THE EFFECTS OF A FIXED CONTROL PERIOD ON THE JOB SHOP SEQUENCING PROBLEM

by 264

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I would first like to dedicate this to my parents, Mr. and Mrs. Louis R. Ptak, without whose efforts I wouldn't have ever started this program. I would like to express extreme appreciation to Dr. L. E. Grosh for his help and patience throughout the preparation of this work. My deepest sympathies and appreciation go to my two typists Miss Dianna L. Klein and Mrs. Marie Jirak, who successfully interpreted my handwriting and did a most commendable job in preparing this manuscript.

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CHAPTER 1

1.1 Introduction

The amount of literature which has appeared concerning the problems of scheduling and dispatching jobs with diverse routings in a shop or the "job-shop problem", is quite large. The problem has been reviewed with the intent of developing and evaluating queue discipline techniques for pure job shops, pure flow shops (where all jobs follow what is essentially the same route through a shop), shops of a configuration falling between these extremes, single-queue, single-machine shops and numerous other models. The major theme in the literature has ranged from progress reports of the research (15, 5) to presentation, documentation and application description of simulation models of systems in real time operation in a plant (16, 22). Of major concern has been the attempt to develope a simple method of queue discipline that will allow jobs to be completed on assigned due dates or, failing this, with minimal total job lateness. The major conclusions and a description of the models of those reports that are relevant to the aims of this thesis will be presented. Before presenting the aims or embarking on a review of the literature, a few terms will be defined.

A _priority rule_ assigns a priority or scheduling preference to a job when it queues in front of a machine. The job with the highest priority is the preferred job. A _local priority rule_ assigns priorities on the basis of the attributes of jobs in a queue in front of a single machine; if all available jobs and/or other operations in the shop are examined as a basis for assigning job priority, the rule is called a _global priority rule_. Some priority rules which have received considerable attention are the first-in, first-out (FIFO) rule, the shortest operation time (SOT) rule and the remaining slack per operation (RSPO) rule. The FIFO rule is an essentially random rule where priorities are assigned according to the arrival of jobs in the shop. The first jobs to arrive are given the highest priority. The SOT rule orders jobs according to predicted or assigned processing times. The lowest priority number (highest preference) is given to the job with shortest operation time for the current operation. For the RSPO rule the time remaining before a job's due date (slack) is determined each time a job is to be put on a machine. This number is then divided by the number of remaining operations, job priority is then assigned according to the values of this number. The highest priority is assigned to the minimum number. Aczel (2) has examined, mathematically, the effect of introducing priority rules as opposed to a random assigning of priorities. He found that the mean queue length can be effectively reduced but actual work content remains the same when priority rules are used, which is consistent with logical expectations. In order to evaluate the operation of these and other priority rules some <u>measures of performance</u> are needed. These measures are merely techniques which evaluate the performance of the priority rules on the basis of preselected criteria. These criteria can be based on individual job performance, e.g. job progress as indicated by the mean and variance of job flow time. Overall shop performance in terms of in-shop inventory, for example, can also serve as a criterion. Since the measures of performance are based on different criteria conflicting evaluations of priority rules can and do occur. It is up to the analyst to determine which criterion are most relevant and choose the measure of performance accordingly.

A machine limited shop model assumes a finite number of machines are available. There are sufficient operators for each machine. Thus scheduling problems center around the availability of machines. In a labor limited shop, a new resource limitation is introduced to the shop model. The number of available machine operators is limited to some number less than the number of available machines. There are now two limited resources, i.e. machines and labor. The interaction of these two resources and the behavior of the shop with these limitations are of considerable interest.

A control period may be regarded as a shift, a day, several days, weeks, etc. It is an imposed period of time during which only one operation may be performed on a job, i.e. jobs which have an operation completed during this period are not available for reassignment on a machine until the next control period. Also, jobs are released to the shop only at the start of a control period. These definitions should be sufficient for now.

1.2 Thesis Goals

The primary purpose of this thesis is to examine the effects of an artificially imposed control period on the operation of a job shop. To date, almost all research on the job shop problem has been restricted to the simple job shop. Conway (6) has enumerated the following as the properties of a simple job shop:

1) There is a single limiting resource for which the jobs compete and wait.
2) The synchronization of two or more machines is never required to perform an operation.

3) All jobs arriving at the shop are "similar" at least in the sense of having come from a common generating mechanism.

4) Operations on each job must be performed in the exact order indicated and by a machine of the type specified.

5) Each machine can work on only one operation of one job at any particular point in time.

6) The time to prepare a machine to perform a particular operation depends only upon that operation and not upon the nature of the operation that preceded upon this machine.

7) The machines of the shop are not subject to random failures that make them unavailable for work. Neither do they perform improper work that causes pieces to be discarded, and hence lot-size of a job to decrease from one operation to the next.

8) Lots cannot be split or combined for any purpose.

9) The system operates continuously and time is not divided into shifts, days or weeks.

Conway, Maxwell and Miller (11) added these restrictions to the job set, the machines and the manner of schedule construction:

1) Each machine is continuously available for assignment

2) Jobs are strictly-ordered sequences of operations, without assembly or partition

3) Each operation can be performed by only one machine in the shop

4) There is only one machine of each type in the shop

5) Once an operation is started on a machine, it must be completed before another operation can begin on that machine

6) A job can be in-process on at most one operation at a time

7) Each machine can handle at most one operation at a time

The introduction of a control period was an attempt to remove the first restriction listed by Conway, Maxwell and Miller. This was done by limiting the accessibility of jobs to the machines (instead of machines to jobs). Thus a more realistic model of a particular type of shop, i.e. one operating with a planning period of some finite time length, could be obtained.

It was felt that Conways first property regarding a single limiting resource, could be profitably eliminated. It was felt that the additional constraint of a limited-labor supply would lead to a more realistic model. The labor-limited aspect had previously been examined only in a trivial manner (18), (6), (16). Thus, the system to be studied with a control period imposed on the shop and a second limiting resource, machine operators, will be considered. In all other respects the characteristics and restrictions of Conway, Maxwell and Miller are maintained.

The system is studied using a computer simulation. This technique has proven to be quite versatile and to yield valid results despite some inherent problems and shortcomings of Monte Carlo simulation (10). In order to make a more significant contribution to the literature in the field it is further intended to develope a model that was easily convertable from a strict job shop to a strict flow shop or any intermediate shop configuration and allow the shop and job parameters of number of machines, operators, operations per job, interarrival time of jobs, operation time per job to be easily and quickly changed. Thus in the development of the program for the model, every effort was made to prepare a realistic, highly flexible model with a minimum of complexity within the limits imposed by the language used. The language used was the GPSS/360 language of IBM.

