The Effect of Estimated Processing Times Versus Actual (Standard) Processing Times on Various Performance Measures in a Pure Job Shop

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Chapter I

INTRODUCTION

During the past 30 years, job sequencing has been recognized as an important production problem. Usually, a sequencing problem arises whenever it is necessary to define a priority dispatching rule for a manufacturing facility that has to process a number of different jobs attempting to achieve specified goals. The term dispatching is often used as a synonym for sequencing.

Three major categories of production activities should be distinguished :

1. Flow Shop : Machines are arranged to manufacture specific products, and the job is considered to be a collection of operations in which a special precedence structure applies. In particular, for all jobs, each operation after the first has exactly one direct predecessor and each operation before the last has exactly one direct successor. Thus each job requires a specific sequence of operations to be carried out for the job to be complete. On the other hand, the sequence of operations for all jobs is either similar or the same thereby creating a common "flow" through the shop.

This type of structure is sometimes called a linear precedence structure or product shop.

2. Job Shop : An intermittent (semi-continuous) production system in which there is no common pattern of job movement from machine to machine. Machines are grouped in departments or centers by their function and the sequence of operations performed on any one job is independent of the sequence required by any other job. The job shop is characterized by the production of unique products, process-type layout, job-lot quantities, and customer-originating jobs. A job shop is also termed a process shop or a function shop.
3. A combination of the flow shop (1) and the job shop (2).

This thesis is concerned with the job shop environment.

1.1 SEQUENCING PROBLEM IN A JOB SHOP

In a large job shop, thousands of jobs may be in-process at the same time. A limited amount of man and machine capacity exists to perform these operations. As a result, the jobs must compete with one another for capacity as they flow through the shop.

The interarrival times and the processing times of jobs are generally not constant. Instead they are characterized by probabilistic distributions. In addition, the system is often disturbed by unpredictable events such as :

1. Unexpected delays in supplying engineering specifications, tools, or raw materials.
2. Variations in workers' performance.
3. Delays due to machine breakdowns.
4. Changes in customers' specifications and delivery requirements.
5. Variations in raw material and product quality.
6. Absenteeism.

The efficient simultaneous sequencing of thousands of jobs is an extremely complex task. Two major phases are involved in sequencing : the first phase - generaly known as scheduling, and the second phase - generaly known as dispatching. Scheduling is concerned with the overall planning of the flow of the jobs through the shop, while dispatching is concerned with the detailed planning of the flow of the jobs at each machine center [66]. Many problems which exist in job shops are caused by insufficient coordination of these two functions.

1.2 THE DISPATCHING FUNCTION

Dispatching is the tactical limit of the strategic activity, scheduling. Perhaps the best way to perceive the difference between scheduling and dispatching is to remember that scheduling decisions focus on the timing of events, whereas dispatching decisions focus on only the sequence or ordering of events [27].

There is a strong interaction between the scheduling and the dispatching functions. Dispatching is the final step of the production-scheduling process. It is the final decision that is made at the moment that action is imminent. It provides an answer to the question, "what should be done next ?", that is asked each time a machine or a man completes a job. The sequence of answers to this question represents the actual machine schedule.

The dispatching function is not the complete scheduling process, but probably is the most important tactical activity if not the most difficult part of the process. It is likely that the preceding decisions in planning and loading are of greater strategic consequence than the questions of detailed order that are decided by dispatching.

Perhaps more important than any benefits obtained directly from the selection of an appropriate dispatching procedure is the effect of the dispatching procedure on the over-all scheduling process. The rate at which individual jobs progress through the shop is important in any scheduling procedure, and vital assumptions about this rate must be made. This rate and the validity of the assumptions depend importantly on the dispatching procedure which is employed.

It would seem that an understanding of the performance of the dispatching function, utilizing different methods of priority assignment, relationship to other independent variables could contribute appreciably to the design of a complete scheduling procedure.

1.3 NEED FOR RESEARCH

In a majority of practical scheduling problems the processing times are not known precisely until after the occurrence, and scheduling decisions are at best based on a priori estimates of the processing times.

Manufacturing engineers in the real world utilize estimated times based on their knowledge of the job and the shop's machine capabilities to predict the amount of time necessary to complete each operation. These estimated times can vary significantly from actual processing times and cause poor performance which incurs certain costs, such as : (1) cost of meeting due dates (penalty costs that may be associated with late delivery), (2) the cost of labor, (3) the cost of carrying in-process inventory, (4) the capital cost of capacity, and (5) shortage or stock-out costs. In fact, the job shop management problem is associated with balancing these costs. Hence, management is concerned with problems related to the variation in estimated processing times which have an effect on queues and can cause congestion, delays in production, idle facilities, and the untimely completion of jobs.

1.4 STATEMENT OF THE PROBLEM

In the literature on job shop dispatching, numerous priority rules have been tested against various shop performance measures for different job shop configurations in an effort to determine which rule will produce the best results. The model investigated in this thesis has been constructed on the basis of a dozen or more assumptions which have limitted relevance to the real job shop environment. One such assumption which might be relaxed in the studies published to date concerns the resetting of job processing times.

In a job shop environment where arriving jobs are constantly new and different, processing times for each operation are determined by estimation. Often the estimated and actual processing times vary considerably. The question arises as to the degree that a variation between actual (standard) and estimated processing times affects, or degrades, the shop's performance.

Therefore, this research addressed the problems that may or may not occur when actual (standard) times vary from the estimated processing times. This problem was expanded to include the ramifications of this variation when employing several different priority rules.

1.5 RESEARCH OBJECTIVE

This thesis is concerned with the dispatching function in a job shop environment. The objective was to investigate the effect of estimated processing times versus actual (standard) processing times on various performance measures in a pure job shop. In addition, three dispatching rules were studied to determine their interaction with variations in processing times.

Since, the most commonly used method of studying dynamic job shop phenomena is through simulation models, the research was conducted through the use of simulation. Using this approach has the advantage that it achieves perhaps the most realistic representation of the job shop.

It should be realized, however, that the actual shop has many factors which are not included in any of the models known to us, factors such as engineering changes, unpredictable workers'performance, use of overtime and subcontracting, variation in product quality, and so forth.

1.6 METHODS OF APPROACH

Significant progress has been made in studying the sequencing problem in the past few years. Various researchers have pursued the problem from different viewpoints and consequently, their models have different characteristics. The major approaches are as follows :

1. Deterministic Approach : The proposed problem is : given N jobs and M machines, each job with a known order of operations on some or all of the M machines, known and constant processing times; what sequence optimizes some desirable objectives. There are $(N!)^M$ possible sequences, but some of these sequences are not feasible because they conflict with the prescribed routing, but the feasible sequences grow very rapidly with M and N.

   Considerable progress has been made in solving the deterministic model by perceiving that it can be formulated and solved as a mixed integer programming problem or a linear programming problem. However, the size of the problem will limit solution using these techniques.

2. Queueing Approach : The shop is viewed as a network of waiting lines. Instead of determining the jobs to be sequenced, the job flow rate is considered and queueing theory is applied to estimate waiting times. The waiting jobs at each service center are assigned to the machines on the basis of their priority classifications and the time which they have spent waiting.

3. Thermodynamic Approach : This approach, rather than attempting to know the location of the job at any particular time, defines the probability of it being in different shop locations. The model only concerns itself with when a job will be completed at a given machine. As stated by Sisson [73] :

> It is possible that the thermodynamic model will be of great value in the design and engineering of actual job shop scheduling systems. In fact, initially, the thermodynamic model can be used in a manner similar to thermal thermodynamics; that is, the basic factors can be determined empirically from experiments and simulation.

4. Simulation Approach : The simulation approach, which is similar to the thermodynamic approach, has the

advantage of achieving the most realistic job shop representation. The researcher simulates the sequencing procedures for a specific shop to predict the shop activity; then, using the best procedure, the simulation is rerun and demonstrates the best results in the actual shop.

There are many other methods proposed in recent years which have not been discussed here. However, for a comprehensive review of the methods of sequencing in job shops one is referred to Sisson [73].

1.7 SHOP MODEL

Briefly stated, the shop structure is a pure job shop with job interarrival times and processing times being variables with probabilistic distributions.

The shop consists of five different machine centers with one machine per center. Each arriving job has an equal probability of being processed by any machine in the shop. Also, the probability of a job going from one machine to any other machine in the shop, or leaving the shop, is equal. However, the job may not have two successive operations processed on the same machine.

Once the job is released to the shop, it follows a previously generated preset route (sequence of operations) through the shop. After each operation has been completed, the job is moved to its next operation. If this machine center is processing another job or is unavailable, the job goes into temporary in-process inventory storage (queue). Jobs are removed from the queue on the basis of a priority dispatching rule (queue discipline) and the prescribed operation is performed. The job continues this process through to its last operation. The entire shop model is detailed in Chapter III.

1.8 ORGANIZATION OF THE THESIS

The remainder of the thesis is composed of four chapters.

Chapter Two contains a review of some of the significant research done concerning static and dynamic job shops.

In Chapter Three, the experimental method and computer simulation model, used in this thesis, are explained.

Chapter Four contains the analysis and interpretation of results obtained through simulation.

A summary of the investigation and the conclusions drawn from the research are presented in Chapter Five.

Chapter II

LITERATURE REVIEW

Scheduling problems can be defined as the allocation of limited available production resources over time to best satisfy a performance measure(s). Typically, the scheduling problem involves ordering and timing a set of tasks to be performed, and the performance measure may involve tradeoffs between early and late completion of a task, holding inventory for the task and frequent production changeovers.

The intent of this chapter is to present an overview of the major works in production scheduling. It should be emphasized that the review's primary focus is on reported work for dynamic job shop problems.

2.1 AN OVERVIEW OF THE LITERATURE

A specific scheduling problem is described by four types of information :

1. The jobs and operations to be processed.
2. The number and types of machines that comprise the shop.
3. Disciplines that restrict the manner in which assignments can be made.

4. The performance measure by which a schedule will be evaluated.

Problems differ by the number of jobs that are to be processed, manner in which the jobs arrive to the shop, and in the order in which different machine numbers appear in the operations of individual jobs. The nature of the job arrivals provides the distinction between STATIC and DYNAMIC problems.

In the static problem a certain number of jobs arrive simultaneously to a shop that is idle and immediately available for work. No further jobs will arrive, so attention can be focused on scheduling this completely known and available set of jobs.

In the dynamic problem the shop is a continuous process, jobs arrive intermittently, at times that are predictable only in a statistical sense, and arrivals continue indefinitely into the future.

As might be expected, entirely different methods are required to analyze sequencing questions for these two different problems. This distinction between static and dynamic problems provides the basis for the organization of this chapter. Review of sequencing studies for static problems are considered in the second section while dynamic problems are treated in the third section. Summary of the investigation and the conclusions drawn from the review of literature are presented in last section of this chapter.

It should be mentioned that in the sequencing/scheduling literature, terms such as scheduling rule, dispatching rule, priority rule, or heuristic are often used interchangably. Gere [27] has made an attempt to distinguish between priority rules, heuristics, and scheduling rules. He considers priority rules as simply a technique by which a number (or value) is assigned to each waiting job according to some method and the job with minimum "value" is selected. Gere defines a heuristic to be simply some "rule of thumb", whereas a scheduling rule can consist of a combination of one or more priority rules and/or one or more heuristics.

2.2 STATIC SEQUENCING

In very general terms, the scheduling problems studied in this section assume that there is a set of resources or servers (machines) and a fixed system of tasks to be serviced by these resources. Based on prespecified properties of, and constraints on the tasks and resources, the overal objective is to determine an efficient algorithm for sequencing the tasks to optimize or attempt to optimize some desired performance measure.

The primary measures studied are schedule length (makespan) and the mean time the jobs are in the system (flowtime). The models of these problems are deterministic in the sense that all information governing the scheduling decision is assumed to be known in advance. In particular, the tasks and all information describing them are assumed to be available at the outset, which is normally taken as time zero.

2.2.1 The Single Machine Case

The simplest sequencing problem is one in which there is a single resource (machine). As simple as it seems, however, it is a building block in the development of a comprehensive understanding of scheduling concepts; an understanding that should ultimately facilitate the modeling of complicated systems.

The basic single-machine problem is characterized by these assumptions : (1) A set of N independent, single-operation jobs is available for processing at time zero. (2) Setup times for the jobs are independent of job sequence and can be included in the processing times. (3) Job descriptors are known in advance. (4) The one machine is continuously available and is never kept idle while work is waiting. (5) Once processing begins on a job, it is processed to completion without interruption.

Under these conditions the total number of distinct solutions to the basic single-machine problem is therefore n!.

A wide variety of results exist for a vast set of problem specifications. The best known of these results are the procedures for minimizing the mean flowtime, Smith [74], and for minimizing the maximum tardiness, Jackson [40]. A slightly more complex procedure is that of Moore [55] for minimizing the number of late jobs.

While the above mentioned problems have proved to be relatively easy, the problem of minimizing weighted tardiness has been considerably more difficult. Indeed this problem has been shown to be NP-Complete by Karp [46]. Emmons [22], Lawler [50], Shwimer [72], Baker and Schrage [8], and Picard and Queyranne [65] have all studied the one machine tardiness problem or a generalized version of it. The recent work of Baker and Schrage [8] seems to have substantially tamed this problem. Sen and Austin [71] obtained comparable computational results with an algorithm which efficiently enumerates undominated schedules, as determined both by Emmons'properties and by new properties introduced by Graves [32].

For the one machine static sequencing rule, the shortest operation time priority rule (SOT), is generally regarded as the best sequencing rule to minimize job lateness over all jobs if the setup times are not considered. However, there are often circumstances where this rule may not be applicable to a particular set of jobs.

2.2.2 The Multiple Machine Case

Static sequencing of multiple machines in series (linear flow shop) has usually been optimized relative to the makespan criterion. A common assumption made by most researchers is to restrict attention to schedules for which the job sequence is identical on all machines.

Literature concerning static sequencing of N jobs on two machines are : Johnson [45], Mitten [54], Nabeshima [58], Garey, Johnson and Sethi [26], Gonzales and Sahni [31]. For the case of N jobs on three machines, the references are : Johnson [45], Story and Wagner [76], Lomnicki [52], Ignall and Scharge [39], Brown and Lomnicki [10], and Lageweg, Lenstra and Rinnooy Kan [49]. Studies of the general flow shop problem (N jobs on M machines) include : Dudek and Ghare [19], Ashour [2], Smith and Dudek [75], Gupta [34], Ignall and Schrage [39], Szwarc [77], Baker [6], Lageweg, Lenstra and Rinnooy Kan [49].

Job shop scheduling is the most general and the difficult of the open shop problems. Most researchers have assumed that all jobs are nonpreemtive and that the criterion is to minimize the maximum flowtime. A notable exception to this, is Fisher's research [25] which considers a general criterion function that includes minimal weighted tardiness . All optimization approaches to this problem appear to be branch and bound procedures. Examples include : Giffler and Thompson [29], Greenberg [33], Balas [9], Schrage [70], Fisher [25], Elmaghraby [20], Ashour, Moore and Chiu [3], and Lageweg, Lenstra and Rinnoy Kan [48]. Despite of the numerous research efforts on this problem, the largest problems reported solved, have less than 10 jobs scheduled on less than 10 machines.

Another approach to static sequencing is one which employs reliable heuristics, also known as combinatorial programming or controlled enumeration. References for the use of reliable heuristics as applied to static sequencing include: Elmaghraby [20], Ignall and Schrage [39], Lomnicki [52], Jeremiah, Lalchandani and Schrage [44] and Gere [28].

