
<tr>
<td>54</td>
<td>DBALQT</td>
<td>Deviation from queue balance (all machines)</td>
</tr>
<tr>
<td>64</td>
<td>Operation run time</td>
<td></td>
</tr>
<tr>
<td>66,67</td>
<td>No in pool before/after loading</td>
<td></td>
</tr>
<tr>
<td>68,69</td>
<td>No of jobs loaded in shop thru special features on PTJOB, ENDSV</td>
<td></td>
</tr>
<tr>
<td>70,71</td>
<td>PWB, PQB</td>
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**TMST** (SSUMA array) : 14 statistics

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<tr>
<td>1-10</td>
<td>BUS(I)</td>
<td>Amount of time machine &quot;I&quot; has been busy</td>
</tr>
<tr>
<td>11</td>
<td>XWKSY</td>
<td>Amount of work in hours in the shop</td>
</tr>
<tr>
<td>12</td>
<td>XYSY</td>
<td>Amount of work in number of jobs in the shop</td>
</tr>
<tr>
<td>13</td>
<td>XOPS</td>
<td>Number of operations performed for jobs in the shop</td>
</tr>
<tr>
<td>14</td>
<td>XWKS</td>
<td>Amount of work already done for jobs in the shop</td>
</tr>
</tbody>
</table>

**HISTO** : 16 statistics

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<tbody>
<tr>
<td>1</td>
<td>TLATE</td>
<td>Time value of job lateness</td>
</tr>
<tr>
<td>2</td>
<td>XP</td>
<td>Number of periods late</td>
</tr>
<tr>
<td>3</td>
<td>ATS</td>
<td>Average time busy in a period per machine</td>
</tr>
<tr>
<td>4</td>
<td>AT</td>
<td>Average percent of load arrived/machine</td>
</tr>
<tr>
<td>5-14</td>
<td>D</td>
<td>Interarrival times for machine I</td>
</tr>
<tr>
<td>15</td>
<td>Interarrival times to the job pool</td>
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</tr>
<tr>
<td>16</td>
<td>Time jobs spend in the pool</td>
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APPENDIX E

DESCRIPTION OF NON-GASP VARIABLES
<table>
<thead>
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<th>Description of Non-GASP Variables</th>
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<tbody>
<tr>
<td><strong>ARATE</strong></td>
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<tr>
<td><strong>AVG(I)</strong></td>
</tr>
<tr>
<td><strong>BUS(I)</strong></td>
</tr>
<tr>
<td><strong>LOC(I)</strong></td>
</tr>
<tr>
<td><strong>MNEXT</strong></td>
</tr>
<tr>
<td><strong>NEN</strong></td>
</tr>
<tr>
<td><strong>NLV</strong></td>
</tr>
<tr>
<td><strong>NM</strong></td>
</tr>
<tr>
<td><strong>NRSET</strong></td>
</tr>
<tr>
<td><strong>NTOTPD</strong></td>
</tr>
<tr>
<td><strong>NTPDS</strong></td>
</tr>
<tr>
<td><strong>PLEN</strong></td>
</tr>
<tr>
<td><strong>SEED</strong></td>
</tr>
<tr>
<td><strong>TISYS</strong></td>
</tr>
<tr>
<td><strong>WBM(I)</strong></td>
</tr>
<tr>
<td><strong>WWW(I)</strong></td>
</tr>
<tr>
<td><strong>X(I,J)</strong></td>
</tr>
<tr>
<td><strong>XSYS</strong></td>
</tr>
<tr>
<td><strong>XWKSY</strong></td>
</tr>
<tr>
<td><strong>I Type</strong></td>
</tr>
<tr>
<td><strong>NHILD</strong></td>
</tr>
</tbody>
</table>
WB(I) Hours of work that has arrived to the shop for each machine.

NRULE Code which indicates queue discipline (dispatching rule) to be used

1- (Dynamic), Dynamic Slack Rule, DS
2- (Dynamic), Dynamic Slack per Operation Rule, DSOP
3- (Dynamic), Expected Work in Next Queue, EWIQ
4- (Not Dynamic), Shortest Processing Time, SPT
5- (Not Dynamic), Due Date, DD
6- (Not Dynamic), First in First Out, FIFO

(Normal GASP procedure for ranking entries in the file is used to maintain ranking of jobs in machine queues for rules 4-7. Rules 1-3 utilize separate subroutines for computing priorities.) Only Rules #2,3,4,6 were used to obtain detailed simulation results in order to save computer time.

MNOW The machine number where the current job has just finished

NRST Used by main to indicate the number of runs in periods. Set by main NRST = NRSET except that if NRSET = 0, then NRST = 9999999. The effect of this is to eliminate the run in period if NRSET = 0.

MAX Equals the largest job number presently in the system (not the number of jobs, but the job number)

AR(I) Last time machine "I" had an arrival

NPREL Number of jobs to be preloaded in the shop

NPREP Number of jobs to be preloaded in the pool, if using a pool, out of the total in NPREL
NDESL  Switch to indicate whether desired aggregate load per machine is to be read individually or calculated using a factor:
        0 = read, 1 = calculated
DESLF  Factor to be used in calculating the desired aggregate load
CAPM(J) Machine capacity for machine "J" (per scheduling period)
DESL(J) Desired aggregate load for machine "J" after loading.
NDML  Switch to indicate if desired queue load at each machine is to be read individually or calculated: 0 = read, 1 = calculated
DMLF  Factor to be used in calculating desired queue load
DQL(J) Desired queue load for machine "J"
QLDAD(J) Variable used to keep track of work in queue for machine J (to be used by work in next queue dispatching rule)
TIMEF(J) Factor used to extend the time generated for a machine operation properly
NSTSW  Switch to determine if the job being handled by ARIVL is to be preloaded directly into the shop regardless of any pool arrangements: 0 = handle normally, 1 = preload directly in shop
XOPS  Number of operations performed already for jobs in shop (see TMST)
XWKS  Amount of work performed already for jobs in the shop (see TMST)
DBAL(J) Deviation from aggregate balance for machine "J" (that is, deviation from desired aggregate load in the shop)
DBALT  Deviation from balance for entire shop
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>NLDR</td>
<td>Loading rule to be used:</td>
</tr>
<tr>
<td></td>
<td>0 = shop with uncontrolled loading or releasing</td>
</tr>
<tr>
<td></td>
<td>1 = pool with desired aggregate load, LP;</td>
</tr>
<tr>
<td></td>
<td>5 = pool, desired queue load, heuristic</td>
</tr>
<tr>
<td>IDUE</td>
<td>Method of job due date generation (1,2)</td>
</tr>
<tr>
<td>NARR</td>
<td>Code to indicate type of arrival rate</td>
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<tr>
<td></td>
<td>1 = Poisson arrivals</td>
</tr>
<tr>
<td></td>
<td>2 = Poisson arrivals with mean interarrival times superimposed on a sine curve</td>
</tr>
<tr>
<td>SHOPLD(J)</td>
<td>Variable used to keep track of the aggregate work in the shop for machine &quot;J&quot;</td>
</tr>
<tr>
<td>DBALQ(J)</td>
<td>Deviation from desired level of work for machine &quot;J&quot; in queue of machine &quot;J&quot;</td>
</tr>
<tr>
<td>DBALQT</td>
<td>Sum of</td>
</tr>
<tr>
<td>A(I,J)</td>
<td>Matrix used by the bounded LP including RHS and two extra rows, one for upper bounds and one for switches</td>
</tr>
<tr>
<td>KBV(I)</td>
<td>Variables which give column number of vector in the basis in the LP programs</td>
</tr>
<tr>
<td>C(J)</td>
<td>Objective row, including objective value in the RHS column</td>
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<tr>
<td>FACDUD</td>
<td>A factor used to assign different weights to the job due dates. A factor of 0 ignores due dates.</td>
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<tr>
<td>NOROW</td>
<td>Number of rows in the LP program, not counting the boundary and switch rows</td>
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<tr>
<td>NOCOL</td>
<td>Number of columns in the LP program, not counting the RHS</td>
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<tr>
<td>INDEX</td>
<td>Number of artificial variables in the final basis</td>
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</tbody>
</table>
| KAU(X,J)     | Column number of the artificial variables in the final basis,
if any.

**Variables Used Internally in Some Subroutines**

**MAIN**

- **XXSD**: A random number used to prime the random number generator

**ENDSV**

- **NOP**: Total number of operations for the job being handled (current job that is just leaving the system)
- **NP23**: NOP + 22. Index used to collect statistics on jobs (time spent on system) depending on their number of operations
- **DDD**: Absolute value of job lateness
- **TLATE**: Job lateness
- **TARDY**: Tardiness = 0 if TLATE is $\leq 0$, = TLATE if TLATE $> 0$
- **XP**: Integer number of periods late for a job (could be negative if job is early)
- **JOB**: Job number for job leaving the system or job number for job entering service
- **LR, LRM**: Variables used to set indices for rolling job attributes when an operation has been finished
- **MBEST**: Value returned to ENDSV by DYNAM and WKINQ giving the column number of the job with top priority (according to the rule in use) in the machine queue where an end of service just occurred
- **WT**: Waiting time for job being placed on machine
- **COLL**: Percent of time busy for a machine
- **TS**: Time busy for all machines this period
TOT  Percent of capacity load arrived for all machines
ATS  Average time busy this period per machine
ATOT Average percent of capacity load arrived per machine
PTJOB
INF  New arrival indicator: 2 from ENDSV, 1 from ARIVL, 3 from JOBDEC
D    Interarrival time

DYNAM
DIF  Due date--work remaining
DS    Dynamic slack
DSOP Dynamic slack per operation
XX    Best dynamic slack value so far
MBEST Column number of best job so far
MNXT  Column number of job being considered
WKINQ
MXT  Column number of job being considered
TWK  Total work content at the machine queue where the job being
     considered would go next
APPENDIX F

SAMPLE INPUT DATA FOR SIMULATION PROGRAM
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**Annotations:**
- **COOLING WATER DATA**
- **CYCLE:** (47)

**Data:**
- **6901:** 17 960 39 8000 900131
- **6902:** 1 62 1 1
- **6903:** 80961
APPENDIX G

SAMPLE OUTPUT FROM SIMULATION PROGRAM
### Various Approaches for Job Shop Loading Using Different Dispatching Rules

**Loading Approach Number 1**

**Dispatching Rule Number 4**

<table>
<thead>
<tr>
<th>Machine</th>
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<tr>
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<tr>
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<td>9.306</td>
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**Deviation from Balance, Aggregate Load**

- **Average:** 123.554
- **Variance:** 2210.457

**Deviation from Balance, Queue Load**

- **Average:** -72.148
- **Variance:** 693.733

**Time Spent in the System**

- **Average:** 51.952
- **Variance:** 1270.387

**Time Spent in the Job Pool**

- **Average:** 8.973
- **Variance:** 201.022

**Time Spent in the System w/o Pool-Time**

- **Average:** 42.981
- **Variance:** 963.242

**Jobs in the Pool Before Loading**

- **Avg:** 6.69
- **Std:** 4.13

**Jobs in the Pool After Loading**

- **Avg:** 2.45
- **Std:** 3.26
### MACHINE UTILIZATION BALANCE MEASURE

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**Shop Balance Measure =** 5.303

**Number of Jobs Entering Shop =** 2118

**Number of Jobs Leaving Shop =** 2128

**Average Job Lateness =** 40.69

**Average Lateness Variance =** 2754.45

**Average Job Tardiness =** 6.504

**Average Tardiness Variance =** 424.258

**Average Shop Utilization =** 81.69

**Average W.I.P. (In Hours of Work) =** 411.768 120.893

### Other Balance Measures

**Average W.I.P. (Average Operations Performed Per Job in the Shop):**

- **Avg =** 51.669
- **Std =** 19.300

**Average W.I.P. (Average Hours of Work Done for Jobs in the Shop):**

- **Avg =** 135.748
- **Std =** 49.945

**Length of Simulation Run Was 500 Time Periods (~4000+ Hours).**
<table>
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<td>ALL</td>
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</table>

PERIOD WORK BALANCE INDEX  
PWB = 4.484

PERIOD QUEUE BALANCE INDEX  
PQB = 11.59
**GASP SUMMARY REPORT**

**SIMULATION PROJECT NO. 1**

BY

IRASTORZA

**DATE** 1/1/1973

**RUN NUMBER** 3

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**GENERATED-FREQUENCY-DISTRIBUTIONS**

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APPENDIX H

RESULTS FROM RANDOM NUMBER GENERATOR TEST SEEDS
Table 21. Results of Tests on Random Number Generator

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<th>CRITICAL VALUES</th>
<th>Goodness of fit $X^2$</th>
<th>Goodness of fit Kolm-Smirnov</th>
<th>Serial correlation $X^2$</th>
<th>Total number of runs (normal)</th>
<th>Number of runs of each length $X^2$</th>
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<th>Serial correlation $X^2$</th>
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<tr>
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APPENDIX I

SUMMARY RESULTS FROM SIMULATION RUNS
Table 22. Simulation Results

Conditions: No Pool, Results after 100 periods, DSOP

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<td>70.4</td>
<td>65.8</td>
<td>66.1</td>
<td>66.2</td>
<td>83.0</td>
<td>74.4</td>
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<td>70.4</td>
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<td>66.1</td>
<td>66.2</td>
<td>83.0</td>
<td>74.4</td>
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<td>6.62</td>
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<td>.938</td>
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<td>8.86</td>
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</tbody>
</table>
Table 24. Simulation Results

Conditions: No Pool, Results after 500 periods, DSOP; Set 1

<table>
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<tr>
<th>Run Number</th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>76.</td>
<td>71.</td>
<td>72.</td>
<td>72.</td>
<td>72.</td>
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<td>72.5</td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>76.</td>
<td>71.</td>
<td>72.</td>
<td>72.</td>
<td>72.</td>
<td>72.</td>
<td>72.5</td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.73</td>
<td>4.59</td>
<td>5.24</td>
<td>5.11</td>
<td>4.89</td>
<td>5.18</td>
<td>4.96</td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.753</td>
<td>.715</td>
<td>1.036</td>
<td>.892</td>
<td>.646</td>
<td>.954</td>
<td>.833</td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>16.2</td>
<td>13.3</td>
<td>14.1</td>
<td>14.6</td>
<td>----</td>
<td>14.0</td>
<td>14.4</td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.00</td>
<td>3.89</td>
<td>4.26</td>
<td>4.28</td>
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<td>4.28</td>
<td>4.14</td>
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<tr>
<td>8. Period queue balance, PQB</td>
<td>190.</td>
<td>47.8</td>
<td>21.7</td>
<td>33.5</td>
<td>----</td>
<td>38.8</td>
<td>66.4</td>
</tr>
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<td>9. Average queue size</td>
<td>3.25</td>
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<td>3.0</td>
<td>3.0</td>
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<td>3.0</td>
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<tr>
<td>10. Average work in process in hours</td>
<td>671.</td>
<td>627</td>
<td>625</td>
<td>623</td>
<td>635</td>
<td>619</td>
<td>633</td>
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<tr>
<td>11. Average number of jobs in the shop</td>
<td>40.</td>
<td>38.2</td>
<td>38.5</td>
<td>38.2</td>
<td>38.</td>
<td>37.9</td>
<td>38.5</td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>96.8</td>
<td>93.1</td>
<td>95.6</td>
<td>96.5</td>
<td>95.9</td>
<td>94.3</td>
<td>95.7</td>
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<td>16. Average job tardiness</td>
<td>4.</td>
<td>1.7</td>
<td>1.6</td>
<td>1.6</td>
<td>2.6</td>
<td>1.4</td>
<td>2.2</td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>116.</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>59.</td>
<td>19.</td>
<td>42.8</td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2132</td>
<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2114</td>
<td>2109</td>
<td>2118</td>
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<tr>
<td>19. Average shop utilization</td>
<td>83.4</td>
<td>83.2</td>
<td>81.5</td>
<td>81.2</td>
<td>82.4</td>
<td>81.4</td>
<td>82.2</td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
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Table 25. Simulation Results