1.3 Previous Work

Conway (5), (6), (9) alone, and in his work with Johnson and Maxwell (9), (10), (8) has done much of the groundwork in job shop simulation research. His RAND report (5) probably is the best introductory material in the literature. In this he reports on his work evaluating some forty basic and combination priority discipline rules. These evaluations are based on individual job progress and shop inventory. On the basis of prior work (3) the majority of the simulations had a shop with only nine machine centers. Results were based on the analysis of data for 87 sets of 100 jobs. This partial sample was used to prevent real performance difference from being obscured by invalid data due to initial loading and final run-out of the shop. Conway could find no natural measure of performance that could be used to compare all methods of scheduling and dispatching. He did find that there was significant improvement over the random policies with any priority discipline rule. Of major importance was his conclusion that of the various rules tested, the selection of operations on the basis of and in the order of increasing time for processing (SOT) could be used with the random rules as a yardstick for an improved rule. He concluded this from the consistently higher performance of the SOT rules. While the rule was not always the best, any rule that gave better performance required considerably more job information and were increasingly complex. He also found this rule to be relatively insensitive to errors in predicting processing times, a fact supported by Eilon (14) in a similar study. When evaluating the different priority discipline schemes on the basis of due dates (predicted date of job completion) a procedure which assigns priority on the basis of slack time (time left until due date) per remaining operation performed better. Conway assigned due dates at random, as a constant amount of time, proportional to the number of operations and proportional to the number of hours of processing time. Eilon (14) did some work with due dates assigning them proportional to estimated processing time and found the SOT rule best. He did not test the slack per operation rule and Conway did find the SOT rule second best on his study so they are not really contradictory.

Baker and Dzielinski (3) ran a study of a simplified job shop using a digital computer simulation. The model was constructed to reflect the operation of a small job shop with 9 to 30 single processing machines. The number of processing operations per job was controlled only on the average and approximately normally distributed. The processing time for each operation was randomly dispersed to reflect imperfect predictions of the processing time. The shop was loaded so each machine had the same expected amount of work. Conclusions were to be based on a shop in a stable state rather than any type of transient condition. On the basis of a statistical analysis of the average total manufacturing times of the jobs it was decided to collect data after 20 jobs had been processed. The measures of performance were based on the average of the jobs' total manufacturing time and the predictability of the jobs' completion time. The SOT rule was found to be most effective on the basis of average manufacturing time. On the basis of predictability, however, a more complex rule involving the preparation of a detailed shop operation schedule with ties broken using the SOT rule proved to be most effective.

All shops in actual operation usually function with limited resources e.g. machines, raw materials, set-up men or machine operators. The trend in the research has been to regard machines as the limiting factor. In actual shop operation the more severe limitation is labor in terms of both number available and limited flexibility. Flexibility refers to the ability of the laborers to operate different machine types. The more skilled an operator the more machines he can operate, only rarely are all operators equally proficient at operating all machines.

More frequently, there are a number of different labor classes with associated ability and authority to operate different machine types.

Only three reports dealing with labor-limited shops have been published. One is a report on a simulation model of an actual, operating shop by Le Grande (16). Allen (18) examines the problem of production leveling in a shop with a decreasing shop load. Production leveling is concerned with adjusting shop operations in the face of a widely fluctuating job load. Nelson (19) suggested a model and ran some preliminary experiments in his paper. Nelson's model will be discussed last since it is the most relevant.

LeGrande is primarily concerned with developing a model which can serve as a study tool for shop management. The shop consisted of five sections: a machine shop, sheet metal shop, processing, waveguide manufacturing and tool manufacturing. There are approximately 1000 machines and 400 to 500 men in the shop. The simulation was used to examine the effects of management decisions on the operation of the shop. The report prepared by LeGrande and a sequel prepared by Steinhoff, Colley and Bullkin (22) is more of a documentation and description of software. There is no actual examination of the labor-limited shop problem. The authors do note that from the reports generated one can determine labor and machine utilization and determine whether limited labor, limited machines or a combination of both are causing a problem in the shop. One should therefore be able to evaluate the effects of various management decisions on these problems, unfortunately no analysis is provided.

The paper by Allen (18) reports an examination of the problem of production leveling through dispatching priority rules and flexibility of men and machines in a shop with a decreasing shop load. This is a study of a shop in a transient rather than steady-state condition but some interesting conclusions are made. The simulation was modeled from an actual job shop. The shop consists of 78 machines and 40 men and is therefore, as a whole, labor-limited but the limited capacity of some machines force a local machine-limited condition. The dispatching rules examined were a random rule, shortest-operation-time and longest-operation time and these rules combined with the possibility of doing some operations on different machines i.e. alternate routes for the jobs were possible if the originally scheduled machines were overloaded. The principle topic was the examination of the relationship between flexibility (of men and machines) and dispatching rules. A specific examination comparing the shortest and longest-operating-time with alternate routing priority rules was made for a highly flexible labor force. In this case, all men could operate all the machines thereby reducing somewhat the degree of labor shortage in the shop. The first eight weeks of simulation time showed no difference between the rules. After this time however, and until the complete run-out of the shop (20 weeks for shortest-operation time, 19 weeks for other rules) the longest-operation-time with alternate routing rule was found to be most efficient. This rule not only provided a higher labor utilization but emptied the shop quicker than did the shortest-operation-time rule. In a comparison of the relationship between alternate routing and labor flexibility and their effect on shop performance the benefits of alternate routing were found to be relatively independent of the level of labor flexibility. Further examination of the effects of labor flexibility of various degrees (e.g. 5 workers of the 40 could work all machines) showed further shop performance improvement with less time required to empty the shop of jobs. The authors concluded that the problem of production leveling can be reduced through the use of detailed computer simulation, dispatching rules which are combinations of simpler rules and shop modification. He argues that shop modification in the form of increased machine and/or labor flexibility is a valid and effective way to reduce the production leveling problem.

Nelson presented a model and design for experimental study of machine and labor-limited production systems. In addition to the normal system parameters of job arrival rate, job routing matrix and shop size, he introduces a limited labor force, a delineation of labor force versatility and flexibility and a control center to direct the assignment of the operators to jobs and machines. Nelson introduced a new control parameter which was used to determine which machine a free operator would select work for. Some possible selection procedures would be to select the machine with the largest number of jobs waiting on it, random assignment of idle labor or a method analogous to the SOT, FCFS or FIFS queue disciplines.

The actual simulation model run by Nelson consisted of a shop with two machine centers with one or two machines in each center and from one to four laborers. The simulation was written in SIMSCRIPT except for the work load generator which was written in FORTRAN. Three queue discipline rules: 1) First-come, first served (FCFS); 2) First in system, first served (FIFS); and 3) Shortest imminent operation time first (SOT) and the five machine selection procedures mentioned in the previous paragraph were examined. The simulation was run for 32,000 jobs.