Monte Carlo techniques have also been applied to static sequencing systems by Heler [36], Elmaghraby [20], Giffler and Thompson [29] and Giffler, Thompson and Van Ness [30].

2.3 DYNAMIC SEQUENCING

Perhaps the most unrealistic condition assumed is that all jobs arrive simultaneously. Most real world situations, that can be identified with the job shop model, are continuous, dynamic processes.

When this assumption is relaxed, many strong and interesting results can be obtained, but an entirely different approach must be employed. Although previous arguments have been almost entirely algebric, a process in which arrivals are intermittent and at times not known in advance must be studied by probabilistic methods. Such a process can be studied as a queueing system with emphasis on the selection rule. The rule is the decision by which one of the jobs waiting in a queue is selected whenever the machine becomes available for reassignment.

2.3.1 The Single Machine Problem

Most of the literature on the single channel (one machine) queueing problem pertains to the special case in which the times between job arrivals are a sequence of independent observations from a fixed exponential distribution. Equivalently, the number of arrivals in a given time interval is a random variable with a poisson distribution. In addition, the most common assumptions for this problem include : (1) exponential service times, (2) mean service rate greater than the mean arrival rate, and (3) first-come, first-served (FCFS) queue discipline.

The criteria by which the performance of this type of system might be evaluated are : (1) mean flowtime or the mean number of jobs in the shop, (mean completion time is essentially meaningless in a continuous process.), (2) the average waiting time for a job, and (3) machine utilization. For an excellent treatment of the work done on single channel queues, the reader should refer to Conway, Maxwell and Miller [18].

2.3.2 The Multiple Machine Problem

One of the most thoroughly studied and widely applied areas of scheduling research involves the dynamic version of the job shop model. In the dynamic model, jobs arrive at the shop randomly over time, so that the shop itself behaves like a network of queues.

More than 20 years ago, a large number of simulation experiments illustrated advantages when considering the job shop as a network of waiting lines. This recognition that the job shop could be represented as a system or network of queues was important, and it inspired a great deal of fundamental research which is still continuing. Evans

[23,24], Jackson [41,42,43], Nelson [60,61,62], and others have treated the job shop as a network of queues.

The most important analytic result in job shop analysis is the decomposition theorem due to Jackson [42]. This gives sufficient conditions under which a general queue network may be treated as an aggregation of independent queues. In essence, the Jackson result is that : (1) if the input to the shop is poisson, (2) if the routing of jobs is determined by a probability transition matrix, (3) if the processing rates are exponential (possibly depending on the number of jobs at the machine group), and (4) if the dispatching rule is independent of a job's routing and processing times; then each machine group behaves, in a probabilistic sense, as an independent machine group.

It should be noted that this result gives only a sufficient condition for decomposition ; the corresponding necessary condition is not known. Moreover, most of the interesting dispatching procedures do not satisfy the conditions for decomposition.

The early research on queueing suggested that an important variable which could be manipulated in sequencing models was the priority dispatching rule (queue discipline), and much of the research has focused upon comparative studies. In this context, scheduling is generally carried out by means of dispatching decisions : at the time a machine becomes free a decision must be made regarding what it should do next. These scheduling decisions are unavoidable in the operation of such a system, and since research has demonstrated substantial differences among dispatching procedures, it is logical to determine the decision rules that promote good performance.

The effect of dispatching rules on queue networks is very difficult to discribe by means of analytic techniques. Nevertheless dynamic job shop scheduling studies have made considerable progress using computer simulation models.

The published literature on the dynamic job shop models includes simulations of both actual and hypothetical systems. The hypothetical shops, in particular, have typically consisted of a small number of machines, usually less than 10. Models of actual shops have sometimes contained 100 or even 1000 machines, but there is no evidence that the number of machines has a significant influence on a dispatching rule's performance, Nanot [59] and Baker [5].

2.3.2.1 Description of Dynamic Job Shop Models

To a certain extent it is desirable for the model to be somewhat simplified in order to focus on the scheduling effect and also to permit experimental results generalization. The successful work in this area exemplifies a convincing simple structure and complex detail blending the following model assumption list which typifies many of the simulation studies :

1. Jobs consist of strictly ordered operation sequences.
2. There is only one machine of each type in the shop.
3. A given operation can be performed by only one type of machine.
4. Processing times as well as due dates are known in advance.
5. Setup times are sequence independent.
6. An operation may not begin until its predecessors are complete.
7. Once an operation is begun on a machine, it must not be interrupted.
8. Each machine can process only one operation at a time.
9. Each machine is continuously available for production.

The first five of these assumptions have frequently been relaxed in simulation experiments; either to achieve a better representation of reality in the simulation of actual job shops or to examine the effects of alternative assumptions on basic results. The remaining assumptions are virtually standard in job shop studies.

The simulation model input is a job file that describes the entire set of jobs appearing at the shop for the duration of the simulation. The jobs arrive randomly over time, and most often the assumption is that the intervals between job arrivals have an exponential distribution.

The literature search indicates that researchers commonly select arrival rates from a poisson distribution or assume interarrival times to be exponentially distributed. Reinitz [66], Jackson [43] and Nanot [59] employ the poisson in their studies. Conway [14,15], Nelson [62], Kuratani and Nelson [47], Hottenstein [37,38], Conway and Maxwell [17], and Jackson [43] have indicated the use of exponentially interarrival times in addressing their specific problems.

Justification for using the poisson distribution has been offered by Reinitz [66]. According to Reinitz, the arrival of units to the various machine centers closely approximates the poisson distribution. He stated :

> But there is also a rationale basis for using the poisson process as a model for a real system input. The poisson process may be looked upon as a limit of disintegration of scheduled processes. The arrivals to a service department originate from completed services in other departments. Each process at each department has some distribution of service time, and the divergence of events from the scheduled times randomizes the input process, an intrinsic characteristic of the poisson law.

The prevalent use of the poisson and exponential distributions is likely a result of its widespread use in queueing theory. The two distributions' interrelationship when applied in queueing theory (specially when the arrival times to a queue occur by a poisson process, the interarrival times have a related exponential distribution) is explained at some length by Saaty [69].

Harris [35] has raised a question as to whether actual arrival rates in a job shop closely fit a poisson distribution. His finding showed that the observed arrival distribution indicates wide variability in the arrival rate mean, and general distribution shape. In addition, he found that the poisson distribution is not sufficient to explain or fit all observed distributions.

Though much of the literature has assumed exponential interarrival times, a few investigations have used an Erlang distribution. Kuratani and Nelson [47] have concluded from empirical data that job arrivals in the shop actually follow a pattern between an exponential and an Erlang distribution. Jackson [43] shows an exception to the general prevalence of the poisson arrival rates or exponential interarrival times with the use of a constant interarrival rate.

In a 1974 study reported by Elvers [21], the effects that various arrival rate distributions may have on the relative success of implementing various job shop heuristic dispatching rules were investigated. In his study, he tested sixteen different arrival rate distributions on ten dispatching rules and concluded that the distribution with respect to shape and range of the arrival rate for incoming jobs is not a significant variable in evaluating the relative dispatching rule effectiveness. However, a question which remains unanswered is that of ascertaining how sensitive are the various heuristic shop dispatching rules to various job arrival rate distributions.

The second factor to be considered in the job file is processing time generation for a job at a given machine or machine center. The most common assumption is that operation processing times are also samples from an exponential distribution, Baker and Dzielinski [7], Conway and Maxwell [17], Conway [15], Jackson [43], Kuratani and Nelson [47]. Other distributions suggested include the Erlang and hyper-exponential distribution, Kuratani and Nelson [47], the normal distribution, Conway, Johnson and Maxwell [16], and the lognormal distribution, Ackerman [1].

Finally, to complete an arriving job's description, it is necessary to specify its number of operations, which may vary among jobs or remain fixed, and its machine routing. In the simulation of dynamic job shops, typically job routes are generated by means of a transition matrix, a stationary Markov chain. In order to use this transition matrix, the first machine in a job route must be specified. This may be done by random sampling from some predetermined distribution.

One important comment should be made with regard to the job route generation containing more operations than there are machines in the shop. For example, if the shop contained only five machines, it would be possible to generate a job route of forty operations for an average of eight operations per machine. Many experimenters have eliminated such a possibility by truncating at some predetermined point. Studies which have set an upper limit on the number of operations to be specified in a job route include, Conway, Johnson and Maxwell [16], who set an upper limit of seven, Ackerman [1], who also set an upper limit of seven, and Kuratani and Nelson [47], who stopped the generation of the job route when more than 12 operations were generated.

As mentioned previously, many dynamic job shop simulations do not consider the possibility of alternate routing. In a real shop simulation, however, alternate routing may be of great importance. Studies by Morse [56], and Russo [68] have shown that shop performance can be improved if the alternate routing is permitted in the model.

2.3.2.2 Types of Priority Rules

As stated earlier, detailed scheduling decisions in a job shop environment are usually determined by dispatching rules. At the completion of an operation a machine becomes free, and the dispatching rule must specify what the machine should do next. One option, of course, is to keep the machine idle for a certain period, but most dispatching rules immediately assign work to the machine as long as there are operations waiting to be processed. This assignment is based on priorities determined for each of the waiting jobs.

The performance measure for a dispatching rule is usually selected from one or more of the following :

(a) Minimize total production cost.

(b) Minimize schedule time.

(c) Decrease inprocess inventory.

(d) Minimize job lateness.

(e) Minimize job flowtimes.

Two types of classifications are important in describing priority rules. First a rule is <u>local</u> if priority assignment is based only on information about the jobs represented in the individual machine queue. Some examples of local rules are:

SOT (Shortest Operation Time) : Highest priority is given to the waiting operation with the shortest imminent operation time.

LWKR (Least Work Remaining) : Highest priority is given to the waiting operation associated with the job having the least amount of total processing time remaining to be performed.

By contrast, a rule is global if it utilizes information from other machines in addition to the one at which the queue has formed. Examples of global rules are:

AWINQ (Anticipated Work In Next Queue) : Highest priority is given to the waiting operation whose direct successor operation will encounter the queue with the least work waiting. This includes work that has not yet arrived there, but that is anticipated to arrive before the direct successor operation can begin.

FOFO (First Off First On) : Highest priority is given to the operation that could be completed earliest. If this operation is not yet in the queue, the machine remains idle until it arrives.

A second dispatching rule classification involves the dynamics of the information base. A rule is static if its relative priority assignment does not change over time and dynamic otherwise. The simplest set of static rules provides that each operation of a given job has the same priority . For example:

FASFS (First Arrival at the Shop First Served) : Highest priority is given to the job that arrived at the shop earliest.

TWORK (Total Work) : Highest priority is given to the job with the least total processing requirement on all operations.

EDD (Earliest Due Date) : Highest priority is given to the job with the earliest due date.

Certain rules, including SOT and TWKR, are static with respect to a particular operation, but dynamic with respect to a particular job in the sense that individual operations of the same job acquire different relative priorities. Here are other examples:

FCFS (First Come First Served) : Highest priority is given to the waiting operation that arrived at the queue first.

MST (Minimum Slack Time) : Highest priority is given to the waiting operation corresponding to the job with minimum slack time. Slack time is equal to the difference between the due date and the time the job could be completed if there were no delays. Essentially, MST assigns a priority equal to the difference between the due date and work remaining on the job.

OPNDD (Operation Due Date) : Highest priority is given to the waiting operation with the earliest operation due date. An operation's due date is determined by dividing the interval between the job's due date and its shop arrival time into as many subintervals as there are operations. The end of each subinterval represent a due date for the corresponding operation.

S/OPN (Slack per Operation) : Highest priority is given to the waiting operation corresponding to the job with the minimum ratio of slack time to remaining operation.

TSOT (Truncated SOT) : Highest priority is given to the waiting operation with the shortest imminent operation time (as with SOT) except when an operation in the queue has waited in this queue more than a certain time units (w). Operations with queue times larger than w are given overriding priority and are dispatched under FCFS.

It is not difficult to devise a reasonable dispatching rule. In some situations the rationale for using a particular rule may be that it helps relieve congestion in the shop, while in other instances the motivating may be the need to meet specific due dates. The major value of simulation research is that it has been able to examine a wide variety of alternative rules and to identify a few simple but effective rules for different situations.

2.3.2.3 Discussion of Popular Priority Rules

The most commonly used shop congestion measure has been mean job flowtime. An equivalent measure is mean number of jobs in the system, because the flowtime-inventory relationship also pertains to the dynamic job shop. Because SOT is known to minimize mean flowtime in single-machine problem, it is natural to expect that a shortest-first strategy would perform well in the job shop situation. Therefore, it is not surprising to find that the major comparative studies by Baker and Dzielinski [7], Conway [14], Legrande [51], and Rowe [67] have found that SOT minimizes mean flowtime among the dozen or so simple dispatching rules that are frequently considered.

In an extensive computer simulation in 1965, Conway [14] performed a more elaborate study, using mean number of jobs in the system as a performance measure, Conway simulated a pure job shop containing nine machines and operating under the assumptions listed earlier. The experiments gathered statistics on approximately 9000 jobs and reported results for over 30 dispatching rules. The results showed that even the global rule AWINQ, was not able to match the performance of SOT, although both performed substantially better than FASFS, which essentially ignores job traits and shop status in determining priorities.

In order to find a rule that performed better than SOT, Conway investigated the performance of several combination rules, SOT and LWKR in combination, and SOT and AWINQ in combination. He concluded that since the pure SOT rule is so much easier to implement, and since it accounts for nearly all of the good performance of the combination rules, it is the best rule for all practical purposes where the objective is to minimize mean flowtime.

As mentioned earlier, several studies have drawn the same conclusions about SOT. One of the most thorough comparative studies was carried out by Nanot [59], who investigated the behavior of several dispatching rules under a variety of shop conditions. He concluded that under all of those conditions SOT was consistently the most effective rule for minimizing mean flowtime.

The mechanism by which SOT reduces mean flowtime should not be difficult to understand. By giving priority to jobs with shortest processing times, it accelerates the progress of several short jobs at the expense of a few long jobs. On the whole the average flowtime is reduced, but long jobs tend to encounter very long waiting times. In other words, the turnaround is good for most of the jobs but extremely poor for the few long jobs that are assigned low priorities.

Several suggestions for improving this aspect of performance have been proposed, but all involve sacrificing some of SOT's benefits with respect to aggregate behavior. Three attempts have been reported by Conway [14] to ameliorate this aspect of SOT.

1. Alternating the SOT rule with a low variance rule to periodically clean out the shop.
2. Forcibly truncating the SOT rule by imposing a limit on the delay that individual jobs will tolerate (TSOT).
3. Use of SOT in a relief role (RSOT) where the normal dispatching rule is FCFS, but when the length of an individual queue grows too long, the local dispatching mechanism switches over to SOT. In particular, when the length of any queue reaches a certain number, the priorities within that queue are assigned according to SOT. However, once the queue length drops below that number the dispatching rule reverts to FCFS. Since FCFS is the normal dispatching mode, long jobs do not typically encounter excessive delays. However, long jobs are sometimes temporarily delayed while SOT provides relief to individual machines facing severe congestion.

Compromise mechanisms such as TSOT and RSOT are necessary in systems that will not tolerate the few very long flowtimes that are produced by SOT. Nevertheless, it is important to recognize that different mechanisms will exhibit different performance trade-offs. In the case of TSOT and RSOT, the experimental results suggest that RSOT is much more effective at preserving pure SOT's mean flowtime performance while meeting the objections raised about long jobs. Therefore, any departure from a desirable pure rule should be thoroughly explored in order to avoid losing the advantages that the pure rule achieves.