Conditions: No Pool, Results after 500 periods, DSOP; Set 2

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<th>Avg.</th>
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<td>1. Time spent in the system</td>
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<td>69.</td>
<td>72.</td>
<td>72.</td>
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<td>73.</td>
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<td>2. Time spent in the shop</td>
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<td>69.</td>
<td>72.</td>
<td>72.</td>
<td>72.</td>
<td>73.</td>
<td>71.7</td>
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<tr>
<td>4. Machine balance measure, MWB</td>
<td>5.17</td>
<td>5.20</td>
<td>5.15</td>
<td>5.27</td>
<td>4.97</td>
<td>4.93</td>
<td>5.12</td>
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<tr>
<td>5. Shop balance measure, SWB</td>
<td>1.07</td>
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<td>.992</td>
<td>.945</td>
<td>.683</td>
<td>.652</td>
<td>.868</td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>13.6</td>
<td>13.6</td>
<td>13.5</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>13.6</td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.15</td>
<td>4.38</td>
<td>4.21</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>4.25</td>
</tr>
<tr>
<td>8. Period queue balance, PQB</td>
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<td>74.0</td>
<td>----</td>
<td>----</td>
<td>----</td>
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</tr>
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<td>9. Average queue size</td>
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<td>2.8</td>
<td>3.0</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>2.9</td>
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<tr>
<td>10. Average work in process in hours</td>
<td>621</td>
<td>598</td>
<td>621</td>
<td>616</td>
<td>625</td>
<td>638</td>
<td>620.</td>
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<tr>
<td>11. Average number of jobs in the shop</td>
<td>38.</td>
<td>36.5</td>
<td>38.2</td>
<td>37.8</td>
<td>37.9</td>
<td>38.7</td>
<td>37.9</td>
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<tr>
<td>12. Average operation done for jobs in shop</td>
<td>95.5</td>
<td>94.2</td>
<td>95.7</td>
<td>94.1</td>
<td>94.6</td>
<td>94.1</td>
<td>94.7</td>
</tr>
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<td>13. Average work hours done for jobs in shop</td>
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<td>288</td>
<td>232</td>
<td>226</td>
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<td>225</td>
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<td>15. Variance of lateness distribution</td>
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<td>810</td>
<td>729</td>
<td>798</td>
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<td>768</td>
<td>768</td>
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<td>1.4</td>
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<td>17.</td>
<td>32</td>
<td>42</td>
<td>23.2</td>
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<tr>
<td>18. Number of jobs entering shop</td>
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<td>2111</td>
<td>2113</td>
<td>2100</td>
<td>2117</td>
<td>2113</td>
<td>2111</td>
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<td>19. Average shop utilization</td>
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<td>81.7</td>
<td>81.1</td>
<td>82.3</td>
<td>82.4</td>
<td>81.7</td>
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<tr>
<td>20. Average number jobs in pool before loading</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
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<td>0</td>
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<td>3.50</td>
<td>3.00</td>
<td>2.50</td>
<td>2.25</td>
<td>Avg.</td>
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<td>--------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
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<td>1. Time spent in the system</td>
<td>84.9</td>
<td>93.5</td>
<td>96.7</td>
<td>102.</td>
<td>109.</td>
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<td></td>
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<td>2. Time spent in the shop</td>
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<td>57.6</td>
<td>56.1</td>
<td>57.5</td>
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<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>97.8</td>
<td>108</td>
<td>112</td>
<td>140.</td>
<td>169.</td>
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<td>4. Machine balance measure, MWB</td>
<td>4.94</td>
<td>5.02</td>
<td>4.84</td>
<td>4.83</td>
<td>4.90</td>
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<td>.704</td>
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<td>.499</td>
<td>.531</td>
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<td>9.4</td>
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<td>7.30</td>
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<td>8.36</td>
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<tr>
<td>8. Period queue balance, PQB</td>
<td>41.6</td>
<td>34.3</td>
<td>24.3</td>
<td>23.4</td>
<td>23.7</td>
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</tr>
<tr>
<td>9. Average queue size</td>
<td>2.50</td>
<td>2.34</td>
<td>2.22</td>
<td>2.14</td>
<td>2.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>535</td>
<td>512</td>
<td>493</td>
<td>485</td>
<td>498</td>
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<td>11. Average number of jobs in the shop</td>
<td>33.2</td>
<td>31.5</td>
<td>30.3</td>
<td>29.5</td>
<td>30.2</td>
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<tr>
<td>12. Average operation done for jobs in shop</td>
<td>81.3</td>
<td>73.5</td>
<td>71.4</td>
<td>66.9</td>
<td>65.5</td>
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<td></td>
</tr>
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<td>13. Average work hours done for jobs in shop</td>
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<td>166</td>
<td>155</td>
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<tr>
<td>15. Variance of lateness distribution</td>
<td>1045.</td>
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<td>1373</td>
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<tr>
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<td>8.14</td>
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<td>24.3</td>
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<tr>
<td>17. Average tardiness variance</td>
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<td>406</td>
<td>382</td>
<td>510</td>
<td>537</td>
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<tr>
<td>18. Number of jobs entering shop</td>
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<td>2113</td>
<td>2113</td>
<td>2113</td>
<td>2113</td>
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<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>81.4</td>
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<td>81.2</td>
<td>81.1</td>
<td>80.8</td>
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<td>22.6</td>
<td>25.9</td>
<td>29.0</td>
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<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>10.00</td>
<td>16.1</td>
<td>19.1</td>
<td>22.5</td>
<td>25.5</td>
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</table>
Table 27. Simulation Results with One Seed

Conditions: Pool, Special loading approach 01101, DSOP, Seed 411719, Various DESLF Values

<table>
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<tr>
<th>Run Number</th>
<th>DESLF</th>
<th>4.25</th>
<th>2.50</th>
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<th>1.50</th>
<th>Avg.</th>
</tr>
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<td>1. Time spent in the system</td>
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<td>74.5</td>
<td>76.9</td>
<td>79.8</td>
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<td></td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>63.0</td>
<td>54.1</td>
<td>53.9</td>
<td>52.8</td>
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</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>111.</td>
<td>97.4</td>
<td>117.</td>
<td>139.</td>
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<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>5.28</td>
<td>5.12</td>
<td>5.09</td>
<td>4.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>0.972</td>
<td>0.849</td>
<td>0.721</td>
<td>0.755</td>
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<td></td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>10.4</td>
<td>7.50</td>
<td>8.21</td>
<td>7.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.36</td>
<td>4.33</td>
<td>4.42</td>
<td>4.27</td>
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<td>8. Period queue balance, PQB</td>
<td>49.8</td>
<td>35.8</td>
<td>27.7</td>
<td>22.0</td>
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<td></td>
</tr>
<tr>
<td>9. Average queue size</td>
<td>2.52</td>
<td>2.05</td>
<td>2.04</td>
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<tr>
<td>10. Average work in process in hours</td>
<td>540.</td>
<td>467</td>
<td>462</td>
<td>453</td>
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<tr>
<td>11. Average number of jobs in the shop</td>
<td>33.3</td>
<td>28.6</td>
<td>28.5</td>
<td>27.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>87.5</td>
<td>79.4</td>
<td>77.4</td>
<td>76.1</td>
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<td></td>
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<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>211.</td>
<td>187</td>
<td>180</td>
<td>172</td>
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<td></td>
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<tr>
<td>14. Average lateness</td>
<td>-17.2</td>
<td>-17.6</td>
<td>-15.2</td>
<td>-12.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>879</td>
<td>1135</td>
<td>1226</td>
<td>1198</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. Average job tardiness</td>
<td>3.01</td>
<td>4.38</td>
<td>6.13</td>
<td>6.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>46.9</td>
<td>69.4</td>
<td>102</td>
<td>103</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2113</td>
<td>2113</td>
<td>2113</td>
<td>2113</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>81.6</td>
<td>81.6</td>
<td>81.4</td>
<td>81.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>7.98</td>
<td>12.2</td>
<td>13.4</td>
<td>15.4</td>
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<td></td>
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<tr>
<td>21. Average number jobs in pool after loading</td>
<td>4.84</td>
<td>9.8</td>
<td>11.4</td>
<td>13.7</td>
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</table>
Table 28. Simulation Results with One Seed

**Conditions:** Pool, Special loading approach 00011, DSOP, Seed 411719, Various DESLF Values

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<td>(11101)</td>
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</tr>
<tr>
<td>Run Number</td>
<td></td>
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<td>2</td>
</tr>
<tr>
<td>1. Time spent in the system</td>
<td></td>
<td>78.8</td>
<td>74.7</td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
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<td>63.4</td>
<td>51.2</td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td></td>
<td>103.</td>
<td>126</td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td></td>
<td>5.11</td>
<td>4.76</td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td></td>
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<td>.666</td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
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<td>7. Period workload balance, PWB</td>
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<tr>
<td>8. Period queue balance, PQB</td>
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<td>38.1</td>
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<tr>
<td>9. Average queue size</td>
<td></td>
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<td>1.90</td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td></td>
<td>539</td>
<td>446</td>
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<tr>
<td>11. Average number of jobs in the shop</td>
<td></td>
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<td>27.1</td>
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<tr>
<td>12. Average operation done for jobs in shop</td>
<td></td>
<td>86.2</td>
<td>76.8</td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
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<td>182</td>
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<td>14. Average lateness</td>
<td></td>
<td>-13.3</td>
<td>-17.4</td>
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<tr>
<td>15. Variance of lateness distribution</td>
<td></td>
<td>810</td>
<td>1235</td>
</tr>
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<td>16. Average job tardiness</td>
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<td>3.95</td>
<td>5.22</td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
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<td>57.9</td>
<td>77.1</td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
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<td>2113</td>
<td>2113</td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td></td>
<td>81.6</td>
<td>81.5</td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td></td>
<td>10.3</td>
<td>13.5</td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td></td>
<td>6.5</td>
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</table>
### Table 29. Simulation Results

Conditions: Job arrival distribution with static mean, No pool, DSOP

<table>
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<tr>
<th>Run Number</th>
<th>1</th>
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<th>3</th>
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<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
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<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>74.9</td>
<td>68.9</td>
<td>69.0</td>
<td>69.1</td>
<td>70.1</td>
<td>70.4</td>
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</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>74.9</td>
<td>68.9</td>
<td>69.0</td>
<td>69.1</td>
<td>70.1</td>
<td>70.4</td>
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</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.477</td>
<td>.689</td>
<td>.507</td>
<td>.672</td>
<td>.631</td>
<td>.595</td>
<td></td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>17.1</td>
<td>12.5</td>
<td>12.6</td>
<td>12.3</td>
<td>13.1</td>
<td>13.5</td>
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</tr>
<tr>
<td>7. Period workload balance, FWB</td>
<td>4.09</td>
<td>4.35</td>
<td>4.13</td>
<td>4.41</td>
<td>4.36</td>
<td>4.27</td>
<td></td>
</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>255.</td>
<td>130.</td>
<td>80.5</td>
<td>32.3</td>
<td>49.1</td>
<td>109.</td>
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</tr>
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<td>9. Average queue size</td>
<td>3.12</td>
<td>2.81</td>
<td>2.83</td>
<td>2.83</td>
<td>2.88</td>
<td>2.89</td>
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<tr>
<td>10. Average work in process in hours</td>
<td>652</td>
<td>592</td>
<td>602</td>
<td>595</td>
<td>602</td>
<td>609</td>
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</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>39.5</td>
<td>36.3</td>
<td>36.6</td>
<td>36.4</td>
<td>36.9</td>
<td>37.1</td>
<td></td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>95.1</td>
<td>94.4</td>
<td>94.9</td>
<td>94.5</td>
<td>94.3</td>
<td>94.6</td>
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<td>13. Average work hours done for jobs in shop</td>
<td>227</td>
<td>228</td>
<td>227</td>
<td>228</td>
<td>227</td>
<td>227</td>
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<td>15. Variance of lateness distribution</td>
<td>1170</td>
<td>834</td>
<td>804</td>
<td>842</td>
<td>822</td>
<td>894</td>
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<tr>
<td>16. Average job tardiness</td>
<td>5.05</td>
<td>1.18</td>
<td>1.46</td>
<td>1.26</td>
<td>1.29</td>
<td>2.05</td>
<td></td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>202</td>
<td>1.18</td>
<td>1.46</td>
<td>1.26</td>
<td>1.29</td>
<td>54.6</td>
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<td>18. Number of jobs entering shop</td>
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<td>2127</td>
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<td>2112</td>
<td>2118</td>
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<td>83.2</td>
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<td>81.5</td>
<td>81.8</td>
<td>82.2</td>
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<tr>
<td>20. Average number jobs in pool before loading</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>21. Average number jobs in pool after loading</td>
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<td>0</td>
<td>0</td>
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</table>
Table 30. Simulation Results

Conditions: Pool, Loading heuristics, DSOP

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<thead>
<tr>
<th>Run Number</th>
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<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
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<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>88.7</td>
<td>78.2</td>
<td>80.6</td>
<td>80.1</td>
<td>77.0</td>
<td>80.9</td>
<td>80.9</td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>70.6</td>
<td>66.9</td>
<td>68.0</td>
<td>67.2</td>
<td>66.6</td>
<td>67.9</td>
<td>67.9</td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>138</td>
<td>129</td>
<td>125</td>
<td>133</td>
<td>125</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.77</td>
<td>5.32</td>
<td>4.80</td>
<td>5.28</td>
<td>5.28</td>
<td>5.09</td>
<td>5.09</td>
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<td>5. Shop balance measure, SWB</td>
<td>0.729</td>
<td>0.925</td>
<td>0.678</td>
<td>0.941</td>
<td>0.874</td>
<td>0.830</td>
<td>0.830</td>
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<tr>
<td>6. Queue workload balance, QWB</td>
<td>12.9</td>
<td>10.8</td>
<td>11.0</td>
<td>10.9</td>
<td>11.4</td>
<td>11.4</td>
<td>11.4</td>
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<tr>
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<td>106</td>
<td>44.2</td>
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<td>16.9</td>
<td>22.1</td>
<td>23.6</td>
<td>43.6</td>
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<td>9. Average queue size</td>
<td>2.96</td>
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<td>2.81</td>
<td>2.75</td>
<td>2.70</td>
<td>2.79</td>
<td>2.79</td>
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<tr>
<td>10. Average work in process in hours</td>
<td>623</td>
<td>575</td>
<td>595</td>
<td>577</td>
<td>570</td>
<td>588</td>
<td>588</td>
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<td>11. Average number of jobs in the shop</td>
<td>37.9</td>
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<td>36.4</td>
<td>35.6</td>
<td>35.1</td>
<td>36.1</td>
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<td>87.4</td>
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<td>88.5</td>
<td>87.4</td>
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<td>210</td>
<td>207</td>
<td>213</td>
<td>210</td>
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<td>14. Average lateness</td>
<td>-1.43</td>
<td>-13.9</td>
<td>-9.3</td>
<td>-11.9</td>
<td>-15.3</td>
<td>-10.4</td>
<td>-10.4</td>
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<td>15. Variance of lateness distrib</td>
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<td>777</td>
<td>828</td>
<td>791</td>
<td>854</td>
<td>854</td>
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<td>16. Average job tardiness</td>
<td>11.1</td>
<td>3.6</td>
<td>5.0</td>
<td>4.5</td>
<td>3.0</td>
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<td>73.0</td>
<td>47.4</td>
<td>102</td>
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<td>18. Number of jobs entering shop</td>
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<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2120</td>
<td>2120</td>
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<tr>
<td>19. Average shop utilization</td>
<td>83.5</td>
<td>81.6</td>
<td>83.2</td>
<td>81.5</td>
<td>81.2</td>
<td>82.2</td>
<td>82.2</td>
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<tr>
<td>20. Average number jobs in pool before loading</td>
<td>11.7</td>
<td>8.2</td>
<td>8.8</td>
<td>8.9</td>
<td>7.6</td>
<td>9.04</td>
<td>9.04</td>
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<tr>
<td>21. Average number jobs in pool after loading</td>
<td>7.4</td>
<td>3.9</td>
<td>4.6</td>
<td>4.7</td>
<td>3.3</td>
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</tbody>
</table>
Table 31. Simulation Results

Conditions: Few interactions, No pool, DSOP

<table>
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<tr>
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<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>34.9</td>
<td>34.4</td>
<td>35.8</td>
<td>36.3</td>
<td>34.5</td>
<td>35.2</td>
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</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>34.9</td>
<td>34.4</td>
<td>35.8</td>
<td>36.3</td>
<td>34.5</td>
<td>35.2</td>
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</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>40.8</td>
<td>40.8</td>
<td>42.3</td>
<td>43.4</td>
<td>40.6</td>
<td>41.6</td>
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<tr>
<td>4. Machine balance measure, MWB</td>
<td>5.89</td>
<td>5.42</td>
<td>5.91</td>
<td>5.41</td>
<td>5.71</td>
<td>5.67</td>
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<tr>
<td>5. Shop balance measure, SWB</td>
<td>1.720</td>
<td>1.453</td>
<td>1.700</td>
<td>1.271</td>
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<td>6. Queue workload balance, QWB</td>
<td>28.6</td>
<td>25.6</td>
<td>31.9</td>
<td>27.6</td>
<td>28.9</td>
<td>28.5</td>
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<td>8. Period queue balance, PQB</td>
<td>340.0</td>
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<td>4.90</td>
<td>5.07</td>
<td>4.77</td>
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<td>170.0</td>
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<td>28.6</td>
<td>29.5</td>
<td>28.0</td>
<td>28.3</td>
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<tr>
<td>12. Average operation done for jobs in shop</td>
<td>16.0</td>
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<td>16.1</td>
<td>17.1</td>
<td>16.7</td>
<td>16.5</td>
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</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
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<td>40.3</td>
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<td>-46.3</td>
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<td>-44.4</td>
<td>-43.6</td>
<td>-46.0</td>
<td>-45.2</td>
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<td>15. Variance of lateness distribution</td>
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<td>1090</td>
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<td>1158</td>
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<td>.30</td>
<td>.14</td>
<td>.13</td>
<td>.21</td>
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<td>17. Average tardiness variance</td>
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<td>3.6</td>
<td>.86</td>
<td>.77</td>
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<td>18. Number of jobs entering shop</td>
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<td>3255</td>
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<td>81.0</td>
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<td>81.8</td>
<td>83.9</td>
<td>82.6</td>
<td>82.5</td>
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</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
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</tbody>
</table>
Table 32. Simulation Results