The results reported by Nelson are quite ambitious when viewed with respect to his actual model. He reports that the FIFS and FCFS rules are both more effective in terms of variance of time in system than the SOT rule. He suggests that his larger sample size explains this reversal of the conclusions of all previously reported findings. With regard to the labor assignment procedure Nelson found that changes in the queue-disciplines caused large absolute changes but also always involved tradeoffs of mean for variance. Both mean and variance could be improved simultaneously albeit on a smaller scale by varying the machine selection procedure. The best combinations for reducing mean or variance were found to be selecting the longest queue machine in conjunction with SOT or FIFS respectively. The flexibility of the labor force was found to directly affect and improve system time statistics. Further experiments which varied the labor assignment procedures, job routing characteristics and the labor efficiency were carried out. Not surprisingly, changes in the job routing structure and the flexibility of the labor assignment procedures effected system time statistics. A comparison of shop operation with a completely flexible labor force (laborers can work on any machine) and an inflexible labor force (laborers are tied to a machine) under two different shop systems showed considerable reductions in both the mean and variance of the time in the system.

Numerous other papers have been written examining the effectiveness of priority rules, methods of assigning and meeting due dates. Despite Nelson's findings to the contrary, he apparently stands alone in his conclusions, Conway and Maxwell (8) offer the best summary of generally accepted conclusions. They concluded that with respect to the mean values for measures of performance with queued network systems there is considerable support for the conjecture that the shortest-imminent-operation-time (SOT) rule is optimal for all local, simple priority rules. Further, the rule seems to be highly insensitive to errors in estimating processing times. They continue to say that inherent shortcomings can be overcome by modifying the rule or obtaining better predictions of the processing times needed to complete individual jobs.

Mean or variance values of system time measures of performance are by no means universally accepted as the sole criterion of evaluation. The shape of curves which illustrate the distribution and variance of jobs completed with respect to due dates or other criteria are equally valid and yield further interesting information. Eilon and Hodgson (14) examine mean values and standard deviations of their measures of performance. Buffa (4) shows distribution curves with respect to job lateness for six different priority rules. From such graphical information and other statistics, the large variance and highly skewed tail of, say, the SOT-priority rule is readily apparent. Hopefully, by analysis of such additional information and growing familiarity with performance of rules, better rules can be developed. In any case, the evaluation and examination of only mean values of measures of performance is certainly less than adequate.

CHAPTER 2

2.1 Model Description

The system simulated consisted of machines, queues of jobs in front of these machines and machine operators. The models were run simulating a job shop operation. The imposition of a control period and imposed limited labor availability were the primary innovations. A control period creates two job pools. One pool collects all stochastically arriving jobs. The other pool holds all jobs which complete an operation during a control period. These pools are emptied at the end of a control period. At that time all newly arrived jobs enter the shop. The processed jobs are then freed for re-sequencing or to leave the shop. Each job, upon completion of an operation, is unavailable for processing until the start of the next control period.

The Rohr Corporation in Chula Vista, California (12) has a system which could be considered as based on a control period concept. The system is a combined materials-handling and information system. The materials-handling system consists of a vertical 16,684 pigeonhole-storage facility and supporting equipment such as conveyors, stacking cranes, etc. The information system consists of three computers which maintain real-time files on in-process and new inventory, tool location, tool requirements, job prioritys and tentative production schedules.

The system operation can be described as follows. When the work available at a processing location is reduced to a critical level, the dispatcher requests more work or more materials to complete the current job. The system processes the order and determines what is needed and where each part, tool or job is located. A package of jobs, materials and tools is prepared according to a pre-programmed priority schedule. The total package is then delivered to its processing location. The completed work is picked up by the system. This work is then stored for later processing, sent immediately to another processing location or stored in a finished parts warehouse. The total operation is monitored and controlled from raw stock to finished parts warehouse by the computer-communications system.

The operation of this system suggests investigation into the size of the work package and critical levels. On what basis should the package size be determined? Some possible bases include; number of jobs, processing time, weight of the package or physical size of the package. If, for example, total processing time is to serve as the basis, what is the optimal total time? A time base suggests that a control period is being imposed on the system. An interesting and informative investigation of this type of system could be made.

The length of any imposed control period must effect the amount of time a job is held in the shop. Obviously, no job can leave the shop before completing all operations. Only one operation can be performed in any one control period. Therefore, the minimum time a job spends in the shop is directly proportional to the number of operations required. Further, the average processing time of an operation may interact with the control period length. In order to investigate this possibility, model runs were made with control period lengths ranging from 100 to 2000 simulation time units.

Two basic shop models were run. Model I was used to investigate the effects of fixed control periods, labor limitations and other aspects detailed earlier. Model II was an attempt to duplicate the results of Conway and Maxwell as reported in (8). In this report, they suggest that the performance of a simulated shop of nine machines exhibits enough of the interaction and complexity of larger shops to allow general conclusions about the behavior of larger shops to be made.

2.2 Shop Model I

Model I simulated a job shop, i.e. all possible machine routings were equally likely. The probability of an operation on a particular machine was unaffected by any previous routing for that job. It should be noted that, in contrast to most models, two or more consecutive operations on the same machine were as likely as any other routing. Separate distribution functions were maintained for each machine. These functions were used to determine the next machine to which a job would be routed. This allows the model to be easily changed to a flow or intermediate stage shop.

Shop size was varied from two to nine machines. Initial runs were made with only machine-limited shops. From these runs, a history of shop operation could be developed. Later runs were made with shops of selected size and with various size labor forces.

In order to bring the simulation to a steady-state, a pre-load of fifty jobs was used. This topic is discussed in detail in section 2.6.

2.3 Shop Model II

As was stated earlier, Model II was designed to show that simulation of a relatively small shop of nine machines would yield conclusions valid for larger shops. This does not imply that larger shops are of no interest or need not be simulated. It does imply that valid general interpretations and an understanding of the functioning of much larger shops can be acquired from small shop simulations. The savings in computer time alone, makes the simulation of smaller shops highly attractive.

There are two major differences between Model I and Model II. First, no jobs were pre-loaded in Model II. Second, there were no stochastic job arrivals in Model II. Shop stability was obtained by defining a fixed job-capacity for the shop. This meant the total number of jobs in the shop was held constant.

The length of the control period was reduced to prevent its effects from obscuring all others. In one set of runs, only newly arrived jobs were pooled. This resulted in a model much closer to that of Conway and Maxwell (8). Runs were made with the shop size varying from two to ten machines. The number of machine operators was always kept equal to the number of machines.

2.4 <u>The Jobs</u>

In Model I, ten pre-loaded jobs are created at the start of the first control period and then ten more at each of 2000, 3000, 4000 and 5000 simulation time units. These jobs enter the shop at these times. All other job arrivals are stochastic with a fixed mean and standard deviation. The generator for these jobs starts operating at the start of the second control period. This was to facilitate the collection of valid statistics. Each job has six parameters or attributes associated with it. These serve to describe various important job characteristics. The significance of each parameter is noted in Table I. The number of operations per job is assigned according to a predefined distribution.