When the scheduling objective involves meeting due dates, the most significant performance measures are likely to be tardiness-based criteria; such as the proportion of jobs tardy or mean job tardiness. In such instances it becomes relevant to consider dispatching strategies that employ due date information. In addition, the attainment of good tardiness performance appears to be a much more complex problem than mean flowtime minimization, because several factors can effect comparative performance.

Since lateness is just the algebraic difference between the completion time and a (given) due date, it can be expected that the mean job lateness distribution will be minimized by SOT. Nevertheless, it is not only the mean lateness that accounts for good tardiness performance, but also the lateness variance. Experimental results show that SOT's behavior tends to minimize mean lateness while allowing some low priority jobs to become quite tardy, (high lateness variance).

A comparative simulation study carried out by Conway [15] provides more specific information about job lateness distributions. The study was primarily concerned with proportion of jobs tardy as a performance measure, and the comparison involved several rules that attempted to represent priority setting found in actual shops. The rule FCFS exhibited the kind of behavior that might be expected from a procedure that is oriented to neither the lateness mean nor the lateness variance.

The experiments showed that FCFS can result in a large proportion of jobs tardy. By comparison the SOT rule was able to achieve a small proportion of jobs tardy because of its extremely low lateness mean, which offsets its relatively high lateness variance. Among the rules that use due-date information, it was surprising to find the OPNDD rule exhibiting an enormous lateness variance, for which there seems to be no explanation. The rule S/OPN exhibited the lowest variance, which accounts for its extremely good performance.

Conway's investigation continued in two other directions that suggest how difficult it is to draw general conclusions about dispatching rules' relative performance. One question involved the manner in which job due dates are set. For the experiment reported by Conway, the time between arrival time and due date was roughly proportional to the total work (TWK) required by the associated job. An alternative was to assign a due date in proportion to the number of operations (NOP) required by the associated job. The TWK and NOP methodologies represent a due date structure that might be encountered in situations where the production facility is itself responsible for assigning due dates. A third method examined was CON, where due dates represented a constant lead time for all jobs, and a fourth method was RDM, where due dates were assigned randomly.

Conway compared FCFS, SOT, EDD, and S/OPN for each of the four methodologies. The striking result was that S/OPN, which achieved the best performance under TWK, performed worse under the other methods, and in fact, yielded the worst performance among the four rules under CON and RDM. On the other hand, SOT was the least sensitive to the due-date assignment method and dominated the other rules when TWK was not employed. This behavior suggests that S/OPN may be relatively ineffective when due dates are set arbitrarily.

A second question addressed by Conway involved the effect of shop load on dispatching rules' relative performance. Conway generated two additional job files that created greater congestion in the shop, resulting in utilization of over 90% in both cases. He compared the percentages of jobs tardy in each of the three different utilization levels for the rules FCFS, SOT, and S/OPN. As would be expected, a given rule performance suffers when utilization is increased. However the performance of S/OPN is quite sensitive to this increase.

The numerical results suggest that when shop loads are quite heavy, the mean-oriented strategy SOT is preferable. Thus there appears to be a crossover point as machine utilization increases, beyond which SOT achieves better performance than S/OPN. Under the experimental conditions of Conway's study this crossover point occured for the utilization near 90%.

It is not difficult to imagine that the crossover point's location is subject to several factors, including the manner in which due dates are assigned and the tightness of the due dates themselves. This type of behavior makes it quite difficult to select a best dispatching rule in practice and may even make the use of a combination rule more inviting.

One of the most comprehensive mean tardiness performance measure studies was carried out by Carroll [12]. Carroll's experiments involved a parametric family of priority dispatching rules called COVERT rules. This type of rule is based on two pieces of information concerning waiting operations : a projected delay cost, as measured by anticipated tardiness for the associated job, and the operation processing time. The priority assigned to a waiting operation is the ratio between delay cost and the operation processing time. The dispatching rule selects the operation with the largest ratio to be sequenced next.

The procedure is similar to WSOT (Weighted Shortest Operation Time) sequencing, although it uses an elaborate means of calculating the delay cost. Critical jobs are those without slack; that is, even if the remaining operations were to completed without any delay, the job still could not be completed early. These jobs are assigned an anticipated delay cost of one. At the other extreme there may be noncritical jobs for which the length of time until the due date exceeds the amount of waiting time anticipated in addition to the remaining processing time required. These jobs are assigned an anticipated delay cost of zero. For those jobs between these two extremes there is positive slack, but it may be insufficient to meet the waiting time requirement that is anticipated.

Carroll's experiments compared the COVERT rule with two benchmark rules FCFS and FASFS along with SOT, TSOT, and S/OPN. Carroll tested a version of S/OPN in which job slack was calculated only when an operation arrives at a machine queue. The priority was not updated while the operation waited in queue, so that the procedure represents an adaptation of S/OPN that is static with respect to a particular operation. There is no reason to believe, however, that S/OPN's dynamic behavior would provide different results. Based on the results achieved by Carroll, he concluded that the COVERT rule is quite effective.

In additional simulations, Carroll examined the relative performance of the COVERT procedure for different experimental conditions. In particular, COVERT's good performance persisted under different shop loads and with different due date allowances. Although the COVERT rule is more complex than SOT or S/OPN, and more difficult to implement, Carroll's experiments indicate that the COVERT strategy may well be desirable in a variety of shop environments.

An important consideration in applying simulation results to actual systems is the role of the typical model assumptions as delineated earlier. When these assumptions do not hold, there may be systematic factors that should be considered. For example, Wayson [78] explored the effects of relaxing the assumption that each operation required a unique machine. In his model, certain operations could be performed by several alternative machines, so that an imminent operation could sometimes avoid a congested queue if an alternate machine assignment was technologically feasible.

Wayson compared the effect of this structure on the relative behavior of FCFS and SOT dispatching when the performance measure is mean number of jobs in the system. He found, for example, that SOT's behavior under unique machine assignments was not very different than FCFS's when an alternate selection could be exploited about 20% of the time. In addition, he observed that as the degree of potential alternate selection rose, the differences between the two dispatching rules became less significant.

Wayson's study illustrates that basic model assumption modifications may complicate priority dispatching rule comparisons, yet the modifications systematic effect on the results may well be predictable, at least qualitatively.

The same theme can also be found in other studies, which have relaxed such assumptions as the linear precedence structure, Maxwell and Mehra [53], sequence-independent setup times, Baker [4], or the implicit assumption that the shop can only be machine-limited as opposed to labor-limited, Nelson [63].

2.4 DIRECTLY RELATED LITERATURE

This section summarizes the conclusions drawn from the research concerning the effect of uncertainty in job processing times on schedules and performance measures. As mentioned earlier, from a search of published literature on job shop dispatching, only two studies were found investigating the effect of imperfect input information on designing optimal schedules.

The objective of the study reported by Muth [57] was to obtain a better understanding of the way the statistical properties of job processing times affect the time to process the jobs, specially under conditions of unreliable information. The main conclusion was that uncertainty about job operation time is of secondary importance in developing optimal scheduling procedures. It seems to be that the schedule span is not very sensitive to moderately large errors in estimated job processing times. Some of the effects are mitigated by having a large file of unfinished jobs. These conclusions were reached on the basis of a simulation of a rather simple scheduling problem, namely, a two stage production process. It is not known to what extent the results generalize to several stages.

Conway [14] also studied whether the SOT rule was sensitive to the reliability of processing time information in situations when priority assignments must employ processing time estimates. His experimentation was motivated by the fact that in practice, it is not always possible in advance to have completely reliable information about operation processing times. Instead, only a processing time estimate is available with the actual time often subject to some uncertainty. Therefore, Conway concluded that the quality of the estimates could be described in terms of their precision.

In his model the actual times were uniformly distributed random variables ranging from a specified proportion below the estimate to the some proportion above the estimate. Conway's experiments showed that the SOT rule is remarkably insensitive to this kind of uncertainty. Even when the estimate is allowed to be off by 100% the deterioration in performance is very slight, suggesting that SOT can still be effective when the quality of available information is relatively poor.

These are not to say, however, that accurate processing times are not needed elsewhere in plant operations, since accurate time data might be necessary for purpose of cost control and methods improvement.

2.5 SUMMARY

Several important themes emerge from the numerous job shop simulation experiments that have been reported. Perhaps the most noticeable aspect in the job shop studies is the great variety of simple, rational, and effective dispatching rules that have been developed and tested.

The practitioner who is faced with the responsibility of selecting and implementing a priority dispatching scheme can consider a rich variety of priority rules in order to choose a strategy that is appropriate and useful. Moreover, an encouraging theme in job shop research is the efficiency of local rules that utilize only a limited information base. In addition, the implication that SOT in particular does not suffer drastically if input information is unreliable suggests that the simplifications often made in experimental models may not be crucial to the adaptation of simulation results to actual shop control.

On the discouraging side, however, is the accumulating evidence that the selection of the best priority rule for a tardiness-based measure may depend critically on such factors as the level of shop load, the manner in which due dates are set, and the tightness of the due dates. This means that a certain amount of caution is necessary when attempting to apply the conclusions of one simulation study to other, different systems.

In conclusion, the simulation approach has been reasonably effective in studying the dynamic job shop. As stated at the outset of this chapter, the primary objectives of simulation research have been to compare specific operating procedures, to test broad conjectures about scheduling rules, and to develop greater insight into the nature of job shop operation. This review should indicate that the experimental work has been distinctly successful in these respects.

There have been many other solutions proposed in recent papers which have not been discussed in this review. However, for an excellent bibliography the reader is referred to Panwalker and Iskander [64].

Chapter III

THE EXPERIMENTAL METHODOLOGY AND COMPUTER SIMULATION MODEL

Although a great deal of research has been conducted on developing job shop scheduling rules and analyzing the efficiency of these rules, there are very few cases reported concerning the sensitivity of the various shop performance measures to the quality of processing time information.

The purpose of this research was to investigate the effect of estimated processing times versus actual (standard) processing times on various shop performance measures using several priority rules. The model studied was a dynamic sequencing, single-component-job model in which the effects of labor were not considered explicitly. The method of analysis was a computer simulation using the FORTRAN IV computer language.

The experimental methodology and the computer simulation model are discussed in this chapter. Following the list of model assumptions, the various components of the simulation model are explained. These components include the controlled variables for the experiment, random parameters, constant parameters, actual processing time generation, priority rules employed, independent variable combinations, simulation dependent variables, and question statements.

The chapter concludes with a general description of the simulation model.

3.1 SIMULATION MODEL ASSUMPTIONS

All simulation models are based on certain assumptions. For this model the following conditions apply :

1. Arrival and processing times are generated from probability density functions. The mean arrival rate is determined arbitrarily but it is set at a value lower than the mean service rate of the job shop in order to prevent shop overload.
2. A job, once started on a machine, continues being processed until the job is completed (i.e., no preemptive priorities).
3. Setup time for a given job's operation is independent of the job ordering and included in the processing time of the job being processed.
4. Job transportation time between machines is negligible.
5. Jobs are independent of each other.
6. Due-dates are fixed.
7. No machine failures.
8. Machines are never unable to process a required operation for lack of an operator, material, or tooling.

9. There is only one machine of each type.
10. No machine processes more than one operation at a time.
11. All the machines are available simultaneously at time zero.
12. The generation of the job routing does not permit consecutive operations on the same machine, but a job could return to a machine after an intervening operation.
13. Alternate routings are not considered.
14. No rework is allowed.
15. Lap-phasing is not allowed.
16. Lot-splitting is not permitted.
17. No overtime or subcontracting is allowed (shop capacity is fixed).
18. Any statistics to be gathered are determined when the system is operating under a steady state condition.

Despite these and other simplifying assumptions it is believed that the model studied extracts the essence of the job shop process, which is essentially a network of queues. Moreover, it is contended that until this basic process is better understood, very little progress can be made toward understanding the effect of different, complicating variations.

3.2 THE CONTROLLED EXPERIMENTAL FACTOR

The mean job interarrival time to the shop is the only controlled, stochastic, experimental factor in this thesis. This factor was selected because it is, to a large extent, within the control of shop management. If the customer demand is temporarily greater than the capacity of the shop, management could be more selective in the jobs it accepts. On the other hand, if demand is low, emphasis could be placed on increased sales activity or lower costs in an effort to attract the orders needed to maintain the desired mean interarrival time.

In order to prevent continual shop overload, the mean arrival rate was set at a lower value than the mean service rate of the shop. The jobs' interarrival times were generated using an exponential distribution whose mean was chosen so as to insure an average shop utilization of sixty percent. Because of the type of jobs arriving to the system each machine's utilization did vary.

Nanot [59] studied the effectiveness of ten different priority rules under six different shop structures. He concluded that the difference due to the use of various priority rules was highly significant, but that the difference due to system configuration such as shop size and difference in loading were much less significant.

3.3 EXPERIMENTAL STOCHASTIC PARAMETERS

In these simulation experiments four parameters were stochastic in nature and are discussed below.

3.3.1 Job Interarrival times

Job interarrival times were determined by randomly selecting a number from an exponential distribution. This distribution has been used in many of the experimental investigations reported in the pure job shop literature. The reader is referred to pages 22 and 23.

3.3.2 Estimated Job Processing Times

Estimated processing times for jobs at a given machine (machine center) were generated from a normal distribution and assumed to be constant for each machine in the shop.

3.3.3 Routing and Number of Operations for Job

The "routing" -the ordered list of machine group specifications- was determined so that a job was equally likely to find its first operation on any machine. Upon operation completion, it was equally likely to move to any other machine or to leave the shop. Two consecutive operations on the same machine were not permitted, but a job could return to a machine after an intervening operation.

Being generated in this way, the number of operations for a job was a random variable whose expected value was equal to half of the number of machines - in this case, 3. These conditions might be said to constitute a "pure job shop" with completely random movement between machines. Routing and number of operations for jobs are presented in Appendix B.

3.3.4 Assignment of Due Dates

The job's due date was assigned upon shop arrival. This due date, is defined as the sum of the job's arrival time at the shop and its allowable shop time. The allowable shop time is the sum of the individual operation processing times on a job's route multiplied by a constant, C. According to Muth [57], errors in estimating these processing times apparently have little effect on overall shop performance. This method of assigning due dates is identical to Conway's TWK method of due date assignment [15].

3.4 EXPERIMENTAL CONSTANTS

Four experimental constants were specified for this model, namely the following :

1. Number of machines in the shop : 5 machines.

2. Mean interarrival time of jobs to the shop : 75 time units.
3. Mean of the processing time distribution : 5 time units.
4. Constant, C, which when multiplied by the job's total processing time yields the allowable shop time : 6.

In the literature concerning the synthetic simulation of dynamic job shops, the number of machines comprising the shop have been small. However, Baker and Dzielinski [7], Conway, Johnson, and Maxwell [16], Conway and Maxwell [17], Nanot [49], and Buffa [11] evaluated shops with from 5 to 30 machines, and found that the size of the shop was not significant. Since shop size has never appeared as a major variable, it was assumed that it was feasible to experiment with relatively small shops and generalize the resulting conclusions.

The mean of the interarrival time distribution was set at 75 time units, and for all simulation runs the mean of the processing time distribution at a given machine was set at 5 time units to insure that the shop would not become permanently overloaded.

The fourth experimental constant, C, was set at 6 to insure that there would be no experiments where all jobs were early or in where all jobs were late. Actual selection of the number 6 resulted from various simulations trials.

3.5 DETERMINATION OF THE ACTUAL PROCESSING TIME

The actual processing times of jobs were also generated from a normal distribution. The manner in which the new (actual) processing times were generated is as follows.