Conditions: Few interactions, Pool, DSOP

<table>
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<tr>
<th>Run Number</th>
<th>1</th>
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<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
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<td>1. Time spent in the system</td>
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<td>62.5</td>
<td>64.3</td>
<td>76.2</td>
<td>66.3</td>
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<td>2. Time spent in the shop</td>
<td>22.1</td>
<td>20.3</td>
<td>24.0</td>
<td>26.3</td>
<td>21.4</td>
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<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
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<td>23.2</td>
<td>28.5</td>
<td>31.2</td>
<td>24.4</td>
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<td>26.5</td>
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<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.72</td>
<td>4.51</td>
<td>5.02</td>
<td>4.81</td>
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<td>.867</td>
<td>.875</td>
<td>.976</td>
<td></td>
<td>.831</td>
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<td>6. Queue workload balance, QWB</td>
<td>16.2</td>
<td>11.0</td>
<td>21.0</td>
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<td>12.4</td>
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<td>16.3</td>
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<tr>
<td>7. Period workload balance, PWB</td>
<td>4.06</td>
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<td>4.17</td>
<td>4.01</td>
<td>3.81</td>
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<tr>
<td>8. Period queue balance, PQB</td>
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<td>17.0</td>
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<td>43.3</td>
<td>10.1</td>
<td></td>
<td>27.5</td>
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<td>2.63</td>
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<tr>
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<td>86.6</td>
<td>82.7</td>
<td>96.9</td>
<td>107.</td>
<td>85.3</td>
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<td>17.6</td>
<td>16.3</td>
<td>19.3</td>
<td>21.5</td>
<td>17.3</td>
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<td>18.4</td>
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<td>12. Average operation done for jobs in shop</td>
<td>7.25</td>
<td>7.10</td>
<td>7.05</td>
<td>8.14</td>
<td>7.32</td>
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<td>7.37</td>
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<td>15.8</td>
<td>13.6</td>
<td></td>
<td>13.6</td>
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<tr>
<td>15. Variance of lateness distribution</td>
<td>1462</td>
<td>1193</td>
<td>1807</td>
<td>939</td>
<td>1116</td>
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<td>16. Average tardiness</td>
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<td>17. Average tardiness variance</td>
<td>156.</td>
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<tr>
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<td>3257</td>
<td>3211</td>
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<td>3255</td>
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<tr>
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<td>81.2</td>
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<td>82.3</td>
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<td>82.2</td>
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<td>20. Average number jobs in pool before loading</td>
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<td>21. Average number jobs in pool after loading</td>
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<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>Avg.</td>
</tr>
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<td>-------</td>
<td>-------</td>
<td>-------</td>
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<td>74.3</td>
<td>72.2</td>
<td>73.3</td>
<td>77.2</td>
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<td>74.5</td>
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<td>2. Time spent in the shop</td>
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<td>72.2</td>
<td>73.3</td>
<td>77.2</td>
<td>75.6</td>
<td></td>
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<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.91</td>
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<td>4.63</td>
<td>5.18</td>
<td>5.06</td>
<td></td>
<td>5.03</td>
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<td>5. Shop balance measure, SWB</td>
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<td>0.987</td>
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<td>0.887</td>
<td>0.838</td>
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<td>15.4</td>
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<td>8. Period queue balance, PQB</td>
<td>52.6</td>
<td>38.7</td>
<td>45.2</td>
<td>47.4</td>
<td>20.7</td>
<td></td>
<td>40.9</td>
</tr>
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<td>9. Average queue size</td>
<td>3.15</td>
<td>3.04</td>
<td>3.11</td>
<td>3.29</td>
<td>3.23</td>
<td></td>
<td>3.16</td>
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<td>10. Average work in process in hours</td>
<td>647</td>
<td>626</td>
<td>644</td>
<td>664</td>
<td>655</td>
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<td>647.</td>
</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>39.8</td>
<td>38.5</td>
<td>39.4</td>
<td>41.1</td>
<td>40.5</td>
<td></td>
<td>39.9</td>
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<tr>
<td>12. Average operation done for jobs in shop</td>
<td>97.2</td>
<td>94.9</td>
<td>97.9</td>
<td>97.4</td>
<td>98.7</td>
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<td>13. Average work hours done for jobs in shop</td>
<td>232</td>
<td>224</td>
<td>235</td>
<td>228</td>
<td>233</td>
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<td>15. Variance of lateness distribution</td>
<td>672</td>
<td>793</td>
<td>754</td>
<td>713</td>
<td>703</td>
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<td>727.</td>
</tr>
<tr>
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<td>2.1</td>
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<td>2.27</td>
<td>2.51</td>
<td>1.92</td>
<td></td>
<td>2.06</td>
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<tr>
<td>17. Average tardiness variance</td>
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<td>41.0</td>
<td>56.2</td>
<td>22.6</td>
<td></td>
<td>33.8</td>
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<td>18. Number of jobs entering shop</td>
<td>2136</td>
<td>2135</td>
<td>2147</td>
<td>2124</td>
<td>2150</td>
<td></td>
<td>2138</td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.2</td>
<td>81.2</td>
<td>83.3</td>
<td>82.4</td>
<td>82.8</td>
<td></td>
<td>82.6</td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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</table>
Table 34. Simulation Results

Conditions: Asymmetric transition matrix, Pool, DSOP

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<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>93.9</td>
<td>85.0</td>
<td>84.8</td>
<td>95.9</td>
<td>95.4</td>
<td></td>
<td>91.0</td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>64.6</td>
<td>62.2</td>
<td>63.9</td>
<td>64.2</td>
<td>65.4</td>
<td></td>
<td>64.0</td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>78.3</td>
<td>93.2</td>
<td>85.4</td>
<td>86.1</td>
<td>87.9</td>
<td></td>
<td>86.2</td>
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<td>4. Machine balance measure, MWB</td>
<td>4.78</td>
<td>5.44</td>
<td>4.91</td>
<td>5.20</td>
<td>5.24</td>
<td></td>
<td>5.11</td>
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<tr>
<td>5. Shop balance measure, SWB</td>
<td>.384</td>
<td>.771</td>
<td>.489</td>
<td>.566</td>
<td>.519</td>
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<td>.546</td>
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<td>7. Period workload balance, PWB</td>
<td>4.43</td>
<td>4.69</td>
<td>4.45</td>
<td>4.65</td>
<td>4.74</td>
<td></td>
<td>4.59</td>
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<td>8. Period queue balance, PQB</td>
<td>27.2</td>
<td>15.1</td>
<td>14.1</td>
<td>19.6</td>
<td>16.4</td>
<td></td>
<td>18.5</td>
</tr>
<tr>
<td>9. Average queue size -</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>552</td>
<td>524</td>
<td>549</td>
<td>543</td>
<td>556</td>
<td></td>
<td>545</td>
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<td>11. Average number of jobs in the shop</td>
<td>34.5</td>
<td>32.9</td>
<td>34.1</td>
<td>34.1</td>
<td>34.8</td>
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<td>34.1</td>
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<tr>
<td>12. Average operation done for jobs in shop</td>
<td>77.8</td>
<td>80.1</td>
<td>83.6</td>
<td>77.7</td>
<td>49.7</td>
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<td>49.8</td>
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<td>184.</td>
<td>198</td>
<td>178</td>
<td>183</td>
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<td>14. Average lateness</td>
<td>3.6</td>
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<td>-5.5</td>
<td>5.04</td>
<td>4.43</td>
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<td>.39</td>
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<td>15. Variance of lateness distribution</td>
<td>760</td>
<td>1001.</td>
<td>900.</td>
<td>915.</td>
<td>1094.</td>
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<td>934</td>
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<td>16. Average job tardiness</td>
<td>11.8</td>
<td>8.49</td>
<td>7.92</td>
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<td>11.3</td>
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<td>17. Average tardiness variance</td>
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<td>149</td>
<td>258</td>
<td>403</td>
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<td>246</td>
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<td>18. Number of jobs entering shop</td>
<td>2136</td>
<td>2135</td>
<td>2147</td>
<td>2124</td>
<td>2150</td>
<td></td>
<td>2138</td>
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<tr>
<td>19. Average shop utilization</td>
<td>83.1</td>
<td>80.8</td>
<td>82.8</td>
<td>81.9</td>
<td>82.0</td>
<td></td>
<td>82.1</td>
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<td>20. Average number jobs in pool before loading</td>
<td>17.8</td>
<td>14.3</td>
<td>13.6</td>
<td>19.2</td>
<td>18.6</td>
<td></td>
<td>16.7</td>
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<tr>
<td>21. Average number jobs in pool after loading</td>
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<td>10.1</td>
<td>9.4</td>
<td>14.9</td>
<td>14.3</td>
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<td>12.4</td>
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</table>
Table 35. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 4.25, SINPER 16, FACDUD 80, DUD generation 1, No pool, DSOP

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>76.5</td>
<td>72.2</td>
<td>79.1</td>
<td>72.7</td>
<td>72.5</td>
<td>74.6</td>
<td></td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>76.5</td>
<td>72.2</td>
<td>79.1</td>
<td>72.7</td>
<td>72.5</td>
<td>74.6</td>
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</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>168.8</td>
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<td>146.1</td>
<td>159.1</td>
<td>152.8</td>
<td>157.4</td>
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<tr>
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<td>.753</td>
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<td>.715</td>
<td>1.036</td>
<td>.892</td>
<td>.893</td>
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<td>13.3</td>
<td>14.1</td>
<td>14.6</td>
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<tr>
<td>7. Period workload balance, PWB</td>
<td>4.00</td>
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<td>9. Average queue size</td>
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<td>11. Average number of jobs in the shop</td>
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<td>95.1</td>
<td>95.7</td>
<td>96.5</td>
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<td>232.1</td>
<td>234.1</td>
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<td>735.1</td>
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<td>791.1</td>
<td>784.1</td>
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<td>1.63</td>
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<td>39.7</td>
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<td>18. Number of jobs entering shop</td>
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<td>81.5</td>
<td>81.2</td>
<td>82.2</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>21. Average number jobs in pool after loading</td>
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<td>0</td>
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<td>0</td>
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</table>
Table 36. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 4.25, SINPER 16, FACDUD 80, DUD generation 1, No pool, EWIQ

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
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<td>1. Time spent in the system</td>
<td>65.7</td>
<td>62.2</td>
<td>61.3</td>
<td>61.6</td>
<td>62.8</td>
<td>62.7</td>
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<td>2. Time spent in the shop</td>
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<td>62.2</td>
<td>61.3</td>
<td>61.6</td>
<td>62.8</td>
<td>62.7</td>
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<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.81</td>
<td>5.28</td>
<td>5.00</td>
<td>5.33</td>
<td>5.52</td>
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<td>8.81</td>
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<td>9.03</td>
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<td>3.95</td>
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<td>3.94</td>
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<td>20.1</td>
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<tr>
<td>10. Average work in process in hours</td>
<td>573</td>
<td>549</td>
<td>547</td>
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<td>552</td>
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<td>553.</td>
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<tr>
<td>11. Average number of jobs in the shop</td>
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<td>32.6</td>
<td>32.8</td>
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<td>32.9</td>
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<td>13. Average work hours done for jobs in shop</td>
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<td>251.</td>
<td>255.</td>
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<td>258.</td>
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<tr>
<td>14. Average lateness</td>
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<td>-30.4</td>
<td>-29.5</td>
<td></td>
<td>-28.6</td>
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<td>15. Variance of lateness distribution</td>
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<td>3749</td>
<td>389</td>
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<td>4296</td>
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<td>16.7</td>
<td>12.4</td>
<td>13.1</td>
<td>12.1</td>
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<td>13.4</td>
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<tr>
<td>17. Average tardiness variance</td>
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<td>1108</td>
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<td>1482</td>
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<tr>
<td>18. Number of jobs entering shop</td>
<td>2124</td>
<td>2117</td>
<td>2126</td>
<td>2118</td>
<td>2109</td>
<td></td>
<td>2119</td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>82.8</td>
<td>81.6</td>
<td>82.9</td>
<td>81.4</td>
<td>81.0</td>
<td></td>
<td>81.9</td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</table>
Table 37. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 4.25, SINPER 16, FACDUD 80, DUD generation 1, No pool, SPT

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>51.2</td>
<td>47.5</td>
<td>48.8</td>
<td>46.7</td>
<td>48.0</td>
<td>48.4</td>
<td></td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>51.2</td>
<td>47.5</td>
<td>48.8</td>
<td>46.7</td>
<td>48.0</td>
<td>48.4</td>
<td></td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>147.</td>
<td>148.</td>
<td>143.</td>
<td>149.</td>
<td>146.</td>
<td>147.</td>
<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>5.05</td>
<td>5.16</td>
<td>4.86</td>
<td>5.17</td>
<td>5.46</td>
<td>5.14</td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.923</td>
<td>.871</td>
<td>.877</td>
<td>.966</td>
<td>1.302</td>
<td>.988</td>
<td></td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>4.35</td>
<td>3.82</td>
<td>3.61</td>
<td>3.66</td>
<td>3.61</td>
<td>3.81</td>
<td></td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.15</td>
<td>4.34</td>
<td>4.00</td>
<td>4.26</td>
<td>4.22</td>
<td>4.19</td>
<td></td>
</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>78.8</td>
<td>27.4</td>
<td>26.5</td>
<td>6.16</td>
<td>12.3</td>
<td>30.2</td>
<td>30.2</td>
</tr>
<tr>
<td>9. Average queue size</td>
<td>1.82</td>
<td>1.68</td>
<td>1.70</td>
<td>1.65</td>
<td>1.70</td>
<td>1.71</td>
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</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>497</td>
<td>465</td>
<td>471.</td>
<td>458.</td>
<td>468.</td>
<td>472</td>
<td></td>
</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>26.4</td>
<td>25.0</td>
<td>25.3</td>
<td>24.7</td>
<td>25.1</td>
<td>25.3</td>
<td></td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>69.5</td>
<td>64.1</td>
<td>66.0</td>
<td>62.7</td>
<td>64.3</td>
<td>65.3</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>161</td>
<td>148.</td>
<td>150.</td>
<td>144.</td>
<td>147.</td>
<td>150.</td>
<td></td>
</tr>
<tr>
<td>14. Average lateness</td>
<td>-39.1</td>
<td>-44.6</td>
<td>-41.5</td>
<td>-45.4</td>
<td>-44.1</td>
<td>-42.9</td>
<td></td>
</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>4783</td>
<td>3189</td>
<td>3434</td>
<td>3086</td>
<td>3158</td>
<td>3530</td>
<td></td>
</tr>
<tr>
<td>16. Average job tardiness</td>
<td>9.78</td>
<td>7.07</td>
<td>7.80</td>
<td>6.52</td>
<td>7.10</td>
<td>7.65</td>
<td></td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>2052</td>
<td>596.</td>
<td>891</td>
<td>547</td>
<td>585</td>
<td>934</td>
<td></td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2118</td>
<td>2118</td>
<td>2124</td>
<td>2118</td>
<td>2104</td>
<td>2116.</td>
<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>82.8</td>
<td>81.6</td>
<td>82.8</td>
<td>81.5</td>
<td>81.2</td>
<td>82.0</td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Table 38. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 4.25, SINPER 16, FACDUD 80, DUD generation 1, No pool, FCFS

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>74.9</td>
<td>73.7</td>
<td>77.4</td>
<td>69.5</td>
<td>77.6</td>
<td>74.6</td>
<td></td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>74.9</td>
<td>73.7</td>
<td>77.4</td>
<td>69.5</td>
<td>77.6</td>
<td>74.6</td>
<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.71</td>
<td>5.19</td>
<td>4.91</td>
<td>5.01</td>
<td>5.19</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.671</td>
<td>.921</td>
<td>.687</td>
<td>.685</td>
<td>.942</td>
<td>.781</td>
<td></td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>15.9</td>
<td>14.4</td>
<td>17.0</td>
<td>12.8</td>
<td>16.4</td>
<td>15.3</td>
<td></td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.06</td>
<td>4.31</td>
<td>4.24</td>
<td>4.38</td>
<td>4.31</td>
<td>4.26</td>
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</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>171.</td>
<td>201.</td>
<td>131.</td>
<td>45.1</td>
<td>100.</td>
<td>130.</td>
<td></td>
</tr>
<tr>
<td>9. Average queue size</td>
<td>3.16</td>
<td>3.05</td>
<td>3.26</td>
<td>2.86</td>
<td>3.25</td>
<td>3.12</td>
<td></td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>668</td>
<td>642</td>
<td>686</td>
<td>611</td>
<td>676</td>
<td>657</td>
<td></td>
</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>39.9</td>
<td>38.7</td>
<td>40.9</td>
<td>36.7</td>
<td>40.7</td>
<td>39.4</td>
<td></td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>105</td>
<td>102</td>
<td>108</td>
<td>95.6</td>
<td>107</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>252</td>
<td>246</td>
<td>259</td>
<td>231</td>
<td>258</td>
<td>249</td>
<td></td>
</tr>
<tr>
<td>14. Average lateness</td>
<td>-15.3</td>
<td>-18.4</td>
<td>-12.7</td>
<td>-22.6</td>
<td>-14.7</td>
<td>-16.7</td>
<td></td>
</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>3092</td>
<td>2834</td>
<td>3046</td>
<td>2713</td>
<td>3148</td>
<td>2967</td>
<td></td>
</tr>
<tr>
<td>16. Average job tardiness</td>
<td>15.7</td>
<td>13.9</td>
<td>16.8</td>
<td>12.0</td>
<td>16.2</td>
<td>14.9</td>
<td></td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>785</td>
<td>624.</td>
<td>800.</td>
<td>498</td>
<td>801</td>
<td>702</td>
<td></td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2129</td>
<td>2107</td>
<td>2115</td>
<td>2112</td>
<td>2108</td>
<td>2114</td>
<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.3</td>
<td>81.6</td>
<td>82.8</td>
<td>81.5</td>
<td>81.6</td>
<td>82.2</td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>21. Average number jobs in pool after loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Table 39. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 4.25, SINPER 16, FACDUD 80, DUD generation 1, Controlled shop with pool, DSOP