PARAMETER	SIGNIFICANCE
1	Number of Operations (Statistic)
2	Current Machine on Job's Route
3	Current Operation Processing Time in Simulation Time Units
4	Number of Operations (Looping Index)
5	Due Date in Simulation Time
6	Number of Control Periods that the Job is in Shop

Table I Job-Transaction Parameters

A uniform distribution with a minimum of one and a maximum of nine operations was arbitrarily selected. The distribution can easily be changed to any desired distribution. This distribution can be used as a control for the shop loading factor.

Job routing is dependent upon the type of shop being modeled. Since this is a job shop, all possible routings are equally likely. As stated earlier, a job may have two or more consecutive operations on the same machine. Processing time on a machine is calculated from the same distribution for all machines. A normal distribution with a mean of 100 and a variance of 10 was used. Individual distributions for each machine and different distributions are easily introduced in the program.

Job due dates are calculated from the following formula:

$$D_D = N_O \, C_{PL} \, K$$

where: D_D - job due date in simulation time units

N_O - number of operations

C_{PL} - control period length in simulation time units

K - constant

K is the most interesting factor in the operation. For a fixed control period length, this factor could be varied to set various due dates for testing performance among other measures of performance. For the simulations run, the minimum reasonable value of K is one. This gives a due date directly proportional to the number of operations. A job is then due exactly N_O control periods after it entered the shop. Values of K should suggest themselves from analysis of shop performance. Jobs are queued in front of machines according to predefined priority rules. The highest priority job is first in the queue.

2.5 Operators

Initially, the operators are created independent of the shop operation. For the initial runs, the number of operators is equal to the number of machines. These first nine operators release jobs for processing and are then removed from the system. Upon completion of the job's processing, a duplicate of the job is created which functions as an operator. The mechanics of this operation are described in Chapter 3.

An operator may operate only one machine at a time. He cannot be interrupted or be reassigned until completion of the operation. Upon completion of an operation, the machine operator is released. His next assignment is on the idle machine with the largest number of jobs in its queue. The shortest operation time job in the queue is selected. If all queue lengths are the same, preference is given to the smaller machine number. If no idle machines exist with a job queue, the operator waits until the beginning of the next control period to get an assignment. Alternative selection modes are possible and easily installed.

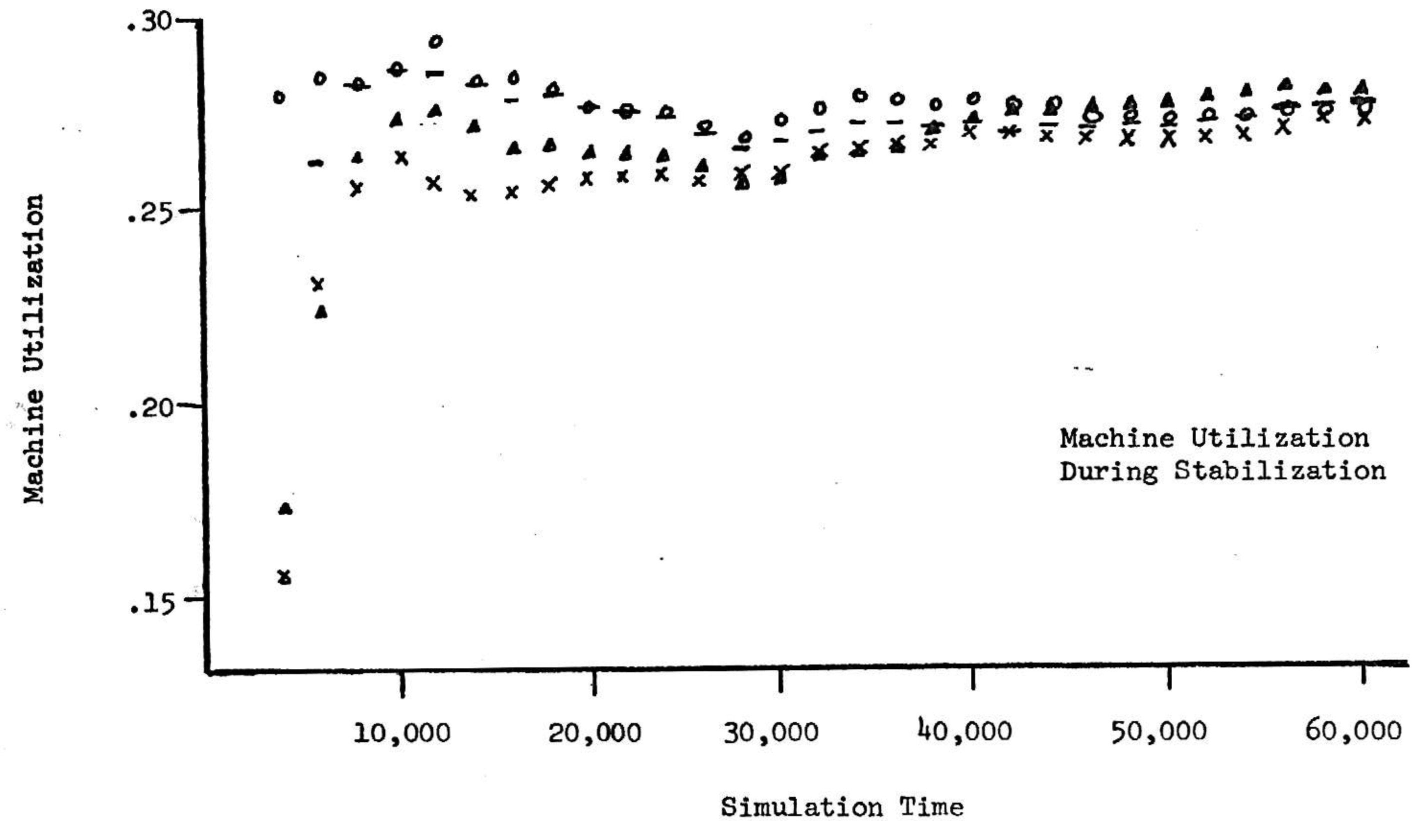
2.6 Stability

Most interest in the literature has concentrated on the operation of a simulation in a stabilized or steady-state condition. The single exception encountered in the literature review was the report by Allen (18). In keeping with this trend, the shop was pre-loaded in order to stabilize the simulation. The shop model has a stable stochastic job arrival pattern. Shop performance is evaluated on the basis of various shop statistics. These statistics tend to fluctuate widely in value until the system has reached a stabilized operating condition. Once the system has been stabilized, the statistic values still fluctuate. However, the range of the fluctuating values is much smaller. These same statistics are effected by such shop variables as number of machine operators and priority discipline techniques. Some sample statistics effected by shop stability are mean time of a job in the shop, machine and operator utilization, number of jobs completed on or before due date, etc. In order to use these statistics as valid measures of performance, the shop should be in a stabilized state. Once a shop has reached a stabilized running condition, then any variation in the statistics can be attributed to changes in shop variables.