If P_{ij} was the original estimated processing time of job i on machine j, then, job i's actual processing time on machine j, was a random variable generated from a normal distribution with mean equal to P_{ij} and standard deviation equal to r times P_{ij} . Where, r is the percentage variation in estimated processing time.

It should be mentioned that, when a job had begun its progression through the shop, as specified by its route, its priority at a given machine was computed on the basis of its original estimated processing time, assuming that the priority assignment required information about processing times.

3.6 THE PRIORITY RULES EMPLOYED IN THE SIMULATION

Although many priority rules have been proposed in the literature, no analytical formulation has been performed which assures optimality. Yet priority rules can do more than accelerate one or more jobs through the shop at the expense of other jobs - they can accelerate the average of all jobs [16]. Hence, though optimality will be difficult to achieve, it has been demonstrated that the choice of priority rule can affect aggregate measures of shop performance [17].

Priority rules are compared on the basis of their effectiveness in meeting a predetermined criterion (or criteria). The effectiveness of the priority rule is measured by the value of the criterion function which results when the rule is followed.

In order to eliminate one sizable source of variability in the experimentation, each priority rule is tested on the same set of jobs, rather than drawing an independent sample of jobs for each experiment.

Throughout the simulation, jobs competing for service at a particular machine were sequenced according to the following priority rules :

FIFO (First In - First Out) : Jobs are loaded on a given machine in the order in which they arrive to the machine's queue.

SOT (Shortest Operation Time) : A job queue for each machine is arranged in the order of increasing expected operation times for that machine. The job with the shortest expected operation time being loaded first.

EDD (Earliest Due Date) : Highest priority is given to the job with the earliest due date. The job with the earliest due date being served first.

3.7 INDEPENDENT VARIABLE COMBINATIONS

Six levels of variation between estimated and actual processing times and three priority dispatching rules, totalling 18 different combinations, were chosen for the simulation. Specifically, six values of variation (zero percent, 20 percent, 40 percent, 60 percent, 80 percent and 100 percent) were selected for investigation in conjunction with three priority rules, FIFO, SOT and EDD. A zero percent variation was introduced as a baseline for the purpose of determinig the statistical significance of the hypotheses.

3.8 SIMULATION DEPENDENT VARIABLES

The dependent variables were the criteria upon which the effect of estimated versus actual processing time distributions were examined. The criteria include :

1. Mean flowtime of all jobs.
2. Mean tardiness of all jobs.
3. Percentage of all jobs completed late relative to their due dates.
4. Average makespan.
5. Average machine utilization.

3.9 STATEMENT OF THE SPECIFIC RESEARCH QUESTIONS

The questions tested concerned the effect of estimated versus actual processing times upon various shop performance measures. These questions were :

1. Effect of estimated processing times on mean flowtime of all jobs.
2. Effect of estimated processing times on mean tardiness of all jobs.
3. Effect of estimated processing times on percentage of late jobs.
4. Effect of estimated processing times on makespan.
5. Effect of estimated processing times on average shop utilization.

3.10 DESCRIPTION OF THE SIMULATION MODEL

The simulation model's components have been described in the preceding sections. In this section the general flow of jobs through the simulator will be discussed. Also included will be a discussion of steady state conditions under which the simulation data was tabulated.

3.10.1 The Flow of Jobs Through the Shop

In this simulation a job was loaded into the shop as soon as it arrived. Upon arrival, a sequence of machines comprising the job route was generated, along with the corresponding processing times. Then the original job's due date was assigned. The job was now ready to begin its progress through the shop.

Upon completion of an operation at a given machine, the job moved to the next machine specified in its routing. If this machine was processing another job, the job joined the machine's queue. When that machine was available, a job was removed (or selected) from the queue on the basis of a priority dispatching rule and the prescribed job's operation was performed. While the sequencing was based on estimated processing time, the time spent on a machine was the actual processing time. The job continued this process through to its last operation. In the event of two or more jobs having equal priority, that job which arrived first in the queue was selected for processing. Figure 3.1 is a general flow diagram representation of the simulation model. Appendix A presents detailed flow diagrams.

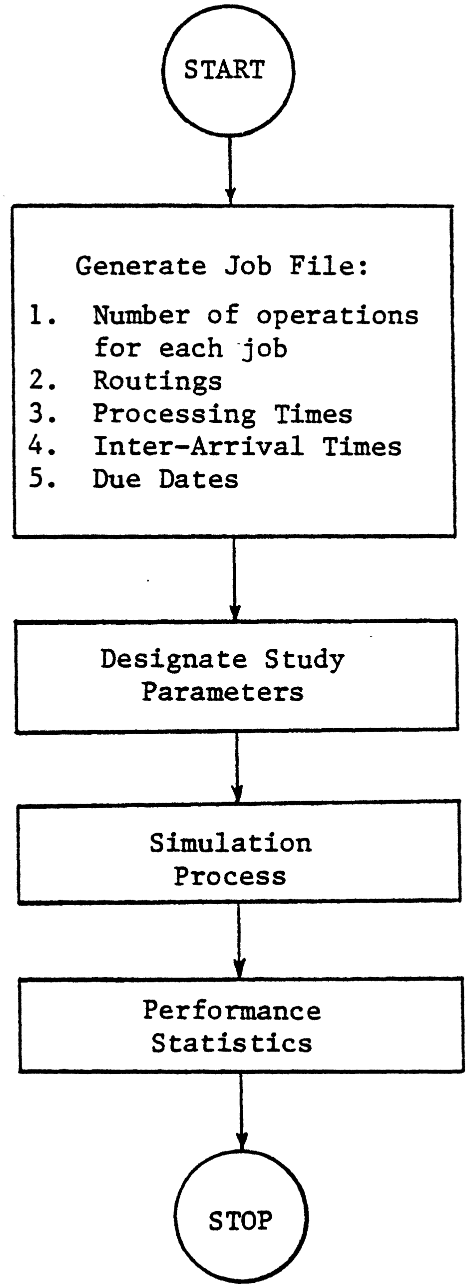

Figure 3.1. Flow Representation of a General Simulation Model.

3.10.2 Explanation of Steady State Convergence

Data was tabulated under steady state conditions in this investigation. The procedure by which steady state was defined in this study was somewhat arbitrary because, as yet, there has been no general agreement on the number of jobs completed by a shop for convergence to steady state. The term steady state, as used here, does not imply constant state as a certain amount of fluctuation is often seen, especially in queueing data.

From many simulation trials, it appeared that the condition where steady state was the latest in occuring was the mean flowtime performance measure (simulation dependent variable) using a FIFO priority dispatching rule. Hence, if steady state could be defined for this combination by the number of jobs completed, it was believed that the other simulation dependent variables would have already reached steady state with the same number of jobs completed.

From the data collected by simulating 5000 jobs for the above system's performance measure and priority rule, using Cumulative Moving Average Method, it appeared that after 1000 jobs were completed steady state was reached with respect to all dependent variables to be measured in this experiment. Graphs of each dependent variable versus the number of jobs processed appeared to be relatively stable after 1000 jobs had been completely processed. Figure 3.2 is a representation of steady state convergence with respect to all dependent variables.

A decision was made to eliminate all data related to the first 1000 jobs (the transient period) in order to exclude the effect of the transient phase data. In addition, to minimize run costs for the simulation experiments used in this research, it was determined that data for 1000 jobs would be sufficient for each simulation. Hence, for all simulation runs conducted in this study, the data collected was obtained on the 1001st through the 2000th jobs completed. The system was not allowed to empty itself, rather jobs continued to arrive throughtout each experiment.

3.10.3 Replications

For each of the 18 combinations, nine replications were made utilizing different seed values. Since the only change between these replications was the random number generator seed for estimating the original processing times, data should not be correlated. Hence, it was assumed that the generated data is independent.

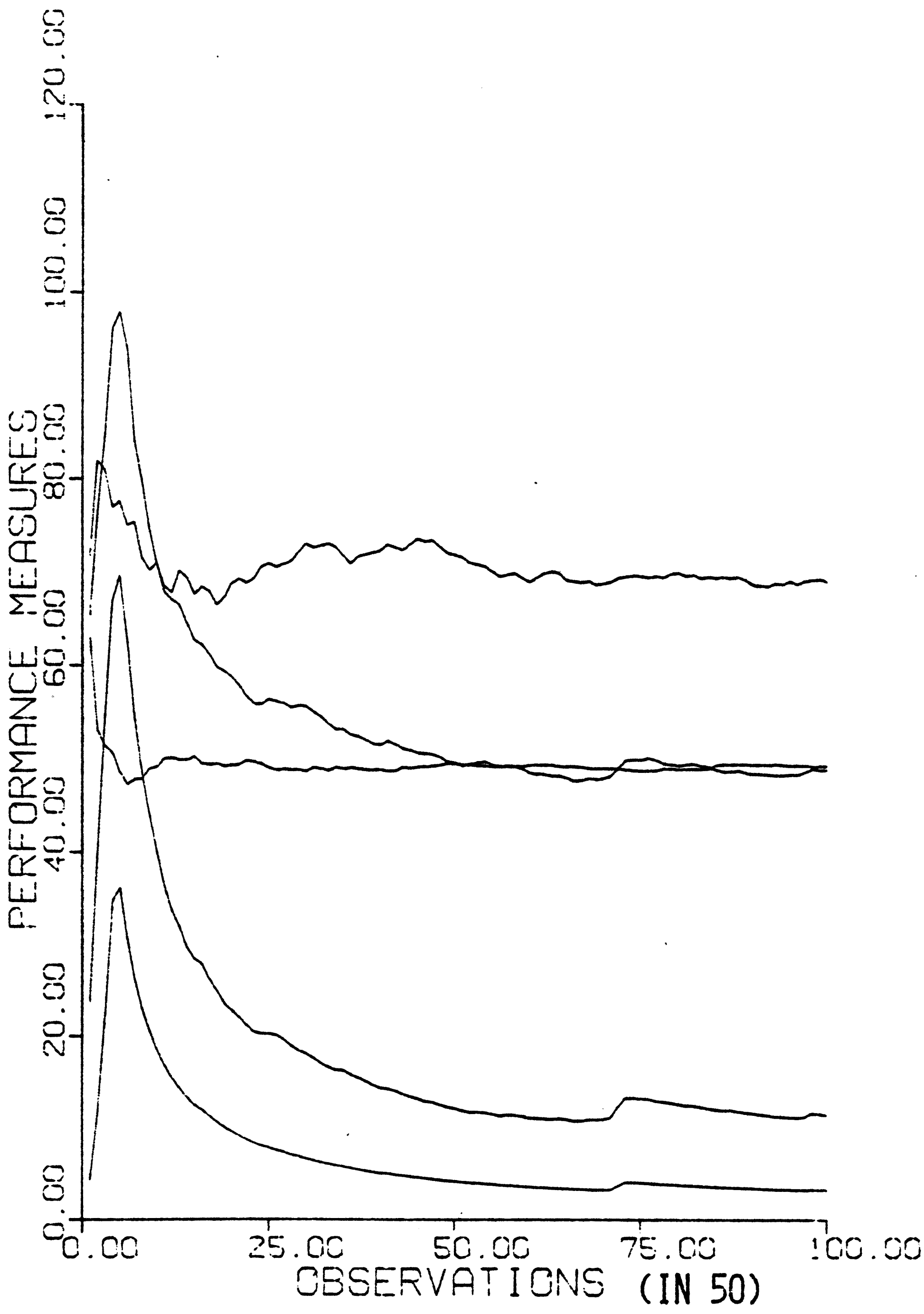

Figure 3.2. Representation of Steady State Convergence.

Chapter IV

ANALYSIS AND INTERPRETATION OF RESULTS

For the simulation analysis performed in this investigation, five performance measures were utilized. In this chapter the simulation output will be examined in order to determine what effect a variation between estimated and actual processing times had upon these five performance measures.

4.1 CALCULATION OF PERFORMANCE MEASURES

Performance measures were calculated after the 1000 jobs were completed, starting with the 1001th job. The results contained cumulative data on the jobs completed to that point in time.

The manner in which the numerical values of the performance measures studied were calculated are as follows.

4.1.1 Determination of the Mean Flowtime of All Jobs

Let R_i be the arrival time of job i at the shop, and let C_i be the corresponding completion time for that job. Then, the mean flowtime is defined as:

$$\overline{F} = \frac{1}{n} \sum_{i=1}^{n} (C_i - R_i)$$

where $\overline{F}$ is the mean flowtime, and n is the number of jobs completed.

4.1.2 Determination of the Mean Tardiness of All Jobs

Let D_i be the due date of job i. Therefore, by definition, the job lateness L_i can be given by :

$$L_i = D_i - C_i$$

It is important to note that the lateness quantity takes on positive values whenever a job is completed early and negative otherwise. Positive lateness represents better services than requested, while negative lateness represents poorer service, i.e.; the job that is late. In many situations, distinct penalties and other costs will be associated with negative lateness, but no benefits will be gained with positive lateness. Therefore, it is helpful to work with a quantity that measures only negative lateness.

Let T_i be the tardiness for job i; the lateness of job i if it fails to meet its required due-date, or zero otherwise. Thus:

$$T_i = \text{Min}\ \{L_i, 0\}$$

Therefore, the mean tardiness is defined as the following:

$$\overline{T} = \frac{1}{n} \sum_{i=1}^{n} T_i$$

where $\overline{T}$ is the mean tardiness, and n is the number of jobs completed by the shop.

4.1.3 Determination of the Percentage of Late Jobs

Let N_2 be the total number of jobs completed late relative to their due dates at the end of simulation (completion of 2000th job). Similarly, let N_1 be the corresponding number at the completion of 1000th job. Then, the percentage of jobs completed late relative to their due dates is :

$$100 \left[\frac{N_2 - N_1}{1000} \right]$$

4.1.4 Determination of Makespan

Makespan is traditionally defined as the time necessary to complete all jobs. For this research makespan (simulation time) is the time elapsed between completion of 1000th job and end of simulation (completion of 2000th job).

4.1.5 Determination of Average Shop Utilization

The formulation of average shop utilization is :

$$\overline{U} = \frac{1}{5} \sum_{j=1}^{5} \left[\left(1 - \frac{\text{Total Idle Time of Machine j}}{\text{Simulation Time}}\right) * 100 \right]$$

Where $\overline{U}$ is the average shop utilization and simulation time is the time elapsed between completion of 1000 and 2000th job (makespan).

4.2 SIMULATION RESULTS

The simulation generated data on each performance measure with respect to each combination of priority dispatching rule and level of variation between estimated and actual processing times are provided in Appendix C. Each table shows the raw data results for each performance measure for all combinations for nine replications.

Tables 4.1 through 4.5 summarize the generated data for each performance measure with all combinations of priority rules and levels of processing time variation.

4.3 STATISTICAL ANALYSIS OF RESULTS

A t-test for paired observations was performed with respect to the performance measure, in determining whether there is a significant difference in pairs of means at a five percent level of significance. It should be mentioned that the t-test assumes sampling from normal populations with identical but unknown variances. However, Cochran [13] showed that the test statistic can be approximated by a t distribution with (n-1) degrees of freedom when sample sizes

Table 4.1. Summary of Results Obtained from Nine Simulation Replications for FIFO, SOT and EDD Priority Dispatching Rules.