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>116.</td>
<td>88.4</td>
<td>100.2</td>
<td>89.3</td>
<td>79.2</td>
<td></td>
<td>94.6</td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>69.2</td>
<td>62.8</td>
<td>64.7</td>
<td>62.5</td>
<td>61.7</td>
<td></td>
<td>64.2</td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>126.</td>
<td>85.2</td>
<td>89.1</td>
<td>88.0</td>
<td>90.3</td>
<td></td>
<td>95.7</td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.68</td>
<td>5.24</td>
<td>4.70</td>
<td>5.34</td>
<td>5.26</td>
<td></td>
<td>5.04</td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.408</td>
<td>.762</td>
<td>.562</td>
<td>.778</td>
<td>.782</td>
<td></td>
<td>.674</td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>11.6</td>
<td>8.99</td>
<td>9.54</td>
<td>8.48</td>
<td>8.96</td>
<td></td>
<td>9.51</td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.21</td>
<td>4.52</td>
<td>4.15</td>
<td>4.61</td>
<td>4.53</td>
<td></td>
<td>4.40</td>
</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>82.5</td>
<td>31.3</td>
<td>21.5</td>
<td>12.9</td>
<td>15.9</td>
<td></td>
<td>32.8</td>
</tr>
<tr>
<td>9. Average queue size</td>
<td>2.89</td>
<td>2.51</td>
<td>2.63</td>
<td>2.49</td>
<td>2.44</td>
<td></td>
<td>2.59</td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>602.</td>
<td>533</td>
<td>559</td>
<td>529</td>
<td>525</td>
<td></td>
<td>550.</td>
</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>37.2</td>
<td>33.2</td>
<td>34.6</td>
<td>33.1</td>
<td>32.6</td>
<td></td>
<td>34.1</td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>71.7</td>
<td>79.0</td>
<td>74.1</td>
<td>77.5</td>
<td>82.5</td>
<td></td>
<td>80.0</td>
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<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>167.</td>
<td>188.</td>
<td>173.</td>
<td>183</td>
<td>196.</td>
<td></td>
<td>181.</td>
</tr>
<tr>
<td>14. Average lateness</td>
<td>25.6</td>
<td>-3.7</td>
<td>10.3</td>
<td>-2.8</td>
<td>-12.9</td>
<td></td>
<td>-4.1</td>
</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>1374</td>
<td>920</td>
<td>956</td>
<td>1026</td>
<td>867</td>
<td></td>
<td>1029</td>
</tr>
<tr>
<td>16. Average job tardiness</td>
<td>31.3</td>
<td>9.1</td>
<td>17.8</td>
<td>10.5</td>
<td>4.3</td>
<td></td>
<td>14.6</td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>762</td>
<td>188</td>
<td>355</td>
<td>223</td>
<td>68</td>
<td></td>
<td>319.</td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.7</td>
<td>81.5</td>
<td>83.1</td>
<td>81.3</td>
<td>81.2</td>
<td></td>
<td>82.2</td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>27.0</td>
<td>15.7</td>
<td>21.0</td>
<td>16.3</td>
<td>11.3</td>
<td></td>
<td>18.3</td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>22.7</td>
<td>11.4</td>
<td>16.7</td>
<td>12.0</td>
<td>7.1</td>
<td></td>
<td>14.0</td>
</tr>
</tbody>
</table>
Table 40. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 4.25, SIMPER 16, FACDUD 80, DUD generation 1, Pool, EWIQ

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>67.3</td>
<td>63.6</td>
<td>63.0</td>
<td>63.2</td>
<td>64.3</td>
<td>64.3</td>
<td></td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>59.4</td>
<td>55.2</td>
<td>55.5</td>
<td>55.4</td>
<td>56.3</td>
<td>56.4</td>
<td></td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>131.</td>
<td>130.</td>
<td>130.</td>
<td>132.</td>
<td>131.</td>
<td>131.</td>
<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.97</td>
<td>5.32</td>
<td>4.86</td>
<td>5.48</td>
<td>5.56</td>
<td>5.24</td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.998</td>
<td>1.199</td>
<td>.946</td>
<td>1.357</td>
<td>1.601</td>
<td>1.220</td>
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</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>8.22</td>
<td>6.24</td>
<td>5.93</td>
<td>5.88</td>
<td>6.08</td>
<td>6.47</td>
<td></td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.00</td>
<td>4.17</td>
<td>3.93</td>
<td>4.18</td>
<td>4.01</td>
<td>4.06</td>
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</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>144.</td>
<td>36.0</td>
<td>34.5</td>
<td>8.6</td>
<td>14.7</td>
<td>47.6</td>
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</tr>
<tr>
<td>9. Average queue size</td>
<td>2.24</td>
<td>2.11</td>
<td>2.13</td>
<td>2.12</td>
<td>2.15</td>
<td>2.15</td>
<td></td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>515.</td>
<td>487.</td>
<td>496</td>
<td>486</td>
<td>493</td>
<td>495.</td>
<td></td>
</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>30.6</td>
<td>29.3</td>
<td>29.6</td>
<td>29.3</td>
<td>29.6</td>
<td>29.7</td>
<td></td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>100.</td>
<td>93.0</td>
<td>94.9</td>
<td>94.2</td>
<td>95.6</td>
<td>95.5</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>240.</td>
<td>222</td>
<td>226</td>
<td>225</td>
<td>229</td>
<td>228.</td>
<td></td>
</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>5188</td>
<td>3194</td>
<td>3514</td>
<td>3002</td>
<td>3246</td>
<td>3629</td>
<td></td>
</tr>
<tr>
<td>16. Average job tardiness</td>
<td>15.7</td>
<td>11.2</td>
<td>11.8</td>
<td>10.4</td>
<td>11.6</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>2409</td>
<td>707</td>
<td>1040</td>
<td>634</td>
<td>742</td>
<td>1106</td>
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<td>18. Number of jobs entering shop</td>
<td>2124</td>
<td>2117</td>
<td>2126</td>
<td>2118</td>
<td>2109</td>
<td>2119</td>
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</tr>
<tr>
<td>19. Average shop utilization</td>
<td>82.8</td>
<td>81.6</td>
<td>83.0</td>
<td>81.5</td>
<td>81.1</td>
<td>82.0</td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>6.08</td>
<td>6.50</td>
<td>5.91</td>
<td>6.18</td>
<td>6.24</td>
<td>6.18</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>1.84</td>
<td>2.27</td>
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<td>2.03</td>
<td>1.95</td>
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</tr>
<tr>
<td>Run Number</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>Avg.</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>------</td>
</tr>
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<td>1. Time spent in the system</td>
<td>54.3</td>
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<td>53.3</td>
<td>52.0</td>
<td>52.5</td>
<td>52.8</td>
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</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>45.3</td>
<td>43.0</td>
<td>44.5</td>
<td>43.1</td>
<td>43.2</td>
<td>43.8</td>
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</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>5.09</td>
<td>5.30</td>
<td>5.03</td>
<td>5.21</td>
<td>5.64</td>
<td>5.25</td>
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</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>936</td>
<td>870</td>
<td>844</td>
<td>874</td>
<td>1.336</td>
<td>972</td>
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</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>3.26</td>
<td>2.68</td>
<td>2.84</td>
<td>2.63</td>
<td>2.46</td>
<td>2.77</td>
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</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.18</td>
<td>4.48</td>
<td>4.20</td>
<td>4.39</td>
<td>4.36</td>
<td>4.32</td>
<td></td>
</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>34.5</td>
<td>11.6</td>
<td>10.8</td>
<td>3.5</td>
<td>5.3</td>
<td>13.1</td>
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</tr>
<tr>
<td>9. Average queue size</td>
<td>1.57</td>
<td>1.46</td>
<td>1.54</td>
<td>1.46</td>
<td>1.46</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>436.</td>
<td>412.</td>
<td>427.</td>
<td>413.</td>
<td>413.</td>
<td>421.</td>
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<td>11. Average number of jobs in the shop</td>
<td>23.9</td>
<td>22.7</td>
<td>23.6</td>
<td>22.7</td>
<td>22.8</td>
<td>23.1</td>
<td></td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>62.9</td>
<td>58.8</td>
<td>63.0</td>
<td>58.5</td>
<td>58.8</td>
<td>60.4</td>
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</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>3941</td>
<td>2754</td>
<td>2973</td>
<td>2810</td>
<td>2790</td>
<td>3054</td>
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</tr>
<tr>
<td>16. Average job tardiness</td>
<td>8.75</td>
<td>6.50</td>
<td>7.48</td>
<td>6.69</td>
<td>6.78</td>
<td>7.24</td>
<td></td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>1517</td>
<td>424.</td>
<td>671.</td>
<td>446.</td>
<td>433.</td>
<td>698.</td>
<td></td>
</tr>
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<td>18. Number of jobs entering shop</td>
<td>2118</td>
<td>2118</td>
<td>2124</td>
<td>2118</td>
<td>2104</td>
<td>2116</td>
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</tr>
<tr>
<td>19. Average shop utilization</td>
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<td>81.7</td>
<td>82.8</td>
<td>81.5</td>
<td>81.3</td>
<td>82.0</td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>6.64</td>
<td>6.69</td>
<td>6.48</td>
<td>6.71</td>
<td>6.82</td>
<td>6.67</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>2.39</td>
<td>2.45</td>
<td>2.23</td>
<td>2.48</td>
<td>2.61</td>
<td>2.43</td>
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</tbody>
</table>
### Table 42. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 4.25, SImPER 16, FACDUD 80, DUD generation 1, Pool, FCFS

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>87.1</td>
<td>77.8</td>
<td>84.3</td>
<td>73.7</td>
<td>79.7</td>
<td>80.5</td>
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</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>63.9</td>
<td>60.2</td>
<td>63.2</td>
<td>59.3</td>
<td>60.1</td>
<td>61.3</td>
<td></td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>90.3</td>
<td>96.2</td>
<td>93.1</td>
<td>95.5</td>
<td>99.1</td>
<td>94.8</td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.588</td>
<td>.745</td>
<td>.544</td>
<td>.636</td>
<td>.906</td>
<td>.684</td>
<td></td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>9.55</td>
<td>8.00</td>
<td>10.2</td>
<td>7.94</td>
<td>7.67</td>
<td>8.67</td>
<td></td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.11</td>
<td>4.47</td>
<td>4.29</td>
<td>4.49</td>
<td>4.34</td>
<td>4.34</td>
<td></td>
</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>79.5</td>
<td>46.6</td>
<td>39.3</td>
<td>18.4</td>
<td>16.1</td>
<td>40.0</td>
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<tr>
<td>9. Average queue size</td>
<td>2.58</td>
<td>2.38</td>
<td>2.53</td>
<td>2.32</td>
<td>2.36</td>
<td>2.43</td>
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</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>567.</td>
<td>528</td>
<td>561</td>
<td>518</td>
<td>524</td>
<td>540.</td>
<td></td>
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<tr>
<td>11. Average number of jobs in the shop</td>
<td>34.2</td>
<td>32.0</td>
<td>33.6</td>
<td>31.4</td>
<td>31.8</td>
<td>32.6</td>
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</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>88.7</td>
<td>82.8</td>
<td>87.7</td>
<td>81.5</td>
<td>82.3</td>
<td>84.6</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>210.</td>
<td>197.</td>
<td>208.</td>
<td>194.</td>
<td>196.</td>
<td>201.</td>
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<tr>
<td>14. Average lateness</td>
<td>-3.1</td>
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<td>-6.0</td>
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<td>-12.4</td>
<td>-10.9</td>
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</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>2785</td>
<td>2527</td>
<td>2812</td>
<td>2518</td>
<td>2707</td>
<td>2670</td>
<td></td>
</tr>
<tr>
<td>16. Average job tardiness</td>
<td>20.2</td>
<td>14.3</td>
<td>18.9</td>
<td>12.7</td>
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<td>16.4</td>
<td></td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>747.</td>
<td>483</td>
<td>722</td>
<td>430</td>
<td>529</td>
<td>582.</td>
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</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2129</td>
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<td>2115</td>
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<td>2108</td>
<td>2114</td>
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</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.4</td>
<td>81.7</td>
<td>82.8</td>
<td>81.5</td>
<td>81.6</td>
<td>82.2</td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>14.4</td>
<td>11.0</td>
<td>13.1</td>
<td>9.6</td>
<td>12.3</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>10.2</td>
<td>6.8</td>
<td>8.9</td>
<td>5.4</td>
<td>8.1</td>
<td>7.9</td>
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</tr>
</tbody>
</table>
Table 43. Simulation Results with One Seed

Conditions: Showing the effects of changes in DESLF with DSOP, Tight due dates, Sine arrivals, SINPER 16, DUDFCT 80, Seed 100933, Pool, DSOP

<table>
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<tr>
<th>Run Number</th>
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<th>5.0</th>
<th>4.25</th>
<th>3.75</th>
<th>3.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td></td>
<td>92.1</td>
<td>101.</td>
<td>116.</td>
<td>124.</td>
<td>126.</td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td></td>
<td>72.</td>
<td>69.9</td>
<td>69.2</td>
<td>67.5</td>
<td>66.3</td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td></td>
<td>.698</td>
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<td>.488</td>
<td>.475</td>
<td>.486</td>
</tr>
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<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>10.6</td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
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<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>4.40</td>
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<td>8. Period queue balance, PQB</td>
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<td>----</td>
<td>----</td>
<td>----</td>
<td>58.6</td>
</tr>
<tr>
<td>9. Average queue size</td>
<td></td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>2.72</td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td></td>
<td>627</td>
<td>607</td>
<td>601</td>
<td>591</td>
<td>577</td>
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<td>11. Average number of jobs in the shop</td>
<td></td>
<td>38.6</td>
<td>37.5</td>
<td>37.2</td>
<td>36.2</td>
<td>35.4</td>
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<tr>
<td>12. Average operation done for jobs in shop</td>
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<td>84.3</td>
<td>78.4</td>
<td>71.7</td>
<td>66.8</td>
<td>63.6</td>
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<td></td>
<td>202</td>
<td>185</td>
<td>167</td>
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<td>146.</td>
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<td>11.3</td>
<td>25.6</td>
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<td>35.6</td>
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<td>15. Variance of lateness distribution</td>
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<td>1374</td>
<td>1158</td>
<td>1044</td>
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<td>31.3</td>
<td>37.2</td>
<td>38.0</td>
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<td>762</td>
<td>751</td>
<td>725</td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
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<td>2132</td>
<td>2132</td>
<td>2132</td>
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<td>19. Average shop utilization</td>
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<td>83.3</td>
<td>83.5</td>
<td>83.7</td>
<td>83.3</td>
<td>83.0</td>
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<td>18.9</td>
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<td>32.4</td>
<td>34.0</td>
</tr>
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<td>14.6</td>
<td>22.7</td>
<td>28.1</td>
<td>29.7</td>
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</table>
Table 44. Simulation Results with One Seed

Conditions: Showing the effects of changes in DESLF with SPT, Tight due dates, Sine arrivals, SINPER 16, DUDFCT 80, Seed 411719M, Pool, SPT

<table>
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<th>3.25</th>
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<th>Avg.</th>
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<td>1. Time spent in the system</td>
<td></td>
<td>52.4</td>
<td>53.5</td>
<td>56.0</td>
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<td>78.9</td>
<td>92.5</td>
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</tr>
<tr>
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<td>43.2</td>
<td>41.9</td>
<td>39.7</td>
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<td>38.3</td>
<td>38.6</td>
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</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td></td>
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<td>101.</td>
<td>83.8</td>
<td>72.1</td>
<td>84.1</td>
<td>101.</td>
<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
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<td>5.52</td>
<td>5.41</td>
<td>5.25</td>
<td>5.09</td>
<td>4.93</td>
<td>4.79</td>
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<td>1.19</td>
<td>1.12</td>
<td>.944</td>
<td>.697</td>
<td>.523</td>
<td>.515</td>
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<tr>
<td>6. Queue workload balance, QWB</td>
<td></td>
<td>2.53</td>
<td>1.35</td>
<td>2.07</td>
<td>1.83</td>
<td>1.98</td>
<td>2.18</td>
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</tr>
<tr>
<td>7. Period workload balance, PWB</td>
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<td>4.38</td>
<td>4.34</td>
<td>4.36</td>
<td>4.45</td>
<td>4.46</td>
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<td>8. Period queue balance, PQB</td>
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<td>9. Average queue size</td>
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<td>1.47</td>
<td>1.40</td>
<td>1.29</td>
<td>1.19</td>
<td>1.21</td>
<td>1.24</td>
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<td>10. Average work in process in hours</td>
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<td>363.</td>
<td>371</td>
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<td>11. Average number of jobs in the shop</td>
<td></td>
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<td>22.2</td>
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<td>20.1</td>
<td>20.3</td>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td></td>
<td>59.7</td>
<td>57.8</td>
<td>54.2</td>
<td>52.2</td>
<td>52.9</td>
<td>53.4</td>
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</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td></td>
<td>137.</td>
<td>132</td>
<td>124.</td>
<td>119.</td>
<td>120.</td>
<td>123</td>
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<tr>
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<td>-38.6</td>
<td>-36.1</td>
<td>-29.8</td>
<td>-13.3</td>
<td>.52</td>
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<tr>
<td>15. Variance of lateness distribution</td>
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<td>2610</td>
<td>2516</td>
<td>2474</td>
<td>2469</td>
<td>2048</td>
<td></td>
</tr>
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<td>16. Average job tardiness</td>
<td></td>
<td>6.68</td>
<td>6.57</td>
<td>6.50</td>
<td>7.28</td>
<td>12.0</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
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<td>322</td>
<td>340</td>
<td>564</td>
<td>712</td>
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</tr>
<tr>
<td>18. Number of jobs entering shop</td>
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<td>2113</td>
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</tr>
<tr>
<td>19. Average shop utilization</td>
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<td>81.5</td>
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<td>81.6</td>
<td>81.5</td>
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</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td></td>
<td>6.95</td>
<td>8.24</td>
<td>10.7</td>
<td>14.9</td>
<td>23.6</td>
<td>30.6</td>
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</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td></td>
<td>2.72</td>
<td>4.00</td>
<td>6.5</td>
<td>10.7</td>
<td>19.4</td>
<td>26.3</td>
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</tr>
</tbody>
</table>
Table 45. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 2.25, SINPER 16, FACDUD 80, DUD generation 1, No pool, SPT