The period of time during which the shop statistics fluctuate widely is known as the transient period. This period occurs as the simulation first starts to function. During this period, the empty shop begins to fill with jobs and queues start to form. The fluctuations that take place in machine and operator utilization and other shop statistics tend to die out gradually as the simulation continues. Unfortunately, the length of time required for these oscillations to die, if left to themselves, can be considerable. One technique used to reduce this time is to specify and maintain a constant load of jobs in the shop. In Model II, this was done by fixing shop job-capacity. A pre-load was used in Model I. During preliminary model runs, various size loads and loading procedures were tried to reduce the transient time. The shop model used had nine machines and five operators available.

The procedure selected uses fifty jobs loaded over time to stabilize the simulation.

In reaching the final pre-load two methods of pre-loading the jobs were tried. The first method involved loading forty or fifty jobs at the end of the first control period. This method was found to induce a high initial peak in operator utilization and a somewhat flatter peak in mean machine utilization. The time for the fluctuations in utilization to die out was considered too long. This led to the second method. This method loaded twenty, thirty, forty and fifty jobs in lots often over a fixed length of time. The first lot was loaded at the beginning of the second control period. This was followed by a second lot at 2000 simulation time units. This was the total load of twenty jobs for one pre-load test. For the other pre-loads for thirty, forty and fifty jobs, lots of ten were loaded at 3000, 4000 and 5000 simulation time units. Figure 1 shows graphs of utilization for the various pre-loading techniques. Using these graphs the final pre-load method was chosen.