PERFORMANCE MEASURE: MEAN FLOWTIME							
PRIORITY RULE		% of Variation in Processing Times					
		0	20	40	60	80	100
FIFO	M	41.25	40.10	46.55	69.48	109.69	250.27
	S	3.16	2.70	6.35	24.04	38.42	118.88
SOT	M	39.80	38.98	41.53	50.47	94.47	212.45
	S	5.84	7.98	6.20	7.78	26.48	56.41
EDD	M	38.97	39.32	44.04	57.26	116.08	274.55
	S	3.48	4.54	5.01	6.50	44.47	145.16

M = mean
S = standard deviation

Table 4.2. Summary of Results Obtained from Nine Simulation Replications for FIFO, SOT and EDD Priority Dispatching Rules.

PERFORMANCE MEASURE: MEAN TARDINESS							
PRIORITY RULE		% of Variation in Processing Times					
		0	20	40	60	80	100
FIFO	M	- .18	- .26	- .73	-7.76	-31.51	-154.17
	S	.09	.37	1.19	11.00	31.13	113.99
SOT	M	-3.18	-2.80	-3.04	-5.65	-35.21	-139.45
	S	2.34	3.28	2.91	3.04	23.28	53.91
EDD	M	- .05	- .02	- .28	-1.36	-34.53	-174.27
	S	.09	.02	.44	1.43	36.71	145.30

M = mean
S = standard deviation

Table 4.3. Summary of Results Obtained from Nine Simulation Replications for FIFO, SOT and EDD Priority Dispatching Rules.

PERFORMANCE MEASURE: % OF TARDY JOBS							
PRIORITY RULE		% of Variation in Processing Times					
		0	20	40	60	80	100
FIFO	M	1.67	1.43	3.53	17.09	39.13	76.14
	S	.65	1.20	3.51	16.65	14.20	15.23
SOT	M	4.00	3.08	4.13	6.97	17.53	31.86
	S	2.44	1.77	2.09	2.84	4.55	4.46
EDD	M	.43	.23	1.63	6.56	40.03	83.17
	S	.75	.34	1.90	3.34	17.31	10.28

M = mean
S = standard deviation

Table 4.4. Summary of Results Obtained from Nine Simulation Replications for FIFO, SOT and EDD Priority Dispatching Rules.

PERFORMANCE MEASURE: AVERAGE MAKESPAN							
PRIORITY RULE		% of Variation in Processing Times					
		0	20	40	60	80	100
FIFO	M	4954.93	5022.77	4969.27	4897.83	4965.58	5021.13
	S	167.89	142.72	100.32	194.38	141.57	149.57
SOT	M	4956.02	5023.31	4973.02	5090.88	4973.40	5051.34
	S	152.78	197.24	193.32	116.98	194.87	129.40
EDD	M	5001.18	5029.48	4980.42	4990.99	4922.98	5079.20
	S	133.53	232.65	101.66	214.21	153.41	190.44

M = mean
S = standard deviation

Table 4.5. Summary of Results Obtained from Nine Simulation Replications for FIFO, SOT and EDD Priority Dispatching Rules.

PERFORMANCE MEASURE: AVERAGE SHOP UTILIZATION							
PRIORITY RULE		% of Variation in Processing Times					
		0	20	40	60	80	100
FIFO	M	69.97	72.50	67.66	71.72	82.02	89.29
	S	12.62	9.66	13.18	10.56	7.60	5.92
SOT	M	68.86	65.05	75.35	76.63	81.94	92.17
	S	10.27	12.85	9.66	5.61	7.56	5.26
EDD	M	70.55	62.72	67.46	75.24	83.54	91.44
	S	15.60	13.99	7.62	11.58	10.49	5.20

M = mean
S = standard deviation

are small and equal. An explanation of the t-test statistical calculation is presented in Appendix D.

Table 4.6 shows the results of the t-tests for paired observations at zero percent variation in estimated processing times for all shop performance measures studied in these simulation experiments.
T-test values used to determine whether there are differences in the shop performance measures for different levels of variation (0%-100%) in estimated processing times for all priority dispatching rules employed in these simulation experiments are shown in Tables 4.7 through 4.15.

4.4 INTERPRETATION AND IMPLICATIONS OF RESULTS

The intent of this section is to examine the stated hypotheses in the light of the statistical analyses just presented. The implications of the results to a job shop will also be developed.

4.4.1 Comparisons Between Priority Rules with No Processing Time Variation

As can be seen, the results of Table 4.6 indicate that computed t values for paired observations with respect to mean flowtime, makespan and average shop utilization are less than the t table values. Therefore, for these three performance measures, the null hypothesis indicates no

Table 4.6. T-Test Values Used in Determinimg Whether There is a Difference in the Performance Measures at Zero Percent Variation in Estimated Processing Times for FIFO, SOT and EDD.

Performance Measures	FIFO vs. SOT	FIFO vs. EDD	SOT vs. EDD
Mean Flowtime	.655	1.455**	.366
Mean Tardiness	3.840*	3.064*	4.009*
% of Late Jobs	2.768*	3.748*	4.195*
Makespan	-.014	-.646	-.667
Avg. Shop Utilization	.204	-.087	-.271

*Significant at the α = .05 level of significance, (± 1.860).

**Significant at the α = 0.10 level of significance, (± 1.397).

Table 4.7. T-Test Values Used in Determining Whether There is a Difference in the Mean Flowtime of Jobs for Different Levels of Variation in Estimated Processing Times.

% Variation	FIFO	SOT	EDD
0 - 100	5.273*	9.133*	4.867*
0 - 80	5.326*	6.048*	5.186*
0 - 60	3.492*	3.290*	7.442*
0 - 40	2.240*	.609	2.493*
0 - 20	- .83*	-----	- .183

*Significant at the α = .05 level of significance, (± 1.860).

Table 4.8. T-Test Values Used in Determining Whether There is a Difference in the Mean Flowtime of Jobs for FIFO, SOT and EDD at the Points of Significance (Also see Table 4.7).

Priority Rules	40	60	80	100
FIFO - SOT	----	2.257*	.978	.862
FIFO - EDD	.930	1.472	- .326	- .388
SOT - EDD	----	-2.01*	-1.252	-1.196

*Significant at the α = .05 level of significance, (± 1.860).

Table 4.9. T-Test Values Used in Determining Whether There is a Difference in the Mean Tardiness of Jobs for Different Levels of Variation in Estimated Processing Times.

% Variation	FIFO	SOT	EDD
0 - 100	4.052*	7.576*	3.597*
0 - 80	3.019*	4.107*	2.818*
0 - 60	2.067*	1.931*	2.743*
0 - 40	1.383	- .112	1.536

*Significant at the $\alpha = .05$ level of significance, ($\pm$ 1.860).

Table 4.10. T-Test Values Used in Determining Whether There is a Difference in the Mean Tardiness of Jobs for FIFO, SOT and EDD at the Points of Significance (Also see Table 4.9).

Priority Rules	60	80	100
FIFO - SOT	- .554	- .285	- .350
FIFO - EDD	-1.730	.188	.326
SOT - EDD	-3.830*	- .047	.674

*Significant at the $\alpha = .05$ level of significance, ($\pm$ 1.860).

Table 4.11. T-Test Values Used in Determining Whether There is a Difference in the Percentage of Late Jobs for Different Levels of Variation in Estimated Processing Times.

% Variation	FIFO	SOT	EDD
0 - 100	-14.656*	-16.440*	-24.082*
0 - 80	- 7.906*	- 7.862*	- 6.857*
0 - 60	- 2.776*	- 2.379*	- 5.372*
0 - 40	- 1.563	- .121	- 1.762

*Significant at the α = .05 level of significance, (± 1.860).

Table 4.12. T-Test Values Used in Determining Whether There is a Difference in the Percentage of Late Jobs for FIFO, SOT and EDD at the Points of Significance (Also see Table 4.11).

Priority Rules	60	80	100
FIFO - SOT	1.797	4.354*	8.370*
FIFO - EDD	1.860*	- .120	- 1.148
SOT - EDD	.280	-3.771*	-13.737*

*Significant at the α = .05 level of significance, (± 1.860).

Table 4.13. T-Test Values Used in Determining Whether There is a Difference in Makespan for Different Levels of Variation in Estimated Processing Times.

% Variation	FIFO	SOT	EDD
0 - 100	- .833	-1.428	-1.006

*Significant at the $\alpha = .05$ level of significance, ($\pm$ 1.860).

Table 4.14. T-Test Values Used in Determining Whether There is a Difference in the Average Shop Utilization for Different Levels of Variation in Estimated Processing Times.

% Variation	FIFO	SOT	EDD
0 - 100	-4.158*	-6.060*	-3.811*
0 - 80	-2.453*	-3.077*	-2.729*
0 - 60	- .319	-2.004*	- .724
0 - 40	-----	-1.380	-----

*Significant at the $\alpha = .05$ level of significance, (± 1.860).

Table 4.15. T-Test Values Used in Determining Whether There is a Difference in the Average Shop Utilization for FIFO, SOT and EDD at the Points of Significance (Also see Table 4.14).

Priority Rules	80	100
FIFO - SOT	.022	-1.091
FIFO - EDD	- .352	- .818
SOT - EDD	- .371	.296

*Significant at the $\alpha = .05$ level of significance, (± 1.860).

significant difference between FIFO, SOT or EDD priority dispatching rules. However, the computed t values for mean tardiness and percentage of late jobs are greater than the t table values. Therefore, the null hypothesis is rejected and concluded that there is significant difference between FIFO, SOT and EDD priority dispatching rules.

It is important to recognize that different mechanisms will exhibit different performance trade-offs. These conclusions were drawn on the basis of model assumptions and parameter settings of this investigation and are subjected to several factors, including the manner in which due dates were assigned and the tightness of the due dates themselves.

4.4.2 The Effect of Estimated Processing Times on Mean Flowtime of All Jobs.

It was hypothesized that as the percentage of variation in estimated processing times of jobs is increased, the mean flowtime of all jobs would increase significantly. The t-test results of Table 4.7 support this hypothesis. Tables 1, 2 and 3 of Appendix C demonstrate the magnitude of changes in mean flowtimes for FIFO, SOT and EDD, respectively, as the percentage of the variation increases.

The results of Table 4.7 and 4.8 indicate that the performance of FIFO and EDD suffer when percentage of error in estimated processing times increases while performance of

SOT does not suffer as drastically. From an examination of the numerical results, there appears to be a crossover point as percentage of variation increases, beyond which SOT achieves better performance than FIFO and EDD. Under the study's experimental conditions this crossover point occured near the 60% variation. Figure 4.1 presents comparisons of mean flowtime for FIFO, SOT and EDD priority rules for different levels of variation in estimated processing times.

The implication of Question 1 is that, for the pure job shop in which mean flowtime is the primary performance measure, more emphasis should be placed on estimating the processing times of jobs if the priority rule employed is FIFO or EDD. On the other hand, under conditions of unreliable information about job processing times, the use of SOT priority dispatching rule is preferable.

4.4.3 The Effect of Estimated Processing Times on Mean Tardiness of All Jobs.

It was hypothesized that as the percentage of variation between actual and estimated processing times is increased, the mean tardiness of all jobs would increase significantly. The t-test values in Table 4.9 support this hypothesis. The magnitude of changes in mean tardiness as the percent of variation increases are presented in Tables 4, 5 and 6 of Appendix C for FIFO, SOT and EDD priority rules, respectively.

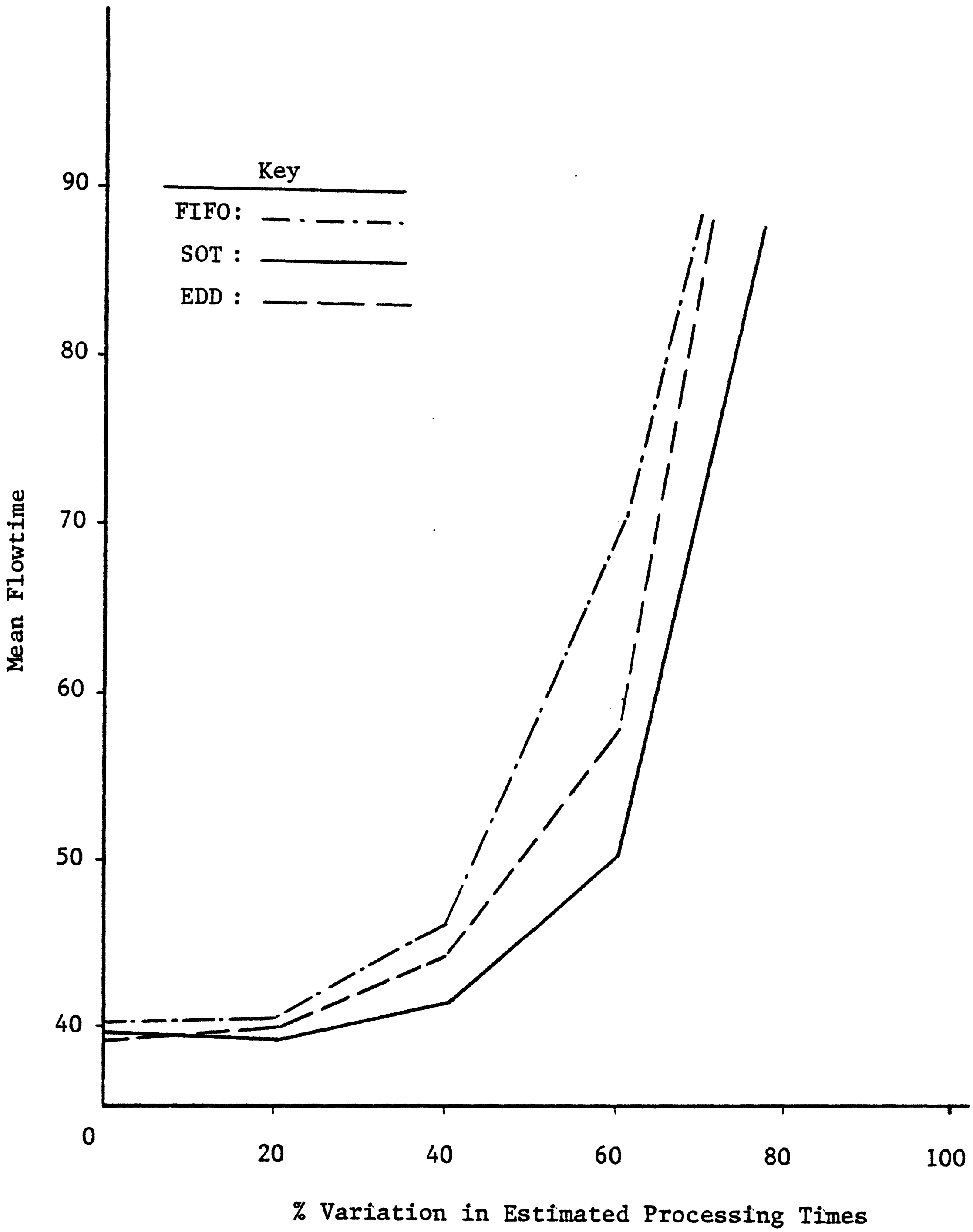

Figure 4.1. Comparisons of Mean Flowtime for FIFO, SOT and EDD Priority Rules.

From an examination of the numerical and statistical results, there appears to be no significant difference in relative performance between FIFO, SOT and EDD as the percentage of variation in estimated processing times increases over 40 percent. It does appear that SOT is not as sensitive to moderately large increases. Figure 4.2 presents comparisons of mean tardiness for FIFO, SOT and EDD priority rules for variation in estimated processing times from 0% to 100%.

4.4.4 The Effect of Estimated Processing Times on Percentage of Late Jobs.

It was hypothesized that as the percentage of variation in estimated processing times is increased, the percentage of jobs completed late would increase. The t-test results of Table 4.11 support this hypothesis. Tables 7, 8 and 9 of Appendix C present the percentage of late jobs for FIFO, SOT and EDD priority rules as the percentage of variation in estimated times increases.