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>49.2</td>
<td>47.2</td>
<td>47.5</td>
<td>47.6</td>
<td>47.2</td>
<td>47.2</td>
<td>47.7</td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>49.2</td>
<td>47.2</td>
<td>47.5</td>
<td>47.6</td>
<td>47.2</td>
<td>47.2</td>
<td>47.7</td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>162</td>
<td>156.</td>
<td>149.</td>
<td>159.</td>
<td>154.</td>
<td>156.</td>
<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.80</td>
<td>5.28</td>
<td>4.84</td>
<td>5.47</td>
<td>5.37</td>
<td>5.15</td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.990</td>
<td>1.279</td>
<td>.958</td>
<td>1.304</td>
<td>1.266</td>
<td>1.16</td>
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</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>3.89</td>
<td>3.69</td>
<td>3.48</td>
<td>3.62</td>
<td>3.58</td>
<td>3.65</td>
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</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>3.84</td>
<td>4.06</td>
<td>3.90</td>
<td>4.22</td>
<td>4.16</td>
<td>4.04</td>
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</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>42.1</td>
<td>17.0</td>
<td>14.7</td>
<td>4.99</td>
<td>7.93</td>
<td>17.3</td>
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<tr>
<td>9. Average queue size</td>
<td>1.78</td>
<td>1.68</td>
<td>1.70</td>
<td>1.70</td>
<td>1.67</td>
<td>1.71</td>
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</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>489</td>
<td>466</td>
<td>468</td>
<td>471</td>
<td>462</td>
<td>471</td>
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</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>26.1</td>
<td>25.0</td>
<td>25.3</td>
<td>25.2</td>
<td>24.8</td>
<td>25.3</td>
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</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>68.1</td>
<td>64.6</td>
<td>66.3</td>
<td>65.1</td>
<td>64.5</td>
<td>65.7</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>155</td>
<td>149</td>
<td>150</td>
<td>149</td>
<td>148</td>
<td>150</td>
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<tr>
<td>14. Average lateness</td>
<td>-40.8</td>
<td>-44.8</td>
<td>-42.8</td>
<td>-44.5</td>
<td>-44.9</td>
<td>-43.6</td>
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<tr>
<td>15. Variance of lateness  distribution</td>
<td>3744</td>
<td>3096</td>
<td>3117</td>
<td>3146</td>
<td>2986</td>
<td>3218</td>
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</tr>
<tr>
<td>16. Average job tardiness</td>
<td>7.89</td>
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<td>6.68</td>
<td>6.74</td>
<td>6.53</td>
<td>6.89</td>
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<tr>
<td>17. Average tardiness variance</td>
<td>1173</td>
<td>537</td>
<td>644</td>
<td>582</td>
<td>474</td>
<td>682</td>
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<tr>
<td>18. Number of jobs entering shop</td>
<td>2132</td>
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<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2120</td>
<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.4</td>
<td>81.5</td>
<td>83.1</td>
<td>81.4</td>
<td>81.2</td>
<td>82.1</td>
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</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Table 46. Simulation Results - Basic Runs

Conditions: Symmetric transition matrix, Tight due date generation--DESLF 2.25, SINPER 16, FACDUD 80, DUD generation 1, Pool, SPT

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>91.2</td>
<td>78.9</td>
<td>89.5</td>
<td>77.8</td>
<td>79.0</td>
<td>83.3</td>
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</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>40.8</td>
<td>38.3</td>
<td>39.6</td>
<td>37.1</td>
<td>36.8</td>
<td>38.5</td>
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</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>97.0</td>
<td>84.1</td>
<td>89.5</td>
<td>76.8</td>
<td>74.6</td>
<td>84.4</td>
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</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.377</td>
<td>.523</td>
<td>.403</td>
<td>.491</td>
<td>.416</td>
<td>.442</td>
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<tr>
<td>6. Queue workload balance, QWB</td>
<td>2.46</td>
<td>1.98</td>
<td>2.21</td>
<td>1.80</td>
<td>1.89</td>
<td>2.07</td>
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<td>7. Period workload balance, PWB</td>
<td>4.08</td>
<td>4.46</td>
<td>4.07</td>
<td>4.47</td>
<td>4.33</td>
<td>4.28</td>
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</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>12.2</td>
<td>3.85</td>
<td>4.18</td>
<td>1.88</td>
<td>2.15</td>
<td>4.85</td>
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<tr>
<td>9. Average queue size</td>
<td>1.36</td>
<td>1.21</td>
<td>1.29</td>
<td>1.15</td>
<td>1.13</td>
<td>1.23</td>
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</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>394</td>
<td>363</td>
<td>380</td>
<td>348</td>
<td>344</td>
<td>366</td>
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<td>11. Average number of jobs in the shop</td>
<td>21.9</td>
<td>20.3</td>
<td>21.2</td>
<td>19.6</td>
<td>19.4</td>
<td>20.5</td>
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<tr>
<td>12. Average operation done for jobs in shop</td>
<td>56.9</td>
<td>52.9</td>
<td>55.0</td>
<td>51.0</td>
<td>50.2</td>
<td>53.2</td>
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<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>128.</td>
<td>120.</td>
<td>123</td>
<td>114</td>
<td>113</td>
<td>120</td>
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<tr>
<td>16. Average job tardiness</td>
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<td>12.0</td>
<td>15.3</td>
<td>10.9</td>
<td>10.9</td>
<td>13.1</td>
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<tr>
<td>17. Average tardiness variance</td>
<td>857</td>
<td>564</td>
<td>649</td>
<td>424</td>
<td>468</td>
<td>592</td>
<td></td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2132</td>
<td>2113</td>
<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2120</td>
<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.2</td>
<td>81.6</td>
<td>83.2</td>
<td>81.5</td>
<td>81.1</td>
<td>82.1</td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>29.1</td>
<td>23.6</td>
<td>28.7</td>
<td>23.6</td>
<td>24.4</td>
<td>25.9</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>24.8</td>
<td>19.4</td>
<td>24.4</td>
<td>19.4</td>
<td>20.1</td>
<td>21.6</td>
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</tbody>
</table>
Table 47. Simulation Results - Basic Runs

Conditions: Pool, DSOP, DESLF 3.5

<table>
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<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
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</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>126.</td>
<td>105.</td>
<td>119.</td>
<td>97.7</td>
<td>90.9</td>
<td>108.</td>
<td></td>
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<tr>
<td>2. Time spent in the shop</td>
<td>66.3</td>
<td>61.2</td>
<td>65.0</td>
<td>58.8</td>
<td>57.2</td>
<td>61.7</td>
<td></td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>157.</td>
<td>121.</td>
<td>145.</td>
<td>104.</td>
<td>73.4</td>
<td>120.</td>
<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.86</td>
<td>5.35</td>
<td>4.77</td>
<td>5.30</td>
<td>5.25</td>
<td>5.11</td>
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</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.486</td>
<td>.665</td>
<td>.472</td>
<td>.693</td>
<td>.540</td>
<td>.571</td>
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</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>10.6</td>
<td>8.60</td>
<td>9.69</td>
<td>7.51</td>
<td>7.82</td>
<td>8.84</td>
<td></td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.40</td>
<td>4.74</td>
<td>4.32</td>
<td>4.66</td>
<td>4.77</td>
<td>4.58</td>
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<tr>
<td>8. Period queue balance, PQB</td>
<td>58.6</td>
<td>25.9</td>
<td>18.7</td>
<td>11.5</td>
<td>13.1</td>
<td>25.6</td>
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</tr>
<tr>
<td>9. Average queue size</td>
<td>2.72</td>
<td>2.41</td>
<td>2.64</td>
<td>2.29</td>
<td>2.20</td>
<td>2.45</td>
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<tr>
<td>10. Average work in process in hours</td>
<td>577</td>
<td>522</td>
<td>563</td>
<td>502</td>
<td>483</td>
<td>529.</td>
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<td>11. Average number of jobs in the shop</td>
<td>35.4</td>
<td>32.2</td>
<td>34.7</td>
<td>31.0</td>
<td>30.1</td>
<td>32.7</td>
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</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>63.6</td>
<td>68.9</td>
<td>65.8</td>
<td>70.6</td>
<td>71.5</td>
<td>68.1</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>146</td>
<td>162</td>
<td>150.</td>
<td>165.</td>
<td>167.</td>
<td>158.</td>
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<tr>
<td>14. Average lateness</td>
<td>35.6</td>
<td>13.1</td>
<td>29.3</td>
<td>5.7</td>
<td>-1.4</td>
<td>16.5</td>
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<tr>
<td>15. Variance of lateness distribution</td>
<td>1044</td>
<td>1644</td>
<td>1210</td>
<td>1491</td>
<td>990</td>
<td>1276.</td>
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<td>16. Average job tardiness</td>
<td>38.0</td>
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<td>33.7</td>
<td>17.8</td>
<td>10.7</td>
<td>24.7</td>
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<td>17. Average tardiness variance</td>
<td>725</td>
<td>685</td>
<td>705</td>
<td>519</td>
<td>209</td>
<td>569</td>
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<tr>
<td>18. Number of jobs entering shop</td>
<td>2132</td>
<td>2113</td>
<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2120</td>
<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.0</td>
<td>80.8</td>
<td>82.9</td>
<td>81.2</td>
<td>80.7</td>
<td>81.7</td>
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</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>34.0</td>
<td>25.5</td>
<td>31.2</td>
<td>22.7</td>
<td>20.0</td>
<td>26.7</td>
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</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>29.7</td>
<td>21.3</td>
<td>27.0</td>
<td>18.5</td>
<td>15.8</td>
<td>22.5</td>
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</table>
Table 48. Simulation Results

Conditions: Normal conditions, DSOP, No pool, Alternative machine pairs

<table>
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<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>50.9</td>
<td>46.8</td>
<td>47.7</td>
<td>47.5</td>
<td>48.9</td>
<td>48.4</td>
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</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>50.9</td>
<td>46.8</td>
<td>47.7</td>
<td>47.5</td>
<td>48.9</td>
<td>48.4</td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>1.234</td>
<td>1.741</td>
<td>1.281</td>
<td>1.857</td>
<td>1.777</td>
<td>1.58</td>
<td></td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>7.95</td>
<td>6.49</td>
<td>6.69</td>
<td>6.64</td>
<td>7.44</td>
<td>7.04</td>
<td></td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>2.90</td>
<td>3.10</td>
<td>3.01</td>
<td>3.12</td>
<td>3.10</td>
<td>3.05</td>
<td></td>
</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>187.</td>
<td>16.0</td>
<td>26.2</td>
<td>8.23</td>
<td>10.9</td>
<td>49.7</td>
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<tr>
<td>9. Average queue size</td>
<td>1.87</td>
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<td>1.72</td>
<td>1.70</td>
<td>1.76</td>
<td>1.74</td>
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</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>454</td>
<td>413</td>
<td>429</td>
<td>417.</td>
<td>430.</td>
<td>429.</td>
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<tr>
<td>11. Average number of jobs in the shop</td>
<td>27.0</td>
<td>24.8</td>
<td>25.5</td>
<td>25.1</td>
<td>25.7</td>
<td>25.6</td>
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</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>77.0</td>
<td>70.4</td>
<td>72.8</td>
<td>71.4</td>
<td>74.1</td>
<td>73.1</td>
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<td>13. Average work hours done for jobs in shop</td>
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<td>166</td>
<td>170</td>
<td>168.</td>
<td>176.</td>
<td>172.</td>
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<tr>
<td>14. Average lateness</td>
<td>-39.3</td>
<td>-45.1</td>
<td>-42.3</td>
<td>-44.6</td>
<td>-43.3</td>
<td>-42.9</td>
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<tr>
<td>16. Average job tardiness</td>
<td>0.741</td>
<td>0.424</td>
<td>0.333</td>
<td>0.376</td>
<td>0.409</td>
<td>0.457</td>
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<tr>
<td>17. Average tardiness variance</td>
<td>14.0</td>
<td>4.74</td>
<td>2.58</td>
<td>4.12</td>
<td>4.22</td>
<td>5.93</td>
<td></td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2132</td>
<td>2113</td>
<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2120</td>
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</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.7</td>
<td>81.5</td>
<td>83.1</td>
<td>81.4</td>
<td>81.1</td>
<td>82.2</td>
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</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>Conditions: Normal conditions, DSOP, Pool, Alternative machine pairs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>---------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Run Number</strong></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>Avg.</td>
</tr>
<tr>
<td>----------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>-----</td>
</tr>
<tr>
<td>1. Time spent in the system</td>
<td>98.0</td>
<td>68.8</td>
<td>97.8</td>
<td>79.1</td>
<td>74.2</td>
<td>83.6</td>
<td></td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>37.8</td>
<td>32.9</td>
<td>38.2</td>
<td>25.0</td>
<td>33.7</td>
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<tr>
<td>5. Shop balance measure, SWB</td>
<td>.708</td>
<td>.799</td>
<td>.620</td>
<td>.879</td>
<td>.829</td>
<td>.767</td>
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</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>3.27</td>
<td>2.16</td>
<td>3.48</td>
<td>2.69</td>
<td>2.45</td>
<td>2.81</td>
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<tr>
<td>7. Period workload balance, PWB</td>
<td>3.41</td>
<td>3.54</td>
<td>3.38</td>
<td>3.54</td>
<td>3.55</td>
<td>3.48</td>
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<tr>
<td>8. Period queue balance, PQB</td>
<td>6.55</td>
<td>2.82</td>
<td>3.74</td>
<td>3.26</td>
<td>2.82</td>
<td>3.84</td>
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</tr>
<tr>
<td>9. Average queue size</td>
<td>1.19</td>
<td>.931</td>
<td>1.20</td>
<td>1.04</td>
<td>.963</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>336</td>
<td>289</td>
<td>336</td>
<td>305</td>
<td>291</td>
<td>311</td>
<td></td>
</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>20.2</td>
<td>17.5</td>
<td>20.3</td>
<td>18.6</td>
<td>17.7</td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>45.3</td>
<td>45.2</td>
<td>45.7</td>
<td>45.1</td>
<td>44.8</td>
<td>45.2</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>97.0</td>
<td>98.8</td>
<td>97.9</td>
<td>97.8</td>
<td>97.6</td>
<td>97.8</td>
<td></td>
</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>847</td>
<td>1471</td>
<td>842</td>
<td>1479</td>
<td>1354</td>
<td>1199</td>
<td></td>
</tr>
<tr>
<td>16. Average job tardiness</td>
<td>15.0</td>
<td>4.13</td>
<td>14.8</td>
<td>7.79</td>
<td>5.07</td>
<td>9.36</td>
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<tr>
<td>17. Average tardiness variance</td>
<td>206</td>
<td>63.7</td>
<td>215</td>
<td>146</td>
<td>88.4</td>
<td>143.8</td>
<td></td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2132</td>
<td>2113</td>
<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2120</td>
<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.1</td>
<td>81.7</td>
<td>83.0</td>
<td>81.5</td>
<td>80.8</td>
<td>82.0</td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>34.3</td>
<td>21.1</td>
<td>34.0</td>
<td>25.4</td>
<td>23.4</td>
<td>27.6</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>30.0</td>
<td>16.8</td>
<td>29.7</td>
<td>21.2</td>
<td>19.2</td>
<td>23.4</td>
<td></td>
</tr>
</tbody>
</table>
Table 50. Simulation Results

Conditions: Symmetric transition matrix, Tight due date generation (method 1), DESLF 4.25, SINGER 16, FACDUD 80, Pool loading, Modified GENMAT to force jobs in the shop 16 hours before required by job content, DSOP