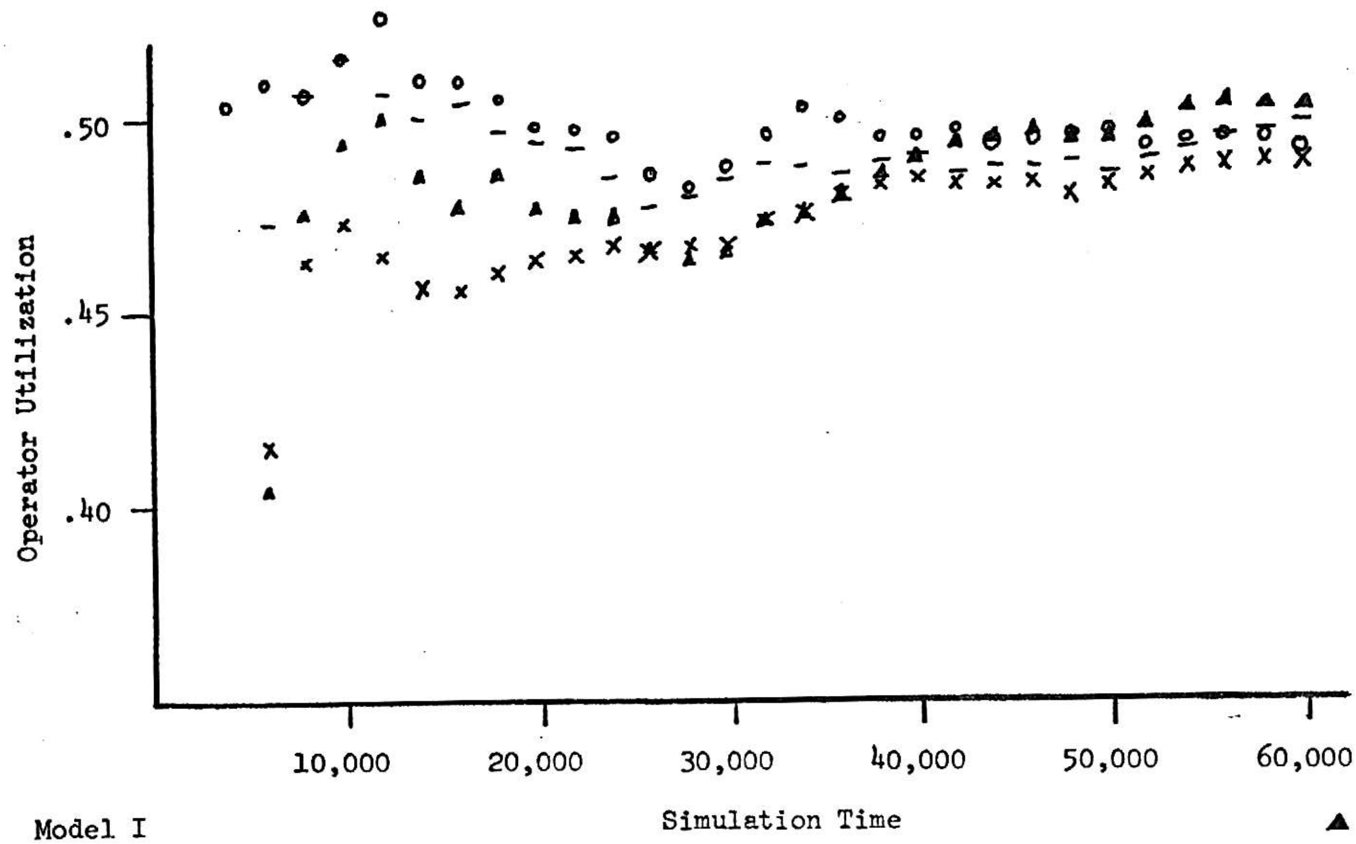
Model I

9 Machines
5 Operators
1000 Control Period Length

Key

▲	40	Jobs at once
O	50	Jobs at once
X	40	Jobs over time
—	50	Jobs over time

Figure 1(A) Pre-Load Methods

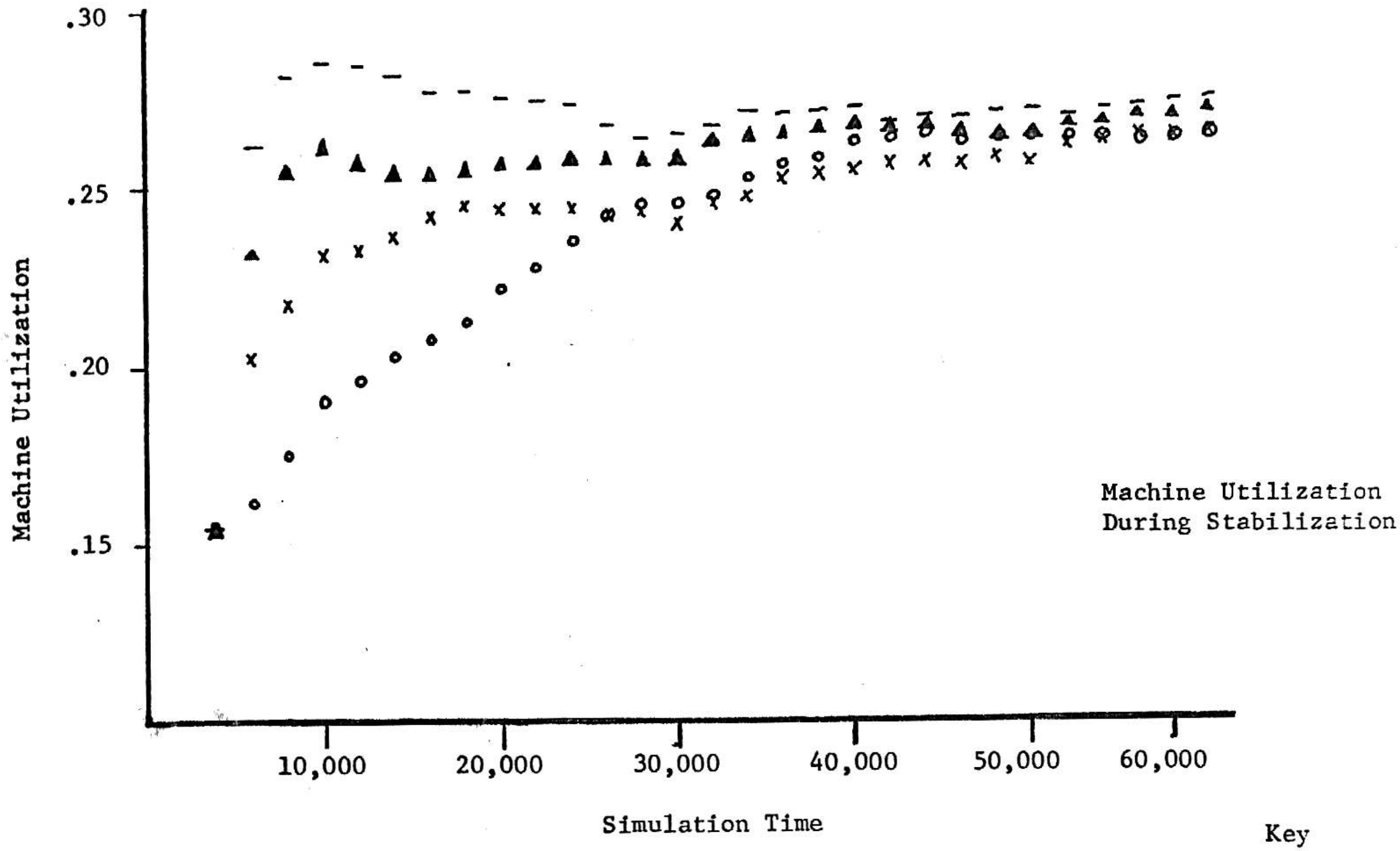


Model I

9 Machines
5 Operators
1000 Control Period Length

Key
▲ 40 Jobs at once
o 50 Jobs at once
x 40 Jobs over time
— 50 Jobs over time

Figure 1(B) Pre-Load Methods



Model I

9 Machines
5 Operators
1000 Control Period Length

Key
- o 20 Jobs over time
- x 30 Jobs over time
- ▲ 40 Jobs over time
- – 50 Jobs over time