Examination of the results indicates that for up to a 40% variation in estimated processing times there is no significant difference in percentage of late jobs with respect to FIFO, or SOT or EDD priority rules, while beyond 40% the use of SOT dispatching rule is statistically preferable. Figure 4.3 presents comparison of percentage of

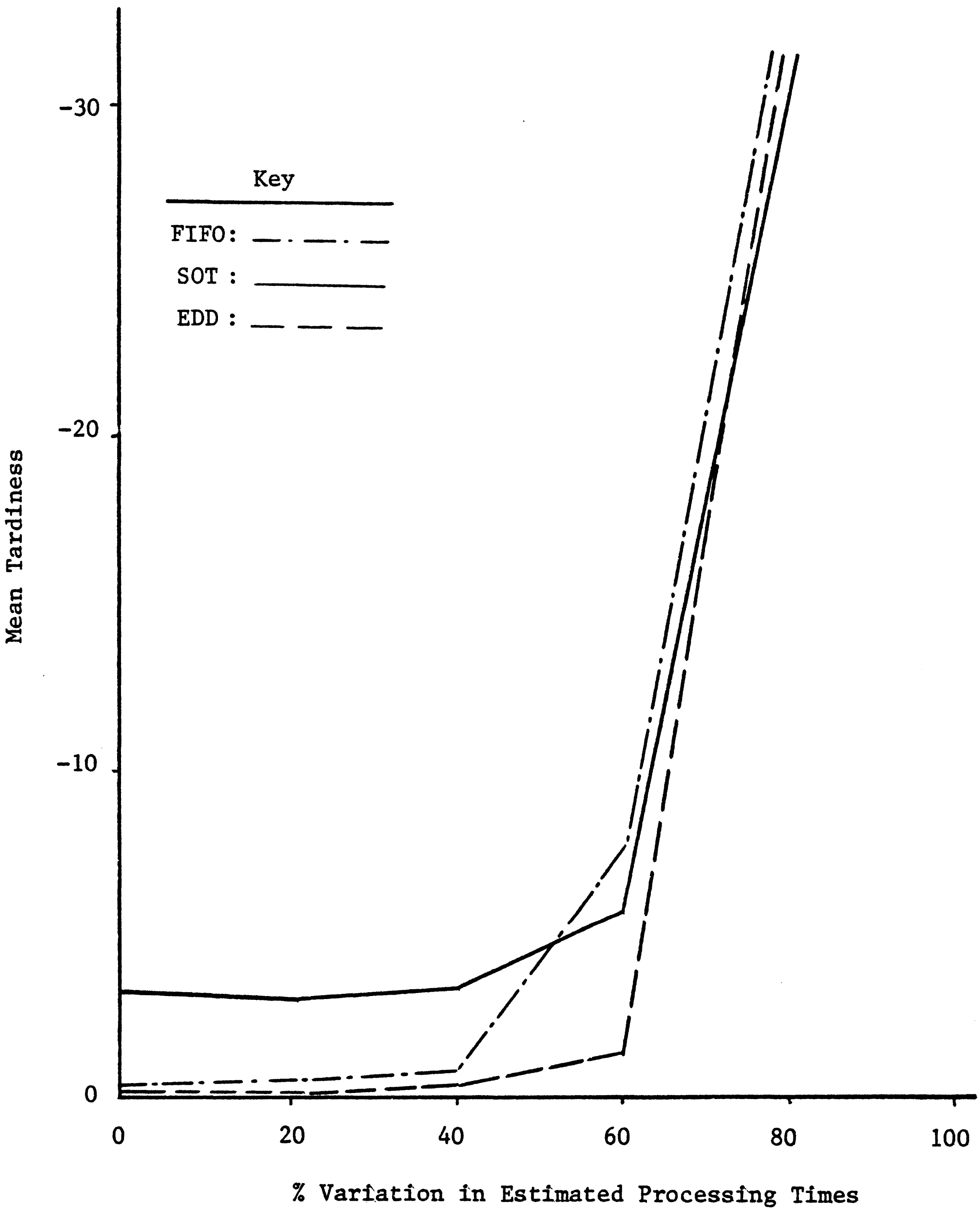

Figure 4.2. Comparisons of Mean Tardiness for FIFO, SOT and EDD Priority Rules.

late jobs for FIFO, SOT and EDD priority rules for different levels of variation in estimated processing times.

The implication of the evidence supporting Questions 2 and 3 is that, for the pure job shop in which mean tardiness or percentage of late jobs is the primary performance measure, more emphasis should be placed on estimating processing times of jobs, and as variation in estimated times increases the use of SOT becomes more inviting.

4.4.5 The Effect of Estimated Processing Times on Makespan.

It was hypothesized that as the percentage of variation in estimated processing times is increased, the makespan would increase significantly.However, the t-test results in Table 4.13 do not support this hypothesis. Tables 10, 11 and 12 of Appendix C present the magnitude of changes in makespan for FIFO, SOT and EDD priority rules as the percentage of variation in estimated times increases.

Examination of results indicates that the makespan is not sensitive to variation even when the estimates are allowed to be off by as much as 100%. Since the makespan was not sensitive to the quality of estimates, no further tests were conducted for extracting the preferable priority dispatching rule among FIFO, SOT and EDD. Figure 4.4 presents comparisons of makespan for FIFO, SOT and EDD for different levels of variation in estimated processing times.

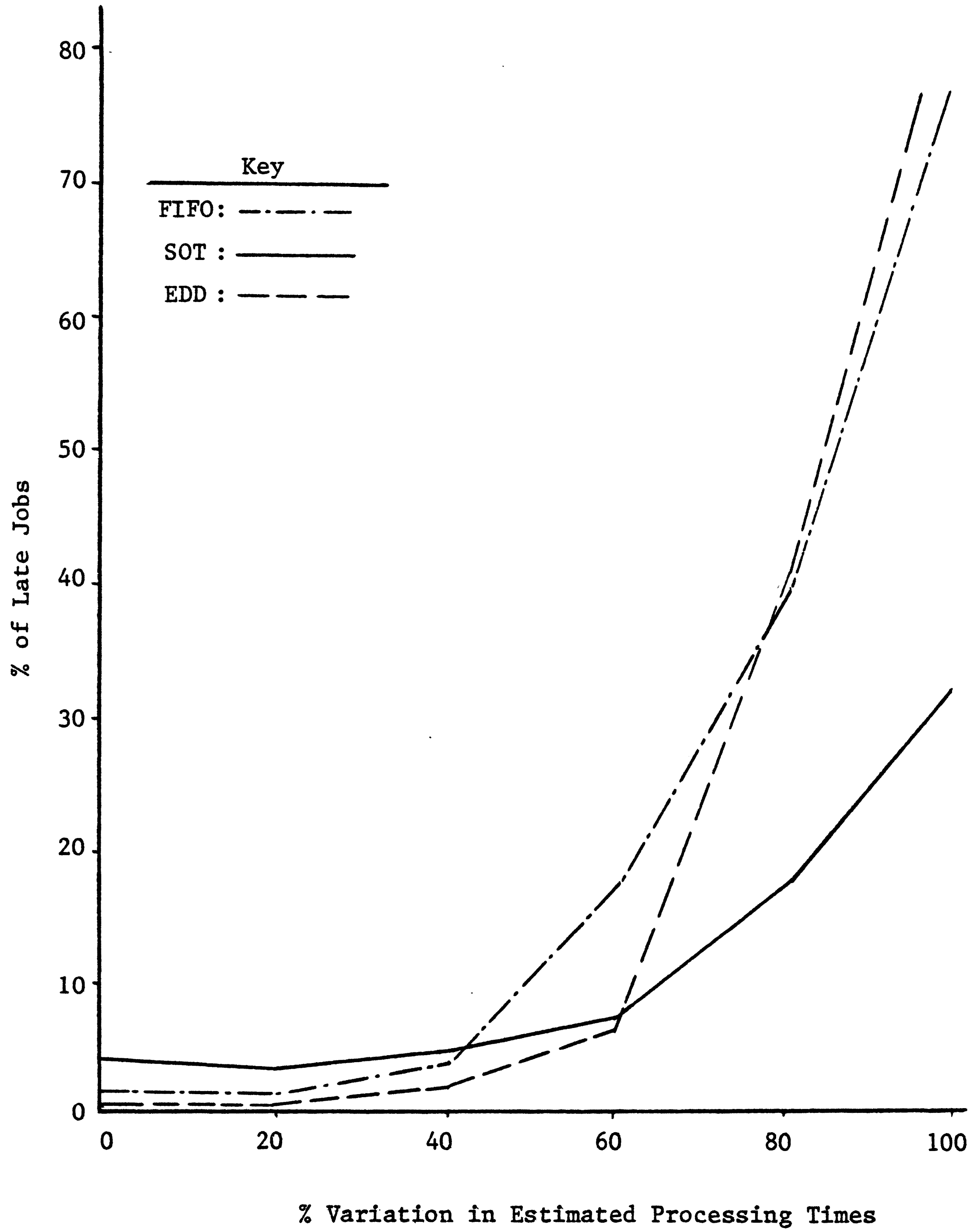

Figure 4.3. Comparisons of Percentage of Late Jobs for FIFO, SOT and EDD Priority Rules.

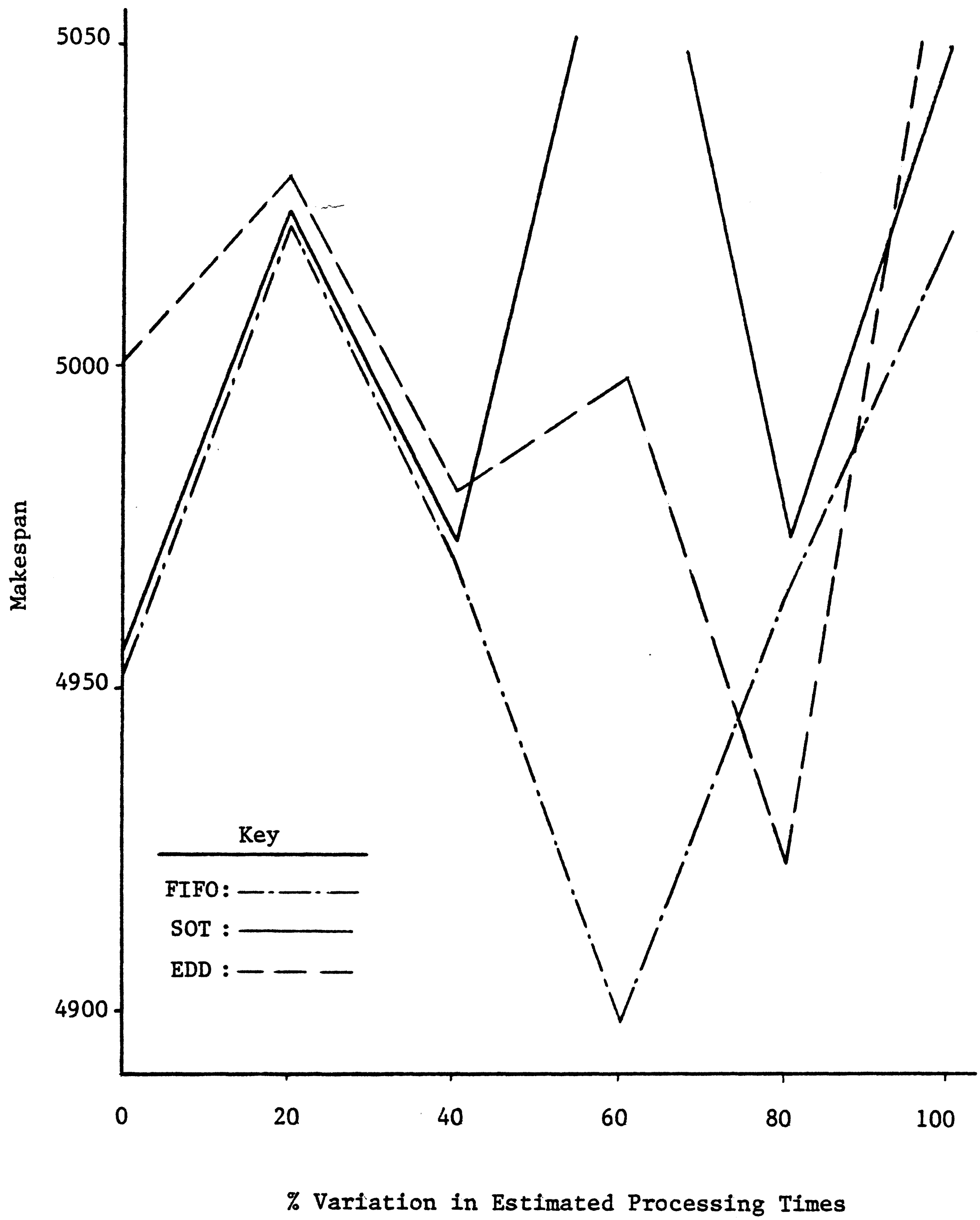

Figure 4.4. Comparisons of Makespan for FIFO, SOT and EDD Priority Rules.

The implication of Question 4 is that, for a pure job shop situation in which makespan is the major performance measure, imperfect information about processing times will have little effect on determining optimal schedules.

4.4.6 The Effect of Estimated Processing Times on Average Shop Utilization.

It was hypothesized that as the percentage of variation in estimated processing times is increased, the average shop utilization would increase. The t-test values from Table 4.14 indicate that for up to a 80% variation the relative performances of FIFO, SOT and EDD do not suffer drastically, or change significantly. Tables 13, 14 and 15 of Appendix C present the values of average shop utilization for different levels of variation in estimated processing times for FIFO, SOT and EDD. Figure 4.5 presents comparisons of average shop utilization between FIFO, SOT and EDD for different levels of variation in estimated processing times.

The implication of Question 5 is that, for a pure job shop in which the average shop utilization is the primary performance measure, the effect of estimated processing times can be ignored. Furthermore, the results of Table 4.15 indicate that as the percentage of error in estimated times increases, there in no significant difference in relative performance of FIFO, SOT or EDD.