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>108</td>
<td>82.2</td>
<td>99.1</td>
<td>83.2</td>
<td>80.9</td>
<td>90.7</td>
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</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>70.3</td>
<td>62.9</td>
<td>66.4</td>
<td>62.1</td>
<td>63.7</td>
<td>65.2</td>
<td></td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>126</td>
<td>93.6</td>
<td>104.</td>
<td>95.7</td>
<td>93.6</td>
<td>102.6</td>
<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>4.63</td>
<td>5.24</td>
<td>4.75</td>
<td>5.21</td>
<td>5.15</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>.490</td>
<td>.777</td>
<td>.531</td>
<td>.771</td>
<td>.702</td>
<td>.654</td>
<td></td>
</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.15</td>
<td>4.51</td>
<td>4.2</td>
<td>4.49</td>
<td>4.50</td>
<td>4.31</td>
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</tr>
<tr>
<td>8. Period queue balance, PQB</td>
<td>91.4</td>
<td>35.7</td>
<td>28.3</td>
<td>11.9</td>
<td>17.1</td>
<td>36.9</td>
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</tr>
<tr>
<td>9. Average queue size</td>
<td>2.93</td>
<td>2.52</td>
<td>2.72</td>
<td>2.50</td>
<td>2.52</td>
<td>2.64</td>
<td></td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>607</td>
<td>534</td>
<td>574</td>
<td>532</td>
<td>539</td>
<td>557</td>
<td></td>
</tr>
<tr>
<td>11. Average number of jobs in the shop</td>
<td>37.7</td>
<td>33.3</td>
<td>35.5</td>
<td>33.1</td>
<td>33.3</td>
<td>34.6</td>
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</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>73.6</td>
<td>81.9</td>
<td>73.2</td>
<td>80.8</td>
<td>82.5</td>
<td>78.4</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>171</td>
<td>196</td>
<td>170</td>
<td>191</td>
<td>197</td>
<td>185</td>
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<tr>
<td>14. Average lateness</td>
<td>18.4</td>
<td>-9.95</td>
<td>-9.08</td>
<td>-9.01</td>
<td>-11.4</td>
<td>-4.21</td>
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</tr>
<tr>
<td>15. Variance of lateness distribution</td>
<td>1020</td>
<td>774</td>
<td>897</td>
<td>803</td>
<td>840</td>
<td>867</td>
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<tr>
<td>16. Average job tardiness</td>
<td>23.9</td>
<td>4.76</td>
<td>16.4</td>
<td>5.76</td>
<td>4.51</td>
<td>10.9</td>
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</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>513</td>
<td>81.9</td>
<td>296</td>
<td>117</td>
<td>73.2</td>
<td>216</td>
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</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2132</td>
<td>2113</td>
<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2120</td>
<td></td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>83.4</td>
<td>81.6</td>
<td>83.2</td>
<td>81.5</td>
<td>81.3</td>
<td>82.2</td>
<td></td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>22.5</td>
<td>12.3</td>
<td>19.5</td>
<td>13.0</td>
<td>11.3</td>
<td>15.7</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>18.2</td>
<td>8.1</td>
<td>15.3</td>
<td>8.7</td>
<td>7.1</td>
<td>11.5</td>
<td></td>
</tr>
</tbody>
</table>
Table 51. Simulation Results

Conditions: Symmetric transition matrix, Loose due date generation (method 2), SINPER 16, No pool, DSOP

<table>
<thead>
<tr>
<th>Run Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>74.1</td>
<td>74.9</td>
<td>75.4</td>
<td>75.4</td>
<td>76.0</td>
<td>75.2</td>
<td></td>
</tr>
<tr>
<td>2. Time spent in the shop</td>
<td>74.1</td>
<td>74.9</td>
<td>75.4</td>
<td>75.4</td>
<td>76.0</td>
<td>75.2</td>
<td></td>
</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>148</td>
<td>138</td>
<td>144</td>
<td>143</td>
<td>142</td>
<td>143</td>
<td></td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>5.30</td>
<td>4.81</td>
<td>5.39</td>
<td>5.33</td>
<td>5.36</td>
<td>5.24</td>
<td></td>
</tr>
<tr>
<td>5. Shop balance measure, SWB</td>
<td>1.17</td>
<td>.929</td>
<td>1.22</td>
<td>1.23</td>
<td>1.21</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>6. Queue workload balance, QWB</td>
<td>14.7</td>
<td>15.7</td>
<td>14.5</td>
<td>15.0</td>
<td>14.8</td>
<td>14.9</td>
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</tr>
<tr>
<td>7. Period workload balance, PWB</td>
<td>4.18</td>
<td>3.89</td>
<td>4.23</td>
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<td>4.13</td>
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<td>8. Period queue balance, PQB</td>
<td>89.5</td>
<td>78.9</td>
<td>23.4</td>
<td>43.6</td>
<td>88.4</td>
<td>64.8</td>
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<tr>
<td>9. Average queue size</td>
<td>3.1</td>
<td>3.17</td>
<td>3.17</td>
<td>3.15</td>
<td>3.17</td>
<td>3.15</td>
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<tr>
<td>10. Average work in process in hours</td>
<td>635</td>
<td>659</td>
<td>646</td>
<td>645</td>
<td>643</td>
<td>646</td>
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<tr>
<td>11. Average number of jobs in the shop</td>
<td>39.2</td>
<td>40.0</td>
<td>39.9</td>
<td>39.7</td>
<td>39.8</td>
<td>39.7</td>
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</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>124</td>
<td>127</td>
<td>126</td>
<td>126</td>
<td>125</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td>13. Average work hours done for jobs in shop</td>
<td>305</td>
<td>313</td>
<td>311</td>
<td>309</td>
<td>308</td>
<td>309</td>
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</tr>
<tr>
<td>14. Average lateness</td>
<td>-96.2</td>
<td>-91.2</td>
<td>-94.9</td>
<td>-95.1</td>
<td>-95.1</td>
<td>-94.5</td>
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<tr>
<td>15. Variance of lateness distribution</td>
<td>4161</td>
<td>3887</td>
<td>4136</td>
<td>4095</td>
<td>4111</td>
<td>4078</td>
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</tr>
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<td>.012</td>
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<td>.002</td>
<td>.006</td>
<td>.001</td>
<td>.005</td>
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<td>17. Average tardiness variance</td>
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<td>.037</td>
<td>.004</td>
<td>.031</td>
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<tr>
<td>18. Number of jobs entering shop</td>
<td>2113</td>
<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2113</td>
<td>2116</td>
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</tr>
<tr>
<td>19. Average shop utilization</td>
<td>81.6</td>
<td>83.1</td>
<td>81.4</td>
<td>81.2</td>
<td>81.5</td>
<td>81.8</td>
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</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Table 52. Simulation Results

Conditions: Symmetric transition matrix, Loose due date generation (method 2), DESLF 3.50, SINTER 16, FACDUD 80, Pool loading, Modified GENMAT to force jobs in the shop 24 hours before required by job content, DSOP

<table>
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<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th>Avg.</th>
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<tbody>
<tr>
<td>1. Time spent in the system</td>
<td>76.0</td>
<td>78.4</td>
<td>72.4</td>
<td>77.9</td>
<td>77.1</td>
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<td>77.4</td>
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<td>2. Time spent in the shop</td>
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<td>58.7</td>
<td>59.6</td>
<td>59.2</td>
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</tr>
<tr>
<td>3. Aggregate deviation from Des. Bal.</td>
<td>84.2</td>
<td>77.3</td>
<td>82.6</td>
<td>84.4</td>
<td>83.7</td>
<td></td>
<td>82.4</td>
</tr>
<tr>
<td>4. Machine balance measure, MWB</td>
<td>5.30</td>
<td>4.76</td>
<td>5.31</td>
<td>5.40</td>
<td>5.18</td>
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<td>5. Shop balance measure, SWB</td>
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<td>.891</td>
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<td>.921</td>
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<td>6.79</td>
<td>8.38</td>
<td>6.59</td>
<td>7.33</td>
<td>6.65</td>
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<td>7.15</td>
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<tr>
<td>7. Period workload balance, PWB</td>
<td>4.37</td>
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<td>4.48</td>
<td>4.42</td>
<td>4.21</td>
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<td>4.32</td>
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<tr>
<td>8. Period queue balance, PQB</td>
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<td>10.5</td>
<td>16.7</td>
<td>48.0</td>
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<td>26.5</td>
</tr>
<tr>
<td>9. Average queue size</td>
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<td>2.29</td>
<td>2.33</td>
<td>2.30</td>
<td></td>
<td>2.33</td>
</tr>
<tr>
<td>10. Average work in process in hours</td>
<td>508</td>
<td>527</td>
<td>503</td>
<td>509</td>
<td>504</td>
<td></td>
<td>511</td>
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<td>11. Average number of jobs in the shop</td>
<td>31.2</td>
<td>32.5</td>
<td>31.1</td>
<td>31.4</td>
<td>31.2</td>
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<td>31.4</td>
</tr>
<tr>
<td>12. Average operation done for jobs in shop</td>
<td>98.5</td>
<td>103</td>
<td>97.8</td>
<td>98.8</td>
<td>97.5</td>
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<td>99.1</td>
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<td>13. Average work hours done for jobs in shop</td>
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<td>248</td>
<td>238</td>
<td>240</td>
<td>238</td>
<td></td>
<td>241</td>
</tr>
<tr>
<td>14. Average lateness</td>
<td>-94.4</td>
<td>-87.5</td>
<td>-92.9</td>
<td>-92.6</td>
<td>-94.0</td>
<td></td>
<td>-92.3</td>
</tr>
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<td>4294</td>
<td>4179</td>
<td>4385</td>
<td>4210</td>
<td>4245</td>
<td></td>
<td>4263</td>
</tr>
<tr>
<td>16. Average job tardiness</td>
<td>.016</td>
<td>.032</td>
<td>.017</td>
<td>.019</td>
<td>.015</td>
<td></td>
<td>.020</td>
</tr>
<tr>
<td>17. Average tardiness variance</td>
<td>.098</td>
<td>.140</td>
<td>.060</td>
<td>.091</td>
<td>.060</td>
<td></td>
<td>.090</td>
</tr>
<tr>
<td>18. Number of jobs entering shop</td>
<td>2113</td>
<td>2132</td>
<td>2113</td>
<td>2110</td>
<td>2113</td>
<td></td>
<td>2116</td>
</tr>
<tr>
<td>19. Average shop utilization</td>
<td>81.6</td>
<td>83.3</td>
<td>81.5</td>
<td>81.3</td>
<td>81.9</td>
<td></td>
<td>81.9</td>
</tr>
<tr>
<td>20. Average number jobs in pool before loading</td>
<td>11.1</td>
<td>11.5</td>
<td>12.0</td>
<td>11.7</td>
<td>11.3</td>
<td></td>
<td>11.5</td>
</tr>
<tr>
<td>21. Average number jobs in pool after loading</td>
<td>6.8</td>
<td>7.2</td>
<td>7.7</td>
<td>7.4</td>
<td>7.0</td>
<td></td>
<td>7.2</td>
</tr>
</tbody>
</table>
APPENDIX J

STATISTICAL TEST RESULTS
Table 53. T Tests, Paired Observations

<table>
<thead>
<tr>
<th>CRITICAL VALUES</th>
<th>Tables 29, 35, flat vs fluctuating arrivals</th>
<th>Tables 30, 39, heuristic vs algorithm</th>
<th>Tables 31, 32, no pool vs pool</th>
<th>Tables 33, 34, no pool vs pool</th>
<th>Tables 35, 39, no pool vs pool</th>
<th>Tables 36, 40, no pool vs pool</th>
<th>Tables 37, 41, no pool vs pool</th>
<th>Tables 38, 42, no pool vs pool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonpaired test</td>
<td>t.95(8) = 1.860</td>
<td>t.95(8) = 1.860</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>t.99(8) = 2.896</td>
<td>t.99(8) = 2.896</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paired tests</td>
<td>t.95(4) = 2.132</td>
<td>t.95(4) = 2.132</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>t.99(4) = 3.747</td>
<td>t.99(4) = 3.747</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R 3, Dev. from BAL</td>
<td>-6.14</td>
<td>5.78</td>
<td>16.04</td>
<td>28.83</td>
<td>10.98</td>
<td>16.91</td>
<td>25.00</td>
<td>12.97</td>
</tr>
<tr>
<td>4, MWB(t)</td>
<td>-3.29</td>
<td>1.55</td>
<td>9.95</td>
<td>-1.21</td>
<td>-2.24</td>
<td>-0.92</td>
<td>-3.70</td>
<td>0.56</td>
</tr>
<tr>
<td>5, SWB</td>
<td>-9.14</td>
<td>6.12</td>
<td>7.03</td>
<td>4.97</td>
<td>5.87</td>
<td>1.81</td>
<td>0.72</td>
<td>3.61</td>
</tr>
<tr>
<td>6, QWB</td>
<td>-1.77</td>
<td>7.97</td>
<td>7.48</td>
<td>13.73</td>
<td>13.66</td>
<td>12.57</td>
<td>14.87</td>
<td>10.71</td>
</tr>
<tr>
<td>8, PQB</td>
<td>+3.34</td>
<td>3.07</td>
<td>2.55</td>
<td>4.77</td>
<td>2.28</td>
<td>1.93</td>
<td>-0.18</td>
<td>4.44</td>
</tr>
<tr>
<td>13, Avg hrs work done</td>
<td>-2.89</td>
<td>6.38</td>
<td>61.82</td>
<td>15.90</td>
<td>10.95</td>
<td>20.41</td>
<td>6.76</td>
<td>11.33</td>
</tr>
<tr>
<td>14, Var of lateness</td>
<td>+2.35</td>
<td>-4.05</td>
<td>-1.19</td>
<td>-4.12</td>
<td>-3.52</td>
<td>19.73</td>
<td>4.93</td>
<td>7.08</td>
</tr>
<tr>
<td>15, Avg tardiness</td>
<td>-0.16</td>
<td>-2.76</td>
<td>-7.35</td>
<td>-7.17</td>
<td>-2.93</td>
<td>9.63</td>
<td>2.13</td>
<td>-1.70</td>
</tr>
</tbody>
</table>
### Table 53. (Concluded)

<table>
<thead>
<tr>
<th></th>
<th>Basic runs, SPT with DESLF = 2.25</th>
<th>No pool vs pool</th>
<th>Basic runs, DSOP with DESLF = 2.50</th>
<th>No pool vs pool</th>
<th>Using alternative machine pairs</th>
<th>No pool vs pool, DSOP</th>
<th>10 machines vs 5 alt mach pairs</th>
<th>No pool vs pool, DSOP</th>
<th>10 machines vs 5 alt mach pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, Dev. from BAL</td>
<td>R 3, Dev. from BAL</td>
<td>16.82</td>
<td>2.58</td>
<td>9.77</td>
<td>-2.02</td>
<td>.67</td>
<td>4.37</td>
<td>3.81</td>
<td></td>
</tr>
<tr>
<td>4, MWB(t)</td>
<td>7.24</td>
<td>-6.18</td>
<td>5.02</td>
<td>-1.55</td>
<td>3.65</td>
<td>5.73</td>
<td>17.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5, SWB</td>
<td>12.57</td>
<td>10.86</td>
<td>5.11</td>
<td>2.67</td>
<td>8.87</td>
<td>-9.07</td>
<td>-7.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6, QWB</td>
<td>15.68</td>
<td>9.61</td>
<td>14.36</td>
<td>2.80</td>
<td>13.73</td>
<td>27.15</td>
<td>13.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7, PWB</td>
<td>-5.87</td>
<td>-12.88</td>
<td>1.10</td>
<td>-5.24</td>
<td>-19.35</td>
<td>20.56</td>
<td>19.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8, PQB</td>
<td>2.67</td>
<td>2.20</td>
<td>1.39</td>
<td>1.72</td>
<td>1.37</td>
<td>2.62</td>
<td>2.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10, Avg WIP hrs</td>
<td>15.88</td>
<td>7.95</td>
<td>10.80</td>
<td>2.60</td>
<td>15.59</td>
<td>50.40</td>
<td>22.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13, Avg hrs work done</td>
<td>16.73</td>
<td>20.38</td>
<td>16.26</td>
<td>12.25</td>
<td>24.64</td>
<td>21.73</td>
<td>14.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14, Var of lateness</td>
<td>5.94</td>
<td>-3.43</td>
<td>3.20</td>
<td>-1.41</td>
<td>.65</td>
<td>-16.42</td>
<td>.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15, Avg tardiness</td>
<td>-6.38</td>
<td>-4.82</td>
<td>-7.37</td>
<td>-4.95</td>
<td>-3.85</td>
<td>3.81</td>
<td>4.77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 54. ANOVA F Tests (F values)

<table>
<thead>
<tr>
<th>F .99(3.16) = 5.29</th>
<th>Tables 35 to 38</th>
<th>Tables 39 to 42</th>
<th>Tables 47, 40, 46, 42</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Pool</td>
<td>Pool, DESLF = 4.25</td>
<td>Pool, DESLF for</td>
</tr>
<tr>
<td></td>
<td>Four Dispatching Rules</td>
<td>Four Dispatching Rules</td>
<td>DSOP = 3.50, SPT = 2.25, Others = 4.25</td>
</tr>
<tr>
<td>R 3, Dev from BAL</td>
<td>1.648</td>
<td>22.14</td>
<td>7.37</td>
</tr>
<tr>
<td>4, MWB</td>
<td>.881</td>
<td>1.17</td>
<td>3.99</td>
</tr>
<tr>
<td>5, SWB</td>
<td>6.815</td>
<td>8.80</td>
<td>21.75</td>
</tr>
<tr>
<td>6, QWB</td>
<td>93.598</td>
<td>47.13</td>
<td>49.87</td>
</tr>
<tr>
<td>7, PWB</td>
<td>6.030</td>
<td>4.86</td>
<td>7.81</td>
</tr>
<tr>
<td>8, PQB</td>
<td>2.904</td>
<td>.134</td>
<td>1.72</td>
</tr>
<tr>
<td>10, Avg WIP hrs</td>
<td>75.155</td>
<td>37.90</td>
<td>47.72</td>
</tr>
<tr>
<td>13, Avg hrs work done</td>
<td>212.97</td>
<td>110.37</td>
<td>198.</td>
</tr>
<tr>
<td>14, Var of lateness</td>
<td>36.78</td>
<td>22.50</td>
<td>20.70</td>
</tr>
<tr>
<td>15, Avg tardiness</td>
<td>66.77</td>
<td>2.51</td>
<td>4.44</td>
</tr>
</tbody>
</table>
Table 55. Duncan Ranking Tests