Figure 1(C) Pre-Load Methods

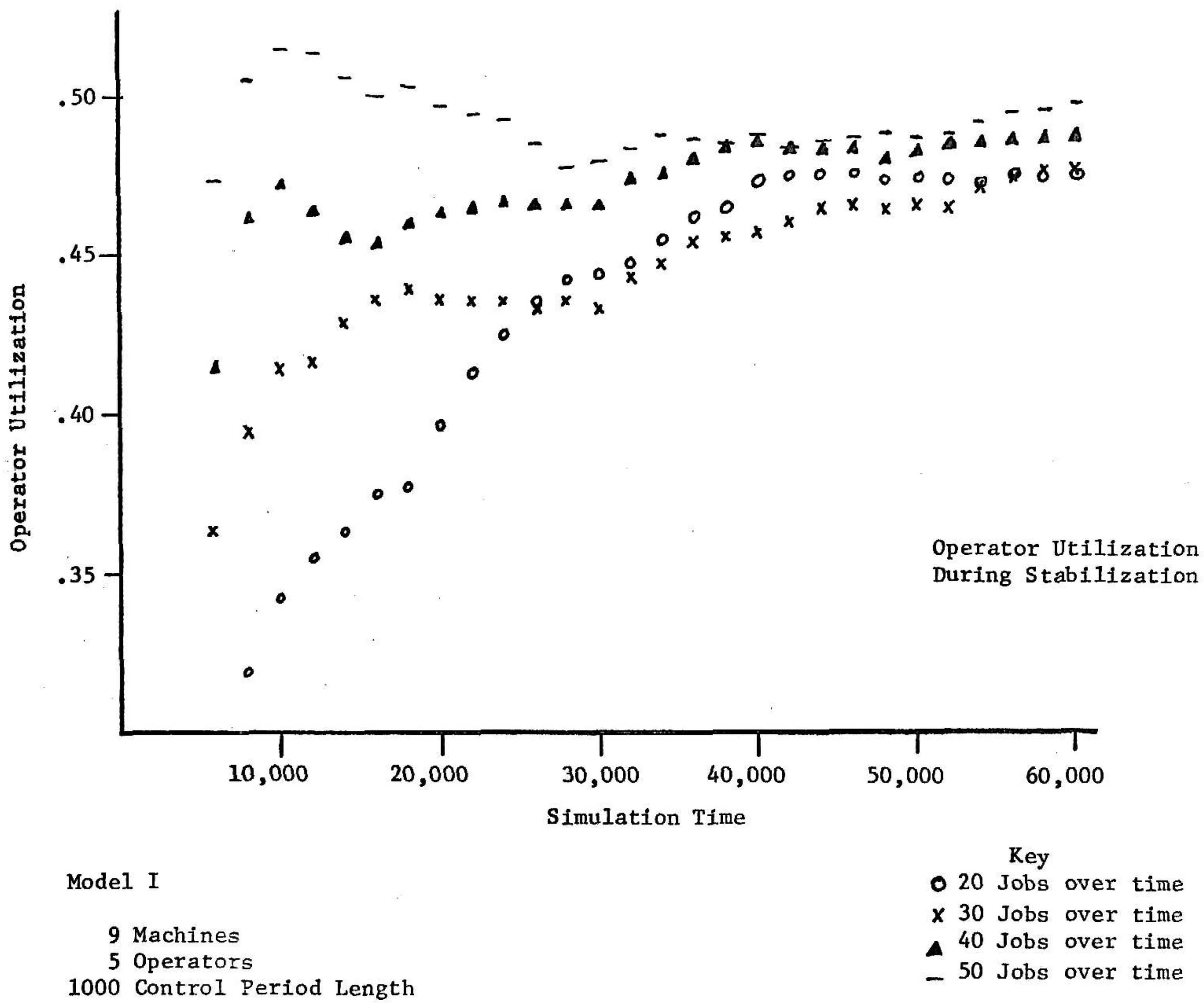


Figure 1(D) Pre-Load Methods

CHAPTER 3

3.1 GPSS/360

The simulation was modeled using the IBM language General Purpose Simulation System/360 (GPSS/360). This language is structured to facilitate programming from block or flow diagrams. Each block represents a particular step in the action of the system. GPSS provides some forty-three different block types which can be used to model a system. Specific system concepts and definitions are defined in the language to provide a consistent notation for describing the system. In addition to providing the basic active steps in a model, GPSS provides computational, statistical and reference blocks or entities. Thus, a completely autonomous simulation can be prepared, i.e. one that can generate all required input information for the model. This is done using a number of specified distributions. Further special statistics can be defined and collected.

The GPSS/360 program operates by moving a single transaction from block-to-block until it is blocked at some point. The movement is analogous to the flow of the real units that the transactions represent. A transaction representing a job, for instance, could be generated, have parameters assigned and then be held in a pool awaiting entrance into a shop. The program moves from scheduled event to scheduled event in progressing through the simulation. The program maintains a calendar of events ordered according to the scheduled time for an event to occur and a clock that records the instant of time reached in the simulation model. This clock is advanced as scheduled events occur. The unit length of system time represented by a unit change of clock time is defined by the user.

3.2 Some Basic Entities

The basic computational entities in the system are Functions and Arithmetic variables. Arithmetic variables are used to represent complex mathematical or logical relationships between system attributes. The construction of the actual relationships is analogous to that used in FORTRAN. Functions can be used to relate the value of independent variables in the simulation to dependent variables of a function and to generate random variable values. By redefining a single function in the current model the distribution of operation times can be changed from normal to uniform or any distribution that can be quantitatively described. Each machine has a function associated with it. This function defines the probability of a job currently on that machine being routed to all others in the shop including the machine it is currently on. These distributions can be redefined to prefer a specific job routing through the shop, thus changing the model from a job to a flow shop. Table II lists each arithmetic variable and function and identifies its purpose in the simulation.

Initial or constant values of shop parameters are set using INITIAL cards. Such parameters as number of machines in the shop, mean operation time, number of operators in the shop, etc. are initialized in this manner.

SAVEVALUE cards are used to collect and store information about the system. Matrices can also be set up as data collectors. See Table II for a description of model entities.

One more program entity of interest is a STORAGE. This is used in GPSS/360 to represent variable-capacity entity. Storage definition

GPSS ENTITY	PURPOSE
FUNCTION i, i=1,,10	Probability Distribution of Job Currently on Machine i being routed next to any Machine j j=1,2,...,m; j=i is possible
" 11	Normal Distribution used to establish Operation Time
" 12	Uniform (1,9) Distribution for assigning Number of Operations Per Job
" 13	Uniform (1,9) Distribution for assigning First Machine a Job is routed to
" 14	Same as 12, but used only for Pre-Load Jobs
VARIABLE 1	Computes Job Due Date
" 2	Computes Time for each Operation
" 3	Determines Job Lateness
" 4	Used to determine Machine Availability
" 5	Computes Number of Control Periods a Job is in the Shop
" 6	Collects Total Machine (Facility) Utilization
" 7	Computes Mean Machine Utilization
SAVEVALUE XHi, i=1,,10	Number of Jobs Queued in front of Machine i
" X11	Number of Machines in the Shop
" X12	Number of Machine Operations
" X13	Number of Job Parameters
" X14	Mean Operation Time
" X15	Standard Deviation of Operation Time
" X16	Number of Jobs Pre-Loaded at One Time
" X17	Mean Arrival Rate for Dynamic Job Arrivals
" X18	Standard Deviation of Arrival Rate
" X19	Control Period Length
" X 1	Total Machine Utilization
" X 2	Mean Machine Utilization
MATRIX 1	Indicates how many Control Periods each Job spent in the Shop with and the Number of Operations of each Job
STORAGE 1	Number of Machine Operators
" 2	Shop Work-Load (Number of Jobs allowed in Shop)
TABLE 1	Tabulates the Time Jobs spend in the Shop
" 2	Tabulates Jobs completed on Time or past Due Date

Table II Simulation Entities

cards are used to define the number of machine operators in the shop. This allows pertinent information to be collected quite easily.

The system provides for tabulating statistics. Mean, standard deviation and number of observations in each specified interval are some of the parameters of the variable tabulated that are automatically computed. In Model I, Table 1 is used to tabulate the time a job spends in the shop. Table 2 tabulates the number of jobs completed on or after their due dates. Table 2 also tabulates how late each job is. See Table II for a description of each entity in the simulation.

3.3 Flow Chart of Model I

Figure 2 details the general model flow chart. Block symbols used are the same as described in the IBM user's manual for GPSS/360. The actual operation of the simulation is tied to two more sub-programs in the simulation. These are the timer and machine-operator generator and controller. These are shown in the flow-charts in Figure 3.

The simulation starts with the generation of the first pre-loaded jobs. These are assigned the parameters: 1) Number of operations; 2) Due date; and 3) First machine in their route. These jobs are then pooled until the beginning of the control period. Stochastic job arrivals follow the same pattern but do not start arriving until the beginning of the second control period. Machine-operators are available from time zero. A job is selected from the machine with the largest number of jobs queued in front of it. If no jobs are in a queue, the operator waits until the start of the next control period and re-tests for the longest queue.

At the beginning of a control period, each job: 1) enters the shop; 2) has a processing time assigned; and 3) queues in front of a machine according to its first operation.