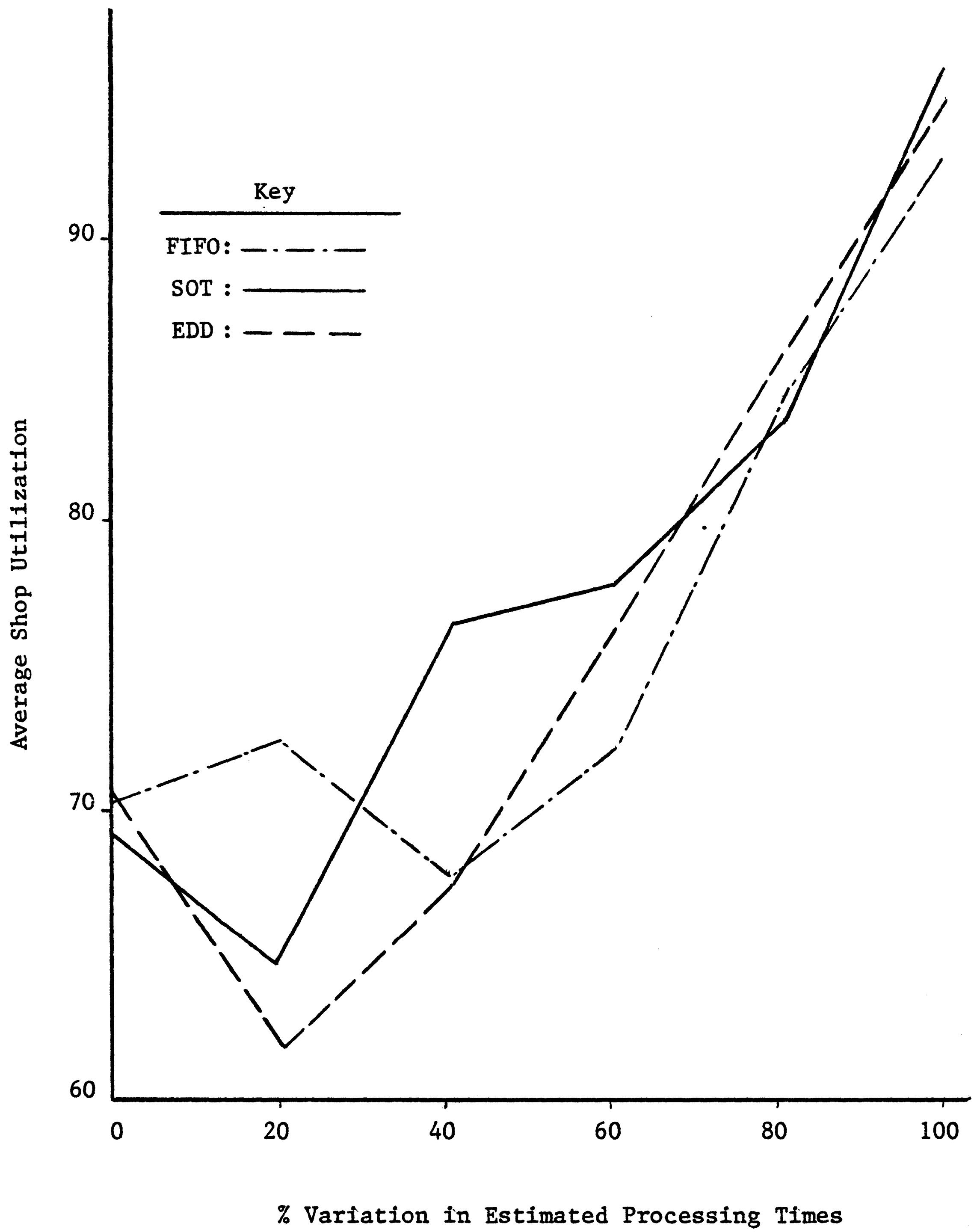

Figure 4.5. Comparisons of Average Shop Utilization for FIFO, SOT and EDD Priority Rules.

4.5 SUMMARY

Analysis and interpretation of the results for each performance measure with respect to each priority rule and level of variations are presented in this chapter. For most of the performance measures studied, the processing time variation was clearly the dominant variable, as an examination of the t-test values indicated. However, it is interesting to note that for some of the performance measures, a maximum level of variation in estimated processing times is achieved beyond which these particular performace measures are insensitive.

The results of the analysis show that, for the assumptions and parameter settings of this study, mean flowtime, mean tardiness and percentage of late jobs were insensitive to variations between actual and estimated processing times for up to 60%.

Another interesting observation concerns the results of t-test for makespan and average shop utilization. From an examination of the results, it can be concluded that the two performance measures were insensitive to a moderately large variation in estimated processing times (up to 100%).

This is not to say, however, that accurate processing times are not needed elsewhere in plant operations, since accurate time data is necessary for cost control and methods improvement.

Chapter V

CONCLUSIONS AND RECOMMENDATIONS

The results of this research have been presented and analyzed in the previous chapter. It appears meaningful at this time to mention again the objective of this investigation so that conclusions can be drawn in its framework.

The purpose of this research was to explore the effect of variations between actual and estimated processing times, in conjunction with three dispatching rules, on various performance measures in a pure job shop; and provide a priority rule which the shop could utilize in case of unreliable input information about processing times.

Six levels of variation in estimated processing times were examined with respect to their effect upon five performance measures :

1. Mean flowtime of all jobs.
2. Mean tardiness of all jobs.
3. Percentage of all jobs completed late relative to their due dates.
4. Average schedule span (makespan).
5. the average machine utilization.

The research was conducted through the use of simulation using FORTRAN IV programming language. The model simulated was that of a pure job shop with five machines. Priority rules studied were FIFO, SOT and EDD. Due dates were assigned to jobs upon entering the shop and were determined by adding to the job's arrival time the product of its total estimated processing time and a constant. Mean interarrival time and mean processing times were set at 75 and 5 time units, respectively. Job interarrival times to the shop were described by an exponential distribution and estimated processing times at given machines were generated from a normal distribution. Actual processing times were also generated from a normal distribution with the estimated time being its mean.

Nine computer replicates were made for each combination of percentage variation in processing times and priority rule, yielding a total of 172 computer simulations. The sample size chosen from each run was determined through consideration of steady state operating characteristics and budgetary constrains.

The analysis of results indicated that, for the all performance measures studied, the level of variation in estimated processing time was a significant factor, except in the case where makespan was the criterion. It was remarkably insensitive to moderately large errors in estimated job processing times. A 40% variation in estimated processing times was found to be the maximum level in which all performance measures with respect to all priority rules studied were insensitive. It is apparent from the results that the performance of FIFO and EDD priority rules suffered drastically when input information was unreliable while SOT was least sensitive to the reliability of processing time information.

As mentioned earlier, it should be realized that these conclusions were reached on the basis of model assumptions and parameter settings for this research. It is not known to what extent the results can be generalized to other systems.

5.1 SUGGESTIONS FOR FURTHER RESEARCH

The following directions are suggested for further research in relation to the study reported herein :

1. Variation of the constant used in determining the allowable shop time when determining job due dates.
2. Priority rules which emphasize preemptive disciplines.
3. Variation of the mean of the processing time distribution for both estimated and actual.

4. Alternating the job routes when there are emergency job classes.

Although the objective of this research has been accomplished, it would be useful to study each of these possibilities to explore the effect of variation in estimated processing times on job shop scheduling problems and provide a better background in designing optimal schedules.

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Appendix A

Logic Flow Diagrams of the Simulator

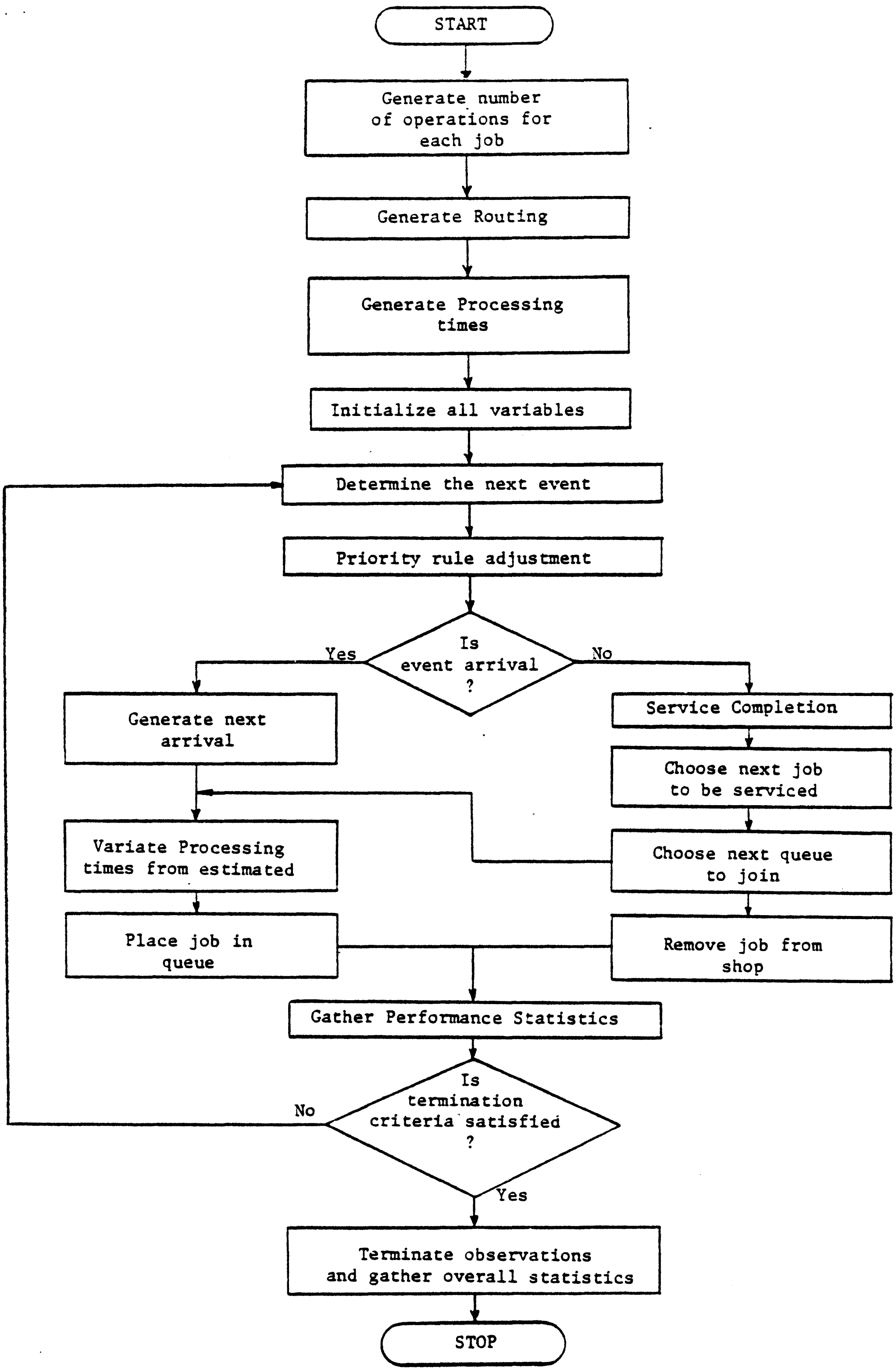

Figure A.1. Logic Flow Diagram of the Simulation Model.

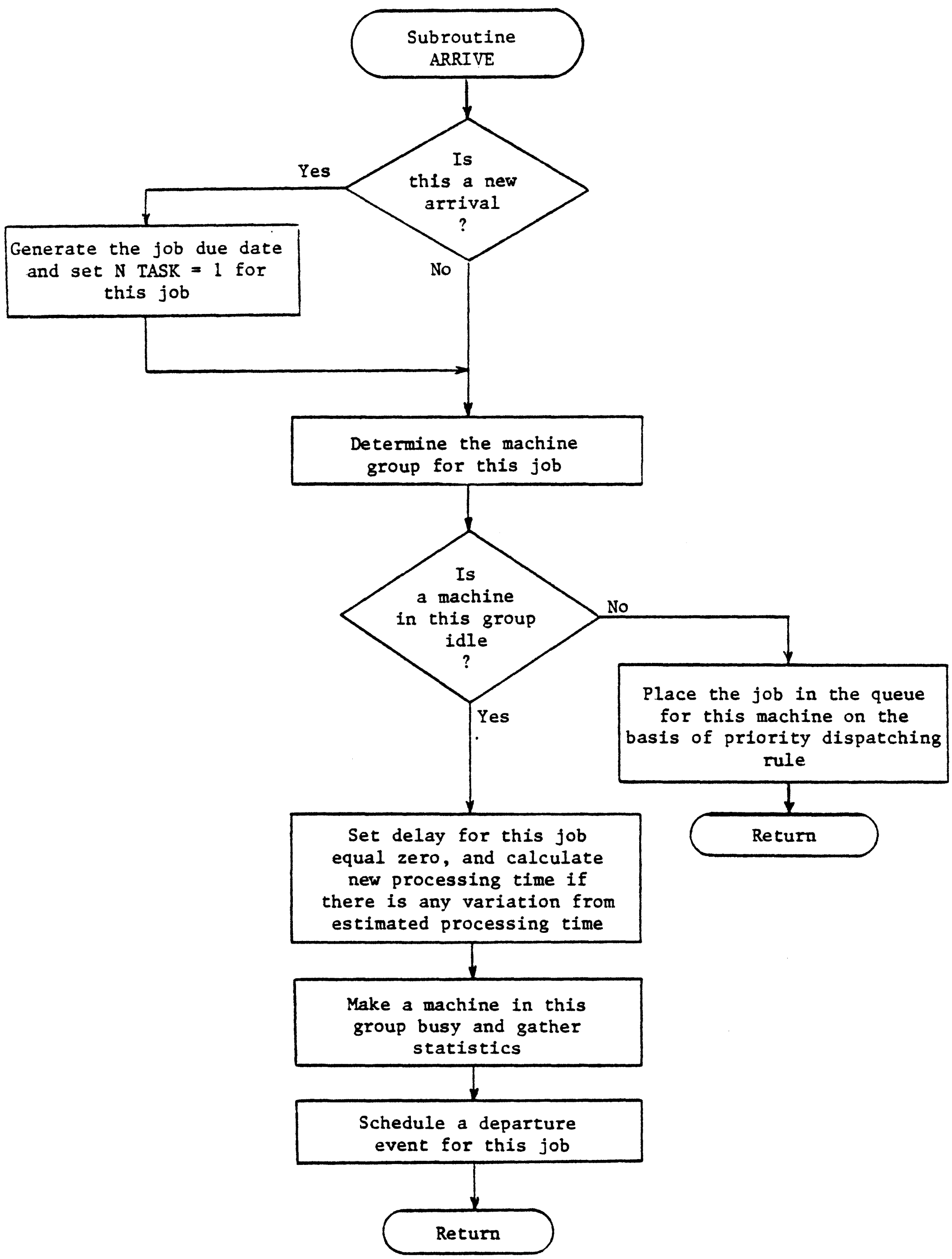

Figure A.2. Flow Diagram for Subroutine ARRIVE.

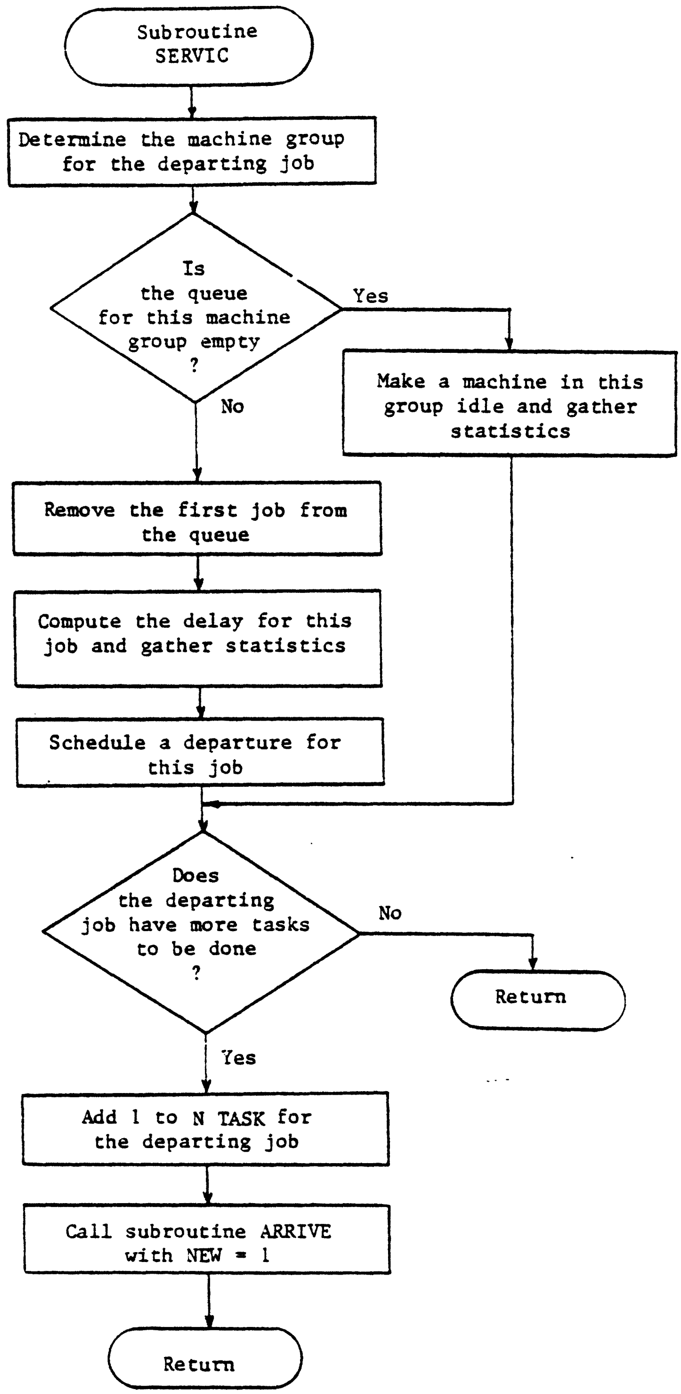

Figure A.3. Flow Diagram for the Subroutine SERVIC.