I -- Tables 35-38

No Pool, four dispatching rules

Row 3, Deviation from Bal
No difference in the means

Row 4, MWB
No difference in the means

Row 5, SWB
EWIQ is different

Row 6, QWB
No difference between DSOP and FCFS
Other groupings are different

Row 7, PWB
EWIQ is different

Row 8, PQB
SPT is different from FCFS

Row 10, Avg WIP (hrs)
DSOP and FCFS show no difference

Row 13, Avg hours work done
No difference between FCFS and EWIQ

Row 14, Variance of lateness dest
No difference between FCFS and SPT

Row 15, Average tardiness
No difference between EWIQ, FCFS

II -- Tables 39-42

Pool, four dispatching rules

Row 3, Deviation from Balance
FCFS and DSOP show no difference
SPT and EWIQ show no difference,
but the two groups are different from each other
Table 55. (Continued)

<table>
<thead>
<tr>
<th>Row</th>
<th>Measure</th>
<th>DSOP</th>
<th>FCFS</th>
<th>SPT</th>
<th>EWIQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>4, MWB</td>
<td>No difference shown</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5, SWB</td>
<td>No difference between DSOP and FCFS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6, QWB</td>
<td>No difference between FCFS and DSOP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7, PWB</td>
<td>EWIQ is different</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8, PQB</td>
<td>No difference</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10, Avg WIP hrs</td>
<td>No difference between FCFS and DSOP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13, Avg hours of work done</td>
<td>All means are different</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14, Var. of lateness</td>
<td>DSOP is different from all others</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Also FCFS and EWIQ are different</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15, Avg tardiness</td>
<td>SPT and FCFS are different</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

III -- Tables 47, 40, 46, 42

Pool, four dispatching rules with the following DESLF values:
DSOP (3, 5), EWIQ (4.25), SPT (2.25), FCFS (4.25)

<table>
<thead>
<tr>
<th>Row</th>
<th>Measure</th>
<th>SPT</th>
<th>FCFS</th>
<th>DSOP</th>
<th>EWIQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, Deviation from balance</td>
<td>No difference between SPT and FCFS or between DSOP and EWIQ. Other comparisons show differences.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, MWB</td>
<td>SPT differs from DSOP and EWIQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5, SWB</td>
<td>EWIQ is different from all others</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Also SPT is different from FCFS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 55. (Concluded)

<table>
<thead>
<tr>
<th>Row 6, QWB</th>
<th>No difference between FCFS and DSOP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPT</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Row 7, PWB</td>
<td>No difference between SPT and FCFS</td>
</tr>
<tr>
<td></td>
<td>EWIQ</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Row 8, PQB</td>
<td>No difference</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Row 10, Avg WIP hrs</td>
<td>SPT is different from all others</td>
</tr>
<tr>
<td></td>
<td>Also EWIQ and FCFS are different</td>
</tr>
<tr>
<td></td>
<td>SPT</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Row 13, Avg hours of work done</td>
<td>All means are different</td>
</tr>
<tr>
<td></td>
<td>SPT</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Row 14, Variance of lateness</td>
<td>No difference between SPT and FCFS</td>
</tr>
<tr>
<td></td>
<td>DSOP</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Row 15, Average tardiness</td>
<td>DSOP is different</td>
</tr>
<tr>
<td></td>
<td>EWIQ</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX K

FORTRAN IV LISTING OF SUBROUTINES CHANGED
FOR THE ALTERNATIVE MACHINE OPTION
IN THE SIMULATION PROGRAM
SUBROUTINE ENDSV (NSET)

*** EVENT SUBROUTINE CALLED WHEN AN END OF SERVICE
*** HAS OCCURRED FOR A JOB OPERATION

DIMENSION NSET(35,1)
COMMON ID,IN,IN1NIT,JENV,JNINIT,MFA,MSSTOP,MX,MXCLCT,
1NHI,NOQ,NCRT,NOT,PRM,NRM,NRUN,NSAT,OUT,SCALE,
2ISEED,TNOW,TSEG,TFIN,XX,NPRNT,NCRDR,NEP,VMQ(25),
3KOF,KLE,KOL,ATRI3(33),ENQ(25),INN(25),JCELS(20,32),
4KRANK(25),JCLR,MAXQ(25),MFE(25),MLC(25),MLE(25),
5NCELS(20),NG(25),PARA(40,4),QTIME(25),SSUMA(20,5),
6SUMA(75,5),NAME(6),NPROM,NON,NDAY,YNR,
COMMON PLEN,NPDS,NTPD,N"XISYS,XWKSY,TDUE,
1ITYPE,MNEXT,LEN,NLV,NHELDM,BM(10),MBM(10),X(10,10),
2BUS(10),NRSET,NRULE,KNOW,NSRT,NENDS,NHOL,NRL,
3WWW(10),SEED,ARATE,LOC(20),MAX,AR(11),
COMMON MPPREL,NPREP,NDESL,NDML,CAP(10),DESL(10),
1DQL(10),DESLF,DMLF,QLOAD(10),XOPS,XKSY,TIMEF(10),
2NSTSW,NLDR,NARR,SHOPLD(10)
COMMON A(25,100),K8V(15),C(100),FACNUS
COMMON ICOUNT,NCOUNT,SINPER,MSW(10),AVGLD
MNOW=ATRI3(11)+0.00001
MNEXT=ATRI3(13)+0.00001
CALL TMST (XOPS,TNOW,13,NSET)
XOPS=XOPS+1.0
CALL TMST (XKSY,TNOW,14,NSET)
XKSY=XKSY+ATRI3(12)
ATRI3(32)=ATRI3(32)+ATRI3(12)
ATRI3(5)=ATRI3(5)-1.0
IF (ATRI3(5)) 1
C
C
10 TISYS=TNOW-ATRI3(3)
CALL COLCT (TISYS,11,NSET)
NOP=ATRI3(10)+0.00001
NP23=NOP+22
CALL COLCT (TISYS,NP23,NSET)
CALL TMST (TISYS,TNOW,12,NSET)
TISYS=TISYS-1.0
CALL TMST (XKSY,TNOW,11,NSET)
XKSY=XKSY-ATRI3(9)
DDD=ABS(TNOW-ATRI3(4))
CALL COLCT (DDD,15,NSET)
TLATE=TNOW-ATRI3(4)
CALL COLCT (TLATE,12,NSET)
CALL HISTO (TLATE,-1.0,2.0,1,NSET)
TARDY=TLATE
IF (TLATE.LT.0.0) TARDY=0.0
CALL COLCT (TARDY,13,NSET)
TSYNPL=TNOW-ATRIB(33)
CALL COLCT (TSYNPL,42,NSET)
NP40=NOP+39
CALL COLCT (TSYNPL,NP40,NSET)
TIPOOL=ATRIB(33)-ATRIB(3)
CALL COLCT (TIPOOL,48,NSET)
PERPOL=TIPOOL/PLEN+0.5
NPEPOL=PERPOL
CALL HISTO (NPEPOL,1.0,1.0,16,NSET)
NP46=NOP+45
CALL COLCT (TIPOOL,NP46,NSET)
B=FLOAT(NTPDS-1)*PLEN
BDUE=ATRIB(4)
IF (BDUE.LT.B) GO TO 30
IF (BDUE.LT.TNOW) GO TO 20
LP= (TNOW-BDUE/PLEN)-.999999
GO TO 40
20 LP=0
GO TO 40
30 LP=(B-BDUE)/PLEN+.999999
40 XP=LP
CALL HISTO (XP,10.5,1.0,2,NSET)
XOPS=XOPS-ATRIB(10)
XWKS=XWKS-ATRIB(9)
NLV=NLV+1
JOB=ATRIB(30)+.001
LOC(JOB)=0
IF (JOB.NE.MAX) GO TO 80
50 MAX=MAX-1
JOB=JOB-1
IF (LOC(JOB).LE.0) GO TO 50
GO TO 80
C
C *** THE JOB IS NOT LEAVING THE SYSTEM
C *** UPDATE THE JOB ATTRIBUTES
C
60 IF (NRULE.LE.3) ATRIB(6)=ATRIB(6)-ATRIB(12)
LRM=ATRIB(5)+.001
LR=2*LRM+9
DO 70 I=11,LR+2
ATRIB(I)=ATRIB(I+2)
70 ATRIB(I+1)=ATRIB(I+3)
ATRIB(LR+2)=0.0
ATRIB(LR+3)=0.0
CALL PTJOB (2,NSET)
C *** CHECK MACHINE QUEUE FOR ANY JOBS
C *** AVAILABLE FOR PROCESSING

80 IF (NQ(MNOW+1)) 81, 81, 100

C *** THERE ARE NO JOBS IN THE QUEUE
C *** CHECK QUEUE FOR COMPANION MACHINE

81 CONTINUE
CAL1= (MN0W+0.1)/2.0
MCAL1= CAL1
MCAL1= 2*MCAL1
MCAL2= MNOW- MCAL1
IF (MCAL2. LE. 0) MNO1=MNOW-1
IF (MCAL2. GT. 0) MNO1=MNOW+1
IF (NQ(MNO1+1)) 90, 90, 82

82 CONTINUE
C *** MORE THAN ONE JOB IS AVAILABLE IN COMPANION
C *** MACHINE(MNO1). COMPUTE PRIORITIES AND BRING IN
C *** THE JOB WITH THE HIGHEST PRIORITY FROM THE QUEUE.

200 MN1=MNO1+1
IF (NQ(MN1). EQ. 1) GO TO 220
IF (NRULE. EQ. 0. OR. NRULE. GT. 3) GO TO 220
IF (NRULE. GT. 2) GO TO 210
MNO2=MNOW
MNOW=MNO1
CALL DYNAM (MBEST, NSET)
CALL RMOVE (MBEST, MN1, NSET)
GO TO 230

210 CALL WKINQ (MBEST, NSET)
MNOW=MNO2
IF (MBEST. EQ. 0) GO TO 220
CALL RMOVE (MBEST, MN1, NSET)
MNOW=MNO2
GO TO 230

220 CALL RMOVE (MFE(MN1), MN1, NSET)

C *** COMPUTE THE WAITING TIME FOR THE JOB AND
C *** DECREASE THE WORKLOAD IN THE MACHINE QUEUE.

230 WT= TNOW- ATRIB(8)
MN15=MNOW+15
CALL COLCT (WT, MN15, NSET)
QLOAD(MNOW)=QLOAD(MNOW)- ATRIB(12)
SHOPLD(MNOW)=SHOPLD(MNOW)- ATRIBE(12)
TIMEVT= ATRIBE(12)*. (8.0/CAPM(MNOW))
ATRIE(1)= TNOW+ TIMEVT
ATRIB(2) = 1.0
JOB = ATRIB(30) + .001
LOC(JOB) = 'FA
ATRIB(11) = MNOW
CALL FILEM(1, NSET)
RETURN

90 CALL TMST(BUS(MNOW), TNOW, MNOW, NSET)
BUS(MNOW) = 0.0
IF (MSW(2) .EQ. 0) GO TO 93
IF (NLDR .EQ. 0) GO TO 93
CALL COLCT(1, 0, 68, NSET)
IF (NQ(12) .LT. 1) GO TO 93
IF (MSW(3) .EQ. 0) GO TO 88
IF (SSUMA(MNOW, 3) .GE. AVGLD9) GO TO 93

*** TRY TO MOVE JOB FROM POOL TO EMPTY MACHINE

88 J = 0
N1 = MFE(12)
91 J = J + 1
NFIRST = FLOAT(NSET(11, N1)) / SCALE + .0001
IF (NFIRST .EQ. MNOW) GO TO 92
N1 = NSET(MX, N1)
IF (N1 .NE. 7777) GO TO 91

*** NO JOB WAS FOUND THAT COULD HELP IDLE MACHINE

GO TO 93

*** PUT JOB FROM POOL IN IDLE MACHINE

92 CALL RMOVE(N1, 12, NSET)
CALL COLCT(1, 0, 69, NSET)
MNEXT = ATRIB(11) + .U0001
CALL PTJOB(3, NSET)

93 RETURN

*** MORE THAN ONE JOB IS AVAILABLE. COMPUTE
*** PRIORITIES AND BRING IN THE JOB WITH THE
*** HIGHEST PRIORITY FROM THE QUEUE.

100 MN1 = MNOW + 1
IF (NQ(MN1) .EQ. 1) GO TO 120
IF (NRULE .EQ. 3 .OR. NRULE .GT. 3) GO TO 120
IF (NRULE .GT. 2) GO TO 110
CALL DYNAM(MBEST, NSET)
CALL RMOVE(MBEST, MN1, NSET)
GO TO 130
110 CALL #KING(MBEST, NSET)
IF (MBEST.EQ.0) GO TO 120
CALL RMOVE (MBEST,MN1,NSET)
GO TO 130
120 CALL RMOVE (MFE(MN1),MN1,NSET)
C
C *** COMPUTE THE WAITING TIME FOR THE JOB AND
C *** DECREASE THE WORKLOAD IN THE MACHINE QUEUE.
C
130 WT=TNOW-ATRIB(8)
MN15=MNOW+15
CALL COLCT (WT,MN15,NSET)
QLOAD(MNOW)=QLOAD(MNOW)-ATRIB(12)
SHOPLD(MNOW)=SHOPLD(MNOW)-ATRIB(12)
TIMEVT=ATRIB(12)*(8*CAPM(MNOW))/
ATRIB(1)+TNOW+TIMEVT
ATRIB(2)=1.0
JOB=ATRIB(30)+.001
LOC(JOB)=MFA
CALL FILEM1,NSET)
RETURN
END
*** THIS SUBROUTINE PLACES THE PARAMETERS FOR THE JOBS
*** IN THE JOB POOL IN THE FORM REQUIRED BY LP

DIMENSION NSET(35,1),DUDFT(5),VEOP(1,7),XKAY(5)
COMMON ID,IN,INIT,JEVT,INIT,FA,STUP,X1X,CNCLT,
INHIST,VRD,VEOP,VRDS,VRUN,VRUNs,STAT,UM,SCALE,
2ISDAF,IND,TOEF,TFIN,XXNPRNT,JCRDN,REP,VMN(25),
3JOF,XLE,K,LATRIP(33),EII(25),ELE(25),JCELS(25,32),
4XRAK(29),JCKX,MAX(25),NFE(25),NCC(25),NCE(25),
5JCELS(20),M(25),PARA(4,4),TIP(25),SSCMA(23,5)

COM PLOT,PLOT,PLOT,PLOT,PLOT,PLOT

1 TYPE, "NEXT": EVNLV, "HELD": "(10)" + "BY" (1), Y (1,1,10),
2 BUS(1), VRSET, "RULE": "M" (11), "MST": "V" (10), "MH": "H" (10),
3MXX (10), SEED, AREAT, LOC(12,1), MAX, AR(11)

COMMON PPREL, FPREL, NDESFL, NDLF, CPM(11), DESL(19),
UCEL(18), DESLF, DMLF, CLOAD (12), XUPS, XKS, TIMEF (10),
2NST, NDR, NARK, SHPOU, FADCUL

COM PLOT A(25,1), XKV(15), C(150), FACDUD

*** REMEMBER TO USE ONLY AN EVEN NUMBER OF MACHINES
*** WITH THIS SPECIALLY MODIFIED PROGRAM
*** OBTAIN NO. OF JOBS IN POOL AND INITIALIZE MATRICES

NPOOL=NN(12)
NPRO=25
NCOl=80
NPOO=NM
NCOl=NPOOL+2*NM
INDEX=0
DO 3 I=1,5
3 AUX(I)=0
OBJH=J,0
DO 4 J=1,1,2
DO 5 J=1,NPOOL
FPO(T, J)=-
4 CONTINUE
1 CONTINUE
DO 5 J=1,1,2
DO 5 J=1,NCOI
2 A(T, J)=1
5 J=J+1