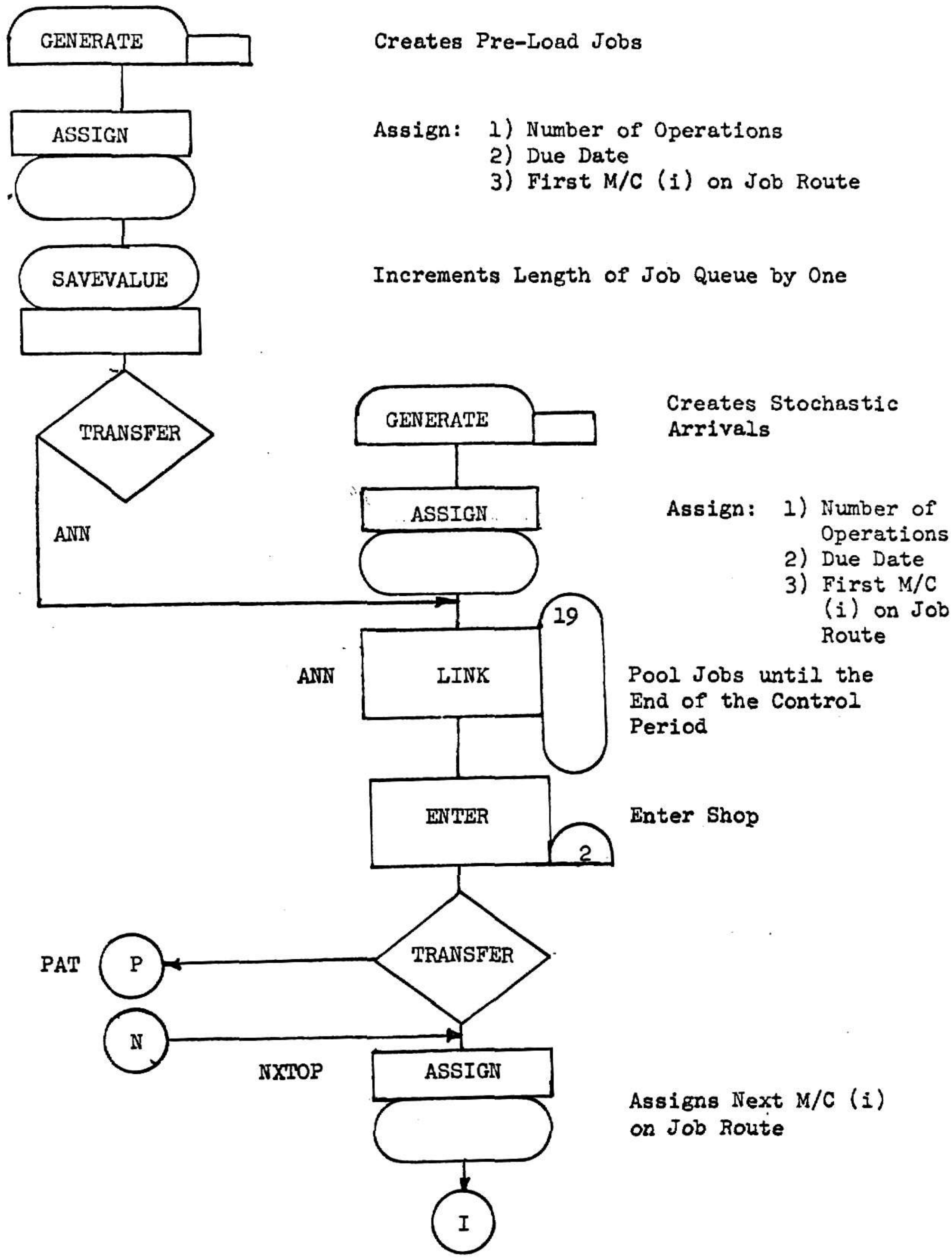


Figure 2 Model I Flow Chart

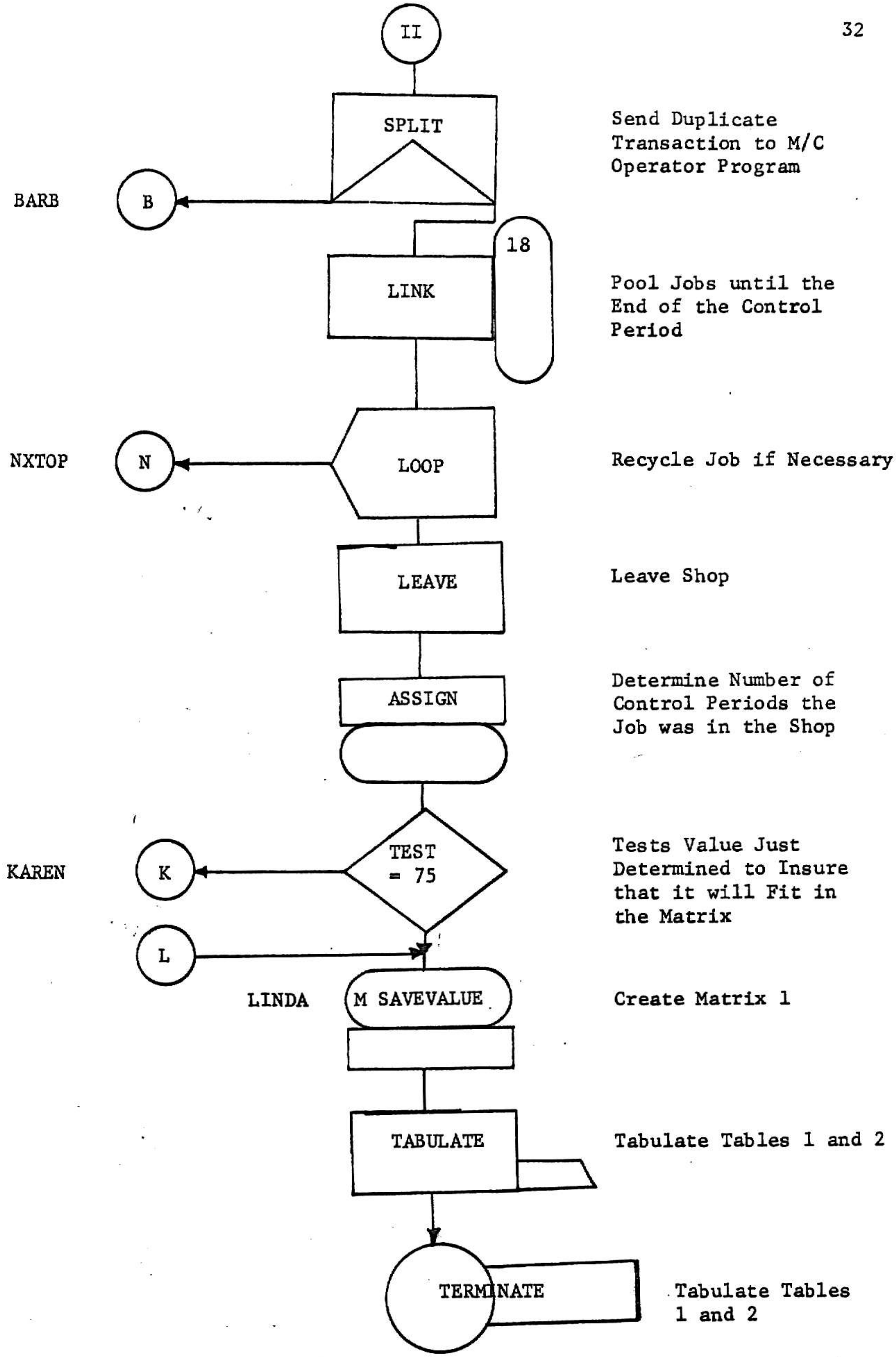


Figure 2 (contd.) Model I Flow Chart