Appendix B

Routing and Number of Operations for Jobs

Routing and Number of Operations for Jobs

Job Type	Machine Groups	No. of Operations
1	5 → 4 → 2	3
2	5 → 3 → 5	3
3	5 → 4	2
4	4 → 1 → 4 → 3	4
5	2 → 4 → 3 → 5	4
6	3 → 2 → 1	3
7	5 → 4 → 3 → 2	4
8	5 → 1 → 4	3
9	5 → 2	2
10	2 → 4 → 1 → 4 → 1	5
11	5 → 4	2
12	3 → 1 → 4	3
13	4 → 5 → 1 → 3 → 4	5
14	1 → 5 → 3 → 2 → 5	5
15	1 → 3 → 4 → 1 → 5	5
16	4 → 3 → 2 → 1	4
17	4 → 2 → 3	3
18	1 → 3 → 5 → 1	4
19	5 → 1 → 5 → 1	4
20	5 → 4 → 5	3
21	1 → 3 → 2 → 1 → 2	5
22	1 → 2 → 4 → 2	4
23	3 → 2	2
24	2 → 3 → 2 → 3 → 2	5
25	2 → 3	2

Appendix C

Raw Data Results

Table C.1. The Mean Flowtime of All Jobs for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for FIFO Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	43.92	36.33	45.79	53.83	149.76	128.56
2	35.59	35.93	40.82	70.51	69.57	412.76
3	45.53	39.83	43.35	74.04	81.37	299.04
4	38.15	42.37	52.27	60.67	188.63	135.45
5	44.14	38.96	45.88	71.66	80.37	135.71
6	42.59	44.05	59.32	55.89	119.75	273.66
7	39.92	42.10	48.82	128.71	105.77	408.84
8	40.79	40.90	37.93	64.03	85.78	320.25
9	40.61	40.43	44.78	45.99	106.24	138.15

Table C.2. The Mean Flowtime of All Jobs for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for SOT Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	40.34	33.68	35.17	50.36	54.04	171.70
2	35.34	34.50	38.84	43.36	126.67	204.35
3	40.76	42.55	49.93	56.56	110.66	286.05
4	42.10	38.91	46.56	52.28	89.51	246.17
5	37.71	53.39	43.71	61.98	109.19	162.37
6	49.73	49.70	48.32	52.90	89.02	285.30
7	46.56	34.79	41.84	55.50	129.83	254.06
8	33.09	31.86	31.52	36.38	67.63	144.48
9	32.53	31.41	37.91	44.91	73.68	157.55

Table C.3. The Mean Flowtime of All Jobs for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for EDD Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	34.22	35.82	36.72	60.93	71.45	239.57
2	40.31	33.93	39.52	57.14	133.29	594.04
3	40.09	43.30	40.84	55.98	191.50	176.15
4	42.14	37.58	51.75	54.03	184.67	126.93
5	37.49	45.25	47.44	57.73	79.28	208.83
6	40.24	44.14	46.78	68.22	90.49	362.77
7	44.92	35.40	49.42	63.90	107.01	369.54
8	35.79	43.12	42.45	47.96	97.58	212.55
9	35.55	35.30	41.44	49.45	89.46	180.56

Table C.4. The Mean Tardiness of All Jobs for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for FIFO Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	- .31	0	- .17	- .4	- 61.12	- 44.57
2	- .13	- .12	- .28	-10.97	- 8.02	-317.40
3	- .28	- .05	- .07	- 4.77	- 9.68	-195.99
4	- .09	- .12	- .85	- 2.87	-101.61	- 40.16
5	- .23	- .13	- .31	- 8.58	- 10.42	- 47.59
6	- .26	-1.18	-3.77	- .92	- 31.96	-169.77
7	- .09	- .15	- .94	-35.37	- 23.86	-305.48
8	- .18	- .11	- .07	- 5.70	- 11.70	-220.42
9	- .07	- .49	- .09	- .22	- 25.25	- 46.15

Table C.5. The Mean Tardiness of All Jobs for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for SOT Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	-3.02	-1.66	- .55	-5.18	- 5.27	- 99.18
2	-1.96	-1.74	-2.58	-3.67	-71.73	-139.37
3	-6.07	-3.10	-8.03	-9.31	-44.10	-209.76
4	-5.28	-1.14	-7.20	-8.27	-31.50	-173.63
5	- .64	-9.03	-2.23	-7.62	-45.24	- 88.62
6	-5.36	-7.60	-4.32	-6.23	-25.55	-207.12
7	-5.22	- .50	-1.90	-7.95	-65.44	-176.30
8	- .37	- .27	- .08	- .19	-12.21	- 75.73
9	- .71	- .14	- .46	-2.42	-15.82	- 85.30

Table C.6. The Mean Tardiness of All Jobs for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for EDD Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	0	0	0	-4.87	- 3.39	-141.21
2	- .26	0	- .08	-1.72	-52.12	-499.53
3	0	- .05	- .01	- .42	-98.35	- 75.15
4	- .14	0	- .78	- .69	-89.77	- 32.11
5	0	- .06	- .22	-1.18	- 7.81	-104.58
6	0	- .0054	- .0055	-1.46	- 6.76	-256.85
7	- .02	0	-1.25	-1.41	-21.52	-263.88
8	0	- .02	- .08	- .24	-16.25	-113.38
9	0	0	- .1	- .22	-14.78	- 81.72

Table C.7. The Percentage of All Jobs Completed Late for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for FIFO Priority Dispatching Rule.

Replications	0	20	40	60	80	100
1	2.50	0	2.20	3.50	57.30	50.40
2	1.50	.90	2.10	23.60	20.90	84.70
3	2.30	1.00	1.00	18.00	24.00	88.50
4	.70	1.00	5.40	10.10	58.50	64.70
5	1.90	1.30	2.90	19.60	27.00	61.80
6	2.40	4.20	11.70	5.70	50.20	87.20
7	1.30	1.40	5.00	56.50	40.50	89.40
8	1.5	.80	.60	15.50	31.20	91.80
9	.90	2.30	.90	1.30	42.60	66.80

Table C.8. The Percentage of All Jobs Completed Late for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for SOT Priority Dispatching Rule.

Replications	0	20	40	60	80	100
1	5.20	2.50	1.70	8.20	9.10	36.10
2	3.90	2.70	4.60	6.40	18.50	26.90
3	3.10	3.60	6.10	8.00	21.20	32.90
4	6.00	3.00	5.30	7.20	15.80	34.10
5	1.90	5.90	5.40	11.80	23.20	28.90
6	7.30	5.80	6.60	7.10	17.60	35.20
7	6.70	1.80	4.50	7.70	22.70	37.10
8	.80	1.60	.50	1.10	13.40	23.90
9	1.10	.80	2.50	5.20	16.30	31.60

Table C.9. The Percentage of All Jobs Completed Late for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for EDD Priority Dispatching Rule.

Replications	0	20	40	60	80	100
1	0	0	0	10.70	16.80	77.10
2	2.0	0	.90	8.20	47.60	79.60
3	0	.70	.10	4.60	63.50	83.60
4	1.40	0	4.90	5.20	66.70	60.30
5	0	.90	1.90	8.90	19.70	88.70
6	0	.20	.10	9.30	29.80	93.70
7	.5	0	4.70	8.60	42.60	94.50
8	0	.30	.90	1.90	39.70	83.40
9	0	0	1.20	1.60	34.30	87.30

Table C.10. Simulation Time (Makespan) for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for FIFO Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	4692.11	4963.33	4884.05	4906.00	4799.74	5214.43
2	5001.52	5201.93	4921.11	4917.16	5152.70	4929.74
3	5026.56	5131.32	4946.49	4592.86	5053.43	4840.33
4	5160.00	4939.84	4903.02	5172.18	4897.43	5187.47
5	4887.28	4743.91	5157.43	4841.80	5043.40	4924.23
6	4875.62	5094.68	4830.73	5043.41	4768.69	5030.30
7	5012.31	5152.79	5056.28	4602.86	5146.99	5161.37
8	5184.59	5045.58	5002.66	5018.01	4948.85	4820.72
9	4754.44	4931.60	5021.70	4986.23	4879.03	5081.58

Table C.11. Simulation Time (Makespan) for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for SOT Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	4855.39	5249.49	5191.22	4972.97	5263.49	4919.88
2	5043.96	5059.43	4893.24	5066.70	4767.60	5082.32
3	4954.66	4886.78	4883.30	5148.46	4798.25	5043.95
4	5146.22	4882.75	5197.35	5139.32	5240.49	5141.65
5	4941.98	4729.85	4862.85	4846.45	4905.96	4991.03
6	4653.66	4861.00	4720.94	5112.79	4914.72	4859.31
7	4952.84	5199.86	5013.43	5243.71	5166.29	5275.04
8	4903.60	5040.76	5229.98	5152.38	4834.27	5163.70
9	5151.86	5299.87	4764.90	5135.17	4869.55	4985.19

Table C.12. Simulation Time (Makespan) for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for EDD Priority Dispatching Rule. Values are in units of time.

Replications	0	20	40	60	80	100
1	4985.36	5200.78	5005.88	5015.09	4788.75	5285.48
2	4729.78	5302.55	5106.77	4903.68	4861.22	5053.49
3	4989.40	4873.29	5025.88	5191.61	4772.03	4916.99
4	5155.72	5134.61	4866.31	5139.66	5060.10	5352.13
5	5001.48	4988.33	4985.15	5205.93	5053.46	5045.35
6	5052.13	4721.10	4905.88	4534.74	4722.12	4986.57
7	4885.53	5373.88	5076.33	4878.06	5166.48	5299.36
8	5046.55	4873.64	4802.73	4908.50	4879.79	4803.39
9	5164.67	4797.12	5048.88	5141.65	5002.86	4970.06

Table C.13. Average Machine Utilization for Nine Simulation Replications, and Six Levels of the Percentage Variation in Estimated Processing Times for FIFO Priority Dispatching Rule.

Replications	0	20	40	60	80	100
1	76.65	84.95	75.71	77.35	72.04	81.84
2	52.81	62.66	53.68	76.54	87.57	94.98
3	86.14	74.18	46.22	91.27	90.15	96.46
4	64.93	65.79	56.45	57.45	82.90	84.23
5	66.48	66.59	74.69	59.07	80.05	94.95
6	76.86	65.02	77.40	77.87	93.61	86.81
7	65.27	84.01	85.73	72.74	80.77	95.00
8	53.44	64.31	63.74	66.99	80.07	85.46
9	87.11	85.02	75.28	66.21	71.02	83.85

Table C.14. Average Machine Utilization for Nine Simulation Replications and Six Levels of the Percentage Variation in Estimated Processing Times for SOT Priority Dispatching Rule.

Replications	0	20	40	60	80	100
1	56.24	53.11	63.76	77.40	77.52	94.55
2	72.96	53.30	83.68	65.08	90.42	92.28
3	76.12	56.87	66.71	86.67	72.65	95.96
4	74.47	77.01	84.34	76.76	80.36	94.10
5	76.63	88.43	66.64	80.02	71.67	94.67
6	78.69	76.82	88.41	77.06	82.25	97.09
7	56.49	63.90	76.02	76.92	91.21	84.02
8	74.73	62.76	82.64	74.48	80.30	82.41
9	53.40	53.29	65.98	75.77	91.05	94.45

Table C.15. Average Machine Utilization for Nine Simulation Replications and Six Levels of the Percentage Variation in Estimated Processing Times for EDD Priority Dispatching Rule.

Replications	0	20	40	60	80	100
1	84.22	63.74	63.80	86.89	59.88	83.52
2	85.08	61.70	63.38	65.90	80.75	92.83
3	35.77	86.02	65.02	76.50	93.68	95.92
4	75.00	45.18	77.18	86.09	81.88	93.43
5	65.36	56.57	76.02	57.22	80.99	95.89
6	65.52	46.79	76.71	82.09	93.24	96.10
7	76.57	53.29	54.64	89.55	90.83	85.09
8	83.97	76.03	65.71	66.70	80.46	85.48
9	63.45	75.18	64.66	66.22	90.19	94.67

Appendix D

Sample Calculation of Statistical T-Test

To illustrate the calculation of t statistic, let performance measure be mean flowtime, percentage variation in estimated processing time equal zero and priority rules FIFO and SOT. From Table 4.1 (Chapter 4) the mean is 41.25 and standard deviation is 3.16 for FIFO and similarly, 39.80 and 5.84 for SOT. Then the statistical test is set up as follows:

H_0 : $M_F - M_S = 0$

H_1 : $M_F - M_S > 0$

$$\text{T.S.} : \quad t = \frac{M_F - M_S}{\sqrt{(S^2{}_F/n_F) + (S^2{}_S/n_S)}} = \frac{41.25 - 39.80}{\sqrt{(9.98/9) + (34.1/9)}}$$

$$= .655$$

R.R. : For $\alpha = .05$ reject H_0 if $t > 1.860$, the t value for $\alpha = .05$ and df = 8.

Since the computed value of t is less than 1.860, the null hypothesis (H_0) is accepted and it is concluded that the difference between the means of the two priority rules is not significant.

The calculations of t for all other performance measures and percentage variations for FIFO, SOT and EDD priority rules were made in a similar fashion.

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The Effect of Estimated Processing Times Versus Actual (Standard) Processing Times on Various Performance Measures in a Pure Job Shop

by

Farzad Emaminezhad

(ABSTRACT)

A comparative simulation study was performed to investigate the effect of uncertainty or unreliability in job processing times on designing schedules in a pure job shop environment. Five performance measures were employed in an effort to examine the effect of variations between estimated and actual processing times. These variations are common in job shop systems where estimations are used to set processing times. It was hypothesized that a variation has an effect on relative system performance. In addition, three priority rules, namely, FIFO, SOT and EDD, were studied to determine the best rule for controling the shop in situations of unreliable processing times data.

The percentage variation in processing times was clearly the dominant variable for most of the performance measures. A 60% variation in estimated processing times appeared to be the maximum level under which the mean flowtime, mean tardiness and percent of late jobs performance measures were insensitive.

The simulation results indicated that the makespan and average shop utilization performance measures were insensitive to reliability of input information about processing times for up to a 100%. The performance of FIFO and EDD priority rules suffered drastically while SOT was the least sensitive to the reliability of processing times information.