*** OBTAIN LP MATRIX ENTRIES FOR EACH JOB

DO 5 J=J+1
\text{WKTIM} = 0.0 \\
\text{NO1} = \text{FLOAT(NSET(1),N1)) / SCALE + 0.00001} \\
\text{DO 35 I=1,NO1} \\
\text{NON1 = 2*2*I} \\
\text{NON2 = \text{FLOAT(NSET(NON1,N1)) / SCALE + 0.00001}} \\
\text{NON3 = NON1 + 1} \\
\text{WOL = \text{FLOAT(NSET(NON3,N1)) / SCALE}} \\
\text{A(NON2,J) = WOL} \\
\text{WKTIM = WKTIM + ACL*(J-8) / \text{CAP}(N((NON2))}} \\
\text{IF (NLDR*NE.2 OR NLDR*NE.3) GO TO 35} \\
\text{IF (NON1,N1) GO TO 35} \\
\text{WPOL(NON2,J) = WOL} \\
\text{CONTINUE} \\
\text{TKIM3 = \text{FLOAT(NSET(4,N1)) / SCALE + 0.00001}} \\
\text{XRKIM3 = \text{FLOAT(NSET(9,N1)) / SCALE + 0.00001}} \\
\text{DUDSLK = TKIM3 - WKTIM} \\
\text{IF (DUDSLK .LE. 0.0) DUDSLK = 0.0} \\
\text{DUDFI(T,J) = FACDUD/((DUDSLK + 0.1))} \\
\text{C} \\
\text{*** OBTAIN NEXT JOO IN THE POOL, IF THERE IS ANY} \\
\text{N1 = NSET(4X,N1)} \\
\text{IF (N1.NE.7777) GO TO 30} \\
\text{C} \\
\text{*** SET UP MATRICES REQUIRED BY LPI} \\
\text{A1 = N1}/2 \\
\text{NOROW = N1} \\
\text{NOCOL = NPOOL + 2 * N1} \\
\text{DO 45 I = 1,N1} \\
\text{DO 45 J = 1,NPOOL} \\
\text{111 = (2*I)-1} \\
\text{112 = 2*I} \\
\text{45 A(I, J) = A(I+1,J)+A(I+2,J)} \\
\text{IF (NLDR*LE.2 OR NLDR*LE.3) GO TO 60} \\
\text{DO 51 I = 1,NOROW} \\
\text{DO 51 J = 1,NOCOL} \\
\text{IF (J .LE. (NPOOL+1))) A(I ,J) = 1.0} \\
\text{IF (J .LE. (NPOOL+1))) A(I ,J) = -1.0} \\
\text{CONTINUE} \\
\text{ULSL2 = UDSL(I11) + UDSL(I12)} \\
\text{SHGPL2 = SHGPL(I11) + SHGPL(I12)} \\
\text{A(I,NOCOL+1) = UDSL2 - SHGPL2} \\
\text{AA = A(I,NOCOL+1)} \\
\text{KBJP(I) = J+1} \\
\text{IF (AA .LE. 0.0) GO TO 51} \\
\text{A(I,NOCOL+1) = -AA} \\
\text{KBV(I) = J+1} \\
\text{GO TO 51}
DO 54 J = 1, NCOL
54 A(I, J) = -A(I, J)
51 CONTINUE
GO TO 71
C
*** MATRIX PREPARATION WHEN NEXT QUEUE RULE IS USED
C
60 DO 61 I = 1, NOROW
DO 62 J = 1, NCOL
II1 = (2*I) - 1
II2 = 2*I
IF (J*LE*NPOOL) A(I, J) = WFOR(I, J) + WFOR(I, J)
IF (J*EQ*(NPOOL + 1)) A(I, J) = 1.
IF (J*EQ*(NPOOL + N*1 + 1)) A(I, J) = -1.0
62 CONTINUE
DGL2 = DGL(I, I1) + DGL(I, I2)
QLOAD2 = QLOAD(I, I1) + QLOAD(I, I2)
A(I, NCOL + 1) = DUL2 - QLOAD2
AA = A(I, NCOL + 1)
OBJIN = OBJIN + ABS(AA)
KBV(I) = NPOOL + I
IF (AA .GE. 0.0) GO TO 61
A(I, NCOL + 1) = -AA
KBV(I) = NPOOL + N*1 + I
DO 64 J = 1, NCOL
64 A(I, J) = -A(I, J)
61 CONTINUE
70 CONTINUE
NRT1 = NOROW + 1
NCT2 = NCOL + 2
NPT2 = NPOOL + (2*N) + 1
DO 72 I = NRT1, NM
DO 72 J = NCT2, NPT2
72 A(I, J) = 0.0
DO 76 J = 1, NCOL
C(J) = 0.0
IF (J .GT. NPOOL) GO TO 77
C(J) = -DUDFT(J)
A(NOROW + 1, J) = 1.0
A(NOROW + 2, J) = 1.0
GO TO 76
77 C(J) = 1.0
A(NOROW + 1, J) = -1.0
A(NOROW + 2, J) = 1.0
76 CONTINUE
C(NCOL + 1) = -OBJIN
A(NOROW + 1, NCOL + 1) = 0.0
A(NOROW + 2, NCOL + 1) = 0.0
DO 88 I = 1, NOROW
DO 88 J=1,NOCOL
   C(J)=C(J)-A(I,J)
88 CONTINUE
IF (NLDR. GE.4) GO TO 91
CALL LPI (NSET,NOROW,NOCOL,NROW,NCOL,INDEX,KAUX)
GO TO 92
91 CALL POOLHE (NSET,NOROW,NOCOL)
92 RETURN
END

*PROC.IS SHOPALT2.JOBDEC

SUBROUTINE JOBDEC (NSET,NOROW,NOCOL)

*** THIS SUBROUTINE USES THE LP RESULTS TO MAKE THE
*** FINAL SELECTION REGARDING THE JOBS THAT SHOULD
*** BE LOADED IN THE SHOP

DIMENSION NSET(35,1),XJOB(100)
COMMON ID, INIT,JEVT, JINIT,MFA,STOP, MX, XIC, NCOLT,
 INITR, NRO, KORPRI, NSETJ, NROUN, NROUS, NSTAT, OUT, SCALE,
 2ISEED, ITH, IFE, IFIN, NPRINT, CDN, TEP, V(25),
 3KOF, KE, KCL, NTRIL(33), ENG(25), ILY(25), JCELS(20,32),
 4KARAK(25),JCLX, MAXJ(25), IPE(25), NLC(25), NLE(25),
 5 NCELS(25), NAX(25), PARAM(p,4), NTIE(25), SSMA(20,5),
 6, SUMA(75,5), XACL(6), NPROJ, CON, NDAY, NFR
COMMON PLEN, TRUS, ITOTPD, XISYS, XKSY, IDIE,
 1NTYPE, INEXT, NSEL, NBL, NHOLD, X(10), Y(10), X(10,10),
 2 JOS(10), NSETJ, HRULE, NKNX, NCR, NORD, NCOL, FJL, 
 3MAX(10), SEL, SATEL, LOC(20), MAX, ARI(11),
 COMMON HREL, PREP, KFSL, KPL, CARP(10), DESL(10),
 1DCL(10), DESLF, DCLF, DCLD(10), XOPS, XKS, NTIE(10),
 2NSIA, ALDR, ARR, SHOPLD(10)
COMMON A(25,100), JRV(15), C(100), FACBUD
R=11: R=2
RPOOL=KX(12)
DO 1 J=1,RPOOL
   XJOB(J)=X(1)
   AA=AXK(12,J)-RPOOL
   IX=IFIX(AA)
1 IF (IX.EQ.1) XJOB(J)=1.0
   IF (NLDR.GE.4) GO TO 20
DO 2 I=1,%
   JJ=KOV(1)
   XJOB(JJ)=A1(1,NCOL+1)
2 CONTINUE

*** VARIABLES IN BASIS AND 2ND UPPER BOUND INDICATOR
**ON, NEED TO BE CALCULATED DIFFERENTLY**

\[ AA1 = A(\text{NCROx} + 2, JJ) - ICCI \]

\[ IA = \text{IFIX}(AA1) \]

IF (IA .NE. -1) GO TO 2

\[ XJOB(JJ) = A(\text{NCROx} + 1, JJ) - A(1, \text{MOCUL} + 1) \]

2 CONTINUE

*** SEARCH JOB POOL FILE AND LOAD IN THE SHOP THOSE JOBS WITH DECISION VARIABLE \( \geq 0.75 \)**

20 J = 0

\[ N1 = \text{IFE}(12) \]
\[ XKSHP1 = 0.0 \]

TDES1 = 0.0

DO 25 I = 1, N1

TDES1 = TDES1 + DESL(I)

25 XKSHP1 = XKSHP1 + TDES(I)

30 J = J + 1

XJOB(J) = XJOB(J)

IF (XJOB(J) .LT. 0.75) GO TO 40

N2 = NSET(MX * N1)

CALL RMOVE (N1, 12, NSET)

XKSHP1 = XKSHP1 + ATSL(1)

VEXT = ATSL(1) + XJOB(J)

CALL PTJOB (3, NSET)

N1 = 1.2

GO TO 41

40 N1 = NSET(MX * N1)

41 CONTINUE

IF (N1 .NE. 7777) GO TO 30

*** SEARCH JOB POOL FILE AND LOAD JOBS WITH DECISION VARIABLES BETWEEN 0.3 AND 0.75 IF TOTAL SHOP LOAD IS LESS THAN DESIRED***

J = 0

IF (XJOB(12) .LE. 1) GO TO 75

N1 = IFE(12)

50 IF (XKSHP1 .GE. TDL51) GO TO 75

55 J = J + 1

IF (J .GT. NCOL) GO TO 75

XJOB(J) = XJOB(J)

IF (XJOB(J) .LT. 0.75) GO TO 55

IF (XJOB(J) .LT. .5) GO TO 65

N2 = NSET(MX * N1)

CALL RMOVE (N1, 12, NSET)

XKSHP1 = XKSHP1 + ATSL(9)

VEXT = ATSL(11) + XJOB(J)
CALL PTJOB (3,NSET)
N1=N2
GO TO 66
65 N1=NSET(MX,N1)
66 CONTINUE
IF (N1.NE.7777) GO TO 50
10 CONTINUE
RETURN
END

FOR IS SHOPALIZED PTJOB

SUBROUTINE PTJOB (INP,NSET)

C
C *** SUBROUTINE WHICH MOVES JOB TO NEXT MACHINE
C *** CENTER
C
DIMENSION NSET(35,1)
COMMON ID, INIT, JENV, JNIT, JFA, MSTOP, MX, XC, NCLLT,
1 INIT, NNO, NCRPT, NDT, NRTYS, NRUN, MNUM, INITOUT, SCALE,
2 SEED, TNOW, LDP, TNEXT, YY1, NPY, ATRIB(3), MSTOP (25),
3 KOF, KLE, XOL, ATRIB (33), ENO (25), INH (25), JCELS (20,32),
4 KMAX (25), JCLL, MAXL (25), MFL (25), MLC (25), MLE (25),
5 JCELS (2O) , NGE (25), PARAM (40,4), NTIME (25), SSUMA (20,5),
6, SUMA (75,5), XAM (6), NPROC, NMON, NDAY, XIA,
COMMON PLNUM, TPDQ, VTD, XISYS, X: KS, IDUE,
1 TYPE, NNEXT, XENV, VHLD, POS (10), PSY (10), X (10,10),
2 BUS (10), NSET, NRLK, NNOW, XST, NENOS, NHAL, X: C,
3 XNW (10), SEED, RATE, LOC (200), MAX, AR (11),
COMMON NPREL, NRPD, DESL, NDNL, CAPN (10), DESL (10),
1 DOLL (10), DESL, PSLF, SLOY (10), XORS, XWS, TIMEF (10),
2 NTSX, NLD, NARR, SHOPLC (10),
COMMON M (25,1,1), KS (15), C (10), FACIDU
COMMON ICOUNT, oICOUNT, SIMPER, MSTOP (10), AVGLD5

C
C *** CHECK IF JOB IS A NEW ARRIVAL
C
IF (INP.NE.1) GO TO 10
ATRIB (3) = TNOW
NEN=NEN+1
C
C *** NEW ARRIVAL* CHECK IF A JOB POOL IS BEING USED
C
IF (NLD, E.C.E.) GO TO 20
C
C *** CHECK IF SHOP IS BEING PRELOADED AND JOB POOL
C *** HAS BEEN COMPLETED.
IF (NSTS* .EG. 1 ) GO TO 20

*** PUT ARRIVING JOB IN THE POOL IF OP. 1 MACHINE IS NOT IDLE

ATRIB(8)=TNO•
JOB=ATRIB(9)+0•001
LCC(JOB)=MFA

*** COLLECT STATISTICS ON INTERARRIVAL TIMES TO THE JOB POOL

D=TNO•-ATRIB(11)
CALL HISTO (0,6,5,5,15,NSET)
ATRIB(11)=TNO•
NFIRST=ATRIB(11)+...+1
IF (NSET(1)*.EG.0.) GO TO 4
IF (TNO•.LE.NFIRST) GO TO 4
IF (BUS(NFIRST)) 5,5,4

4 CALL FILEM(12,NSET)
GO TO 70

*** IF FIRST OPERATION MACHINE IS IDLE, CONSIDER THE JOB AS COMING FROM POOL AND PUT IN THE SHOP

5 CONTINUE
IF (NSET(3)*.EG.0.) GO TO 6
IF (SSUMA(NFIRST,3)*.GE.AVGLD9) GO TO 4

6 NEXT=NFIRST
CALL COLCT (1,0•69,NSET)
GO TO 20

*** JOB IS NOT A NEW ARRIVAL. CHECK IF IT IS COMING FROM THE POOL

10 IF (INP.EQ.2) GO TO 40

*** JOB IS COMING FROM THE POOL.
*** ALSO REVISE JOBS SUCH A POOL IS NOT USED ARRIVE AT THIS POINT
*** UPDATE STATUS OF WORK IN SHOP AND ALSO UPDATE *** AGGREGATE LOAD IT. SHOP QUEUES FOR EACH MACHINE.

20 CALL TEST (XISYS+XISYS+12,NSET)
CALL TEST (XISYS+XISYS+11,NSET)
XISYS=XISYS+1•
X.ISY=X.ISY+ATRIB(3)
ATRIB(13)=TNO•
...X.X.X.X+2•+ATRIB(11)+...+1
DO 37 J=11,MAX+2
J=ATRIo(1)
37 SHOPLD(J)=SHOPLD(J)+ATRIo(I+1)
C
C *** JOB IS NOT GOING INTO THE POOL. COLLECT STATISTICS
C *** ON INTERARRIVAL TIMES TO THE CURRENT MACHINE

40 D=TNOW-ANR+MNEXT+4
CALL HI5T0(D,0,5,5,MN4,INSET)
ANR+MNEXT+TNOW
C
C *** CHECK ON THE STATUS OF MACHINE FOR NEXT
C *** JOB OPERATION
C
IF (BUS(MNEXT)) 60,61,41
C
C *** NEXT MACHINE IS BUSY. JOB CÀN NOT BE PUT ON
C *** MACHINE. CHECK COMPANION MACHINE.

41 CONTINUE
CAL1=(MNEXT+11)/2.0
MCAL1=CAL1
MCAL1=2*MCAL1
MCAL2=MNEXT-MCAL1
IF (MCAL2.LE.0) MNEX1=MNEXT-1
IF (MCAL2.GT.0) MNEX1=MNEXT+1
IF (BUS(MNEX1)) 42,42,50
C
C *** COMPANION MACHINE IS NOT BUSY.
C *** PUT JOB IN COMPANION MACHINE.

42 CONTINUE
CALL TMST (BUS(MNEX1),TNOX,MNEX1,INSET)
BUS(MNEX1)=1.0
WT=0.0
MX15=MNEXT+15
CALL COLCT (WT,MX15,INSET)
TIMEVT=ATRIo(12)*(8.0/CAPN(MNEXT))
ATRIo(1)=TNOX+TIMEVT
ATRIo(2)=1.0
ATRIo(11)=MNEX1
J=ATRIo(11)
SHOPLD(J)=SHOPLD(J)-ATRIo(12)
JOB=ATRIo(30)+J
LOC(JOB)=MFA
CALLFILL(1,INSET)
GO TO 70
C  *** NEXT MACHINE AND ITS COMPANION ARE BUSY.
C  *** JOB CAN NOT BE PUT ON EITHER MACHINE.
C
50 ATRIB(6)=TNOW
  MX1=MNEXT+1
  JOB=ATRIB(30)+0.3J1
  LOC(JOB)=MFA
  QLOAD(MNEXT)=QLOAD(MNEXT)+ATRIB(12)
  CALL FILEM(MX1,NSET)
  GO TO 70
C
C  *** NEXT MACHINE IS NOT BUSY.
C  *** JOB MAY BE PUT ON MACHINE
C
60 CALL TMST(BUS(MNEXT),TNOW,MNEXT,NSET)
  BUS(MNEXT)=1.0
  WT=0.0
  MX15=MNEXT+15
  CALL COLCT(MT,MX15,NSET)
  TIMEVT=ATRIB(12)*(8.0/CAPM(MNEXT))
  ATRIB(1)=TNOW+TIMEVT
  ATRIB(2)=1.0
  J=ATRIB(11)
  SHOPLD(J)=SHOPLD(J)-ATRIB(12)
  JOB=ATRIB(30)+0.3J1
  LOC(JOB)=MFA
  CALL FILEM(1,NSET)
70 NSTS=0
RETURN
END
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BIBLIOGRAPHY (Continued)


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VITA

Joseph C. Irastorza was born in Matanzas, Cuba and is now a citizen of the United States. He is married and has three children. His education includes a B.S.E.E. with highest honors from the Georgia Institute of Technology, M.S.E.E. (Control Systems) also from Georgia Tech, M.S.I.E. (Operation Research) from Lehigh University, and doctoral studies in I.E. at Georgia Tech. The honors obtained by Mr. Irastorza include the following:

Selected as the outstanding Electrical Engineering Senior in 1960.
Recipient of the Tau Beta Pi scholarship cup for the outstanding Georgia Tech senior in 1960.

Membership in the following Honor Societies:
Phi Eta Sigma, Eta Kappa Nu, Tau Beta Pi, Phi Kappa Phi, and Pi Tau Sigma.

Mr. Irastorza is a senior member of the American Institute of Industrial Engineering, and a member of the Institute of Electrical and Electronic Engineers and Institute of Management Sciences.

He has worked with the Ministry of Industries in Cuba, Western Electric Company and as a Lecturer in the Industrial Engineering School at Georgia Tech. Since December 1963, he has been with Kurt Salmon Associates and is currently a Principal in its Management Systems Division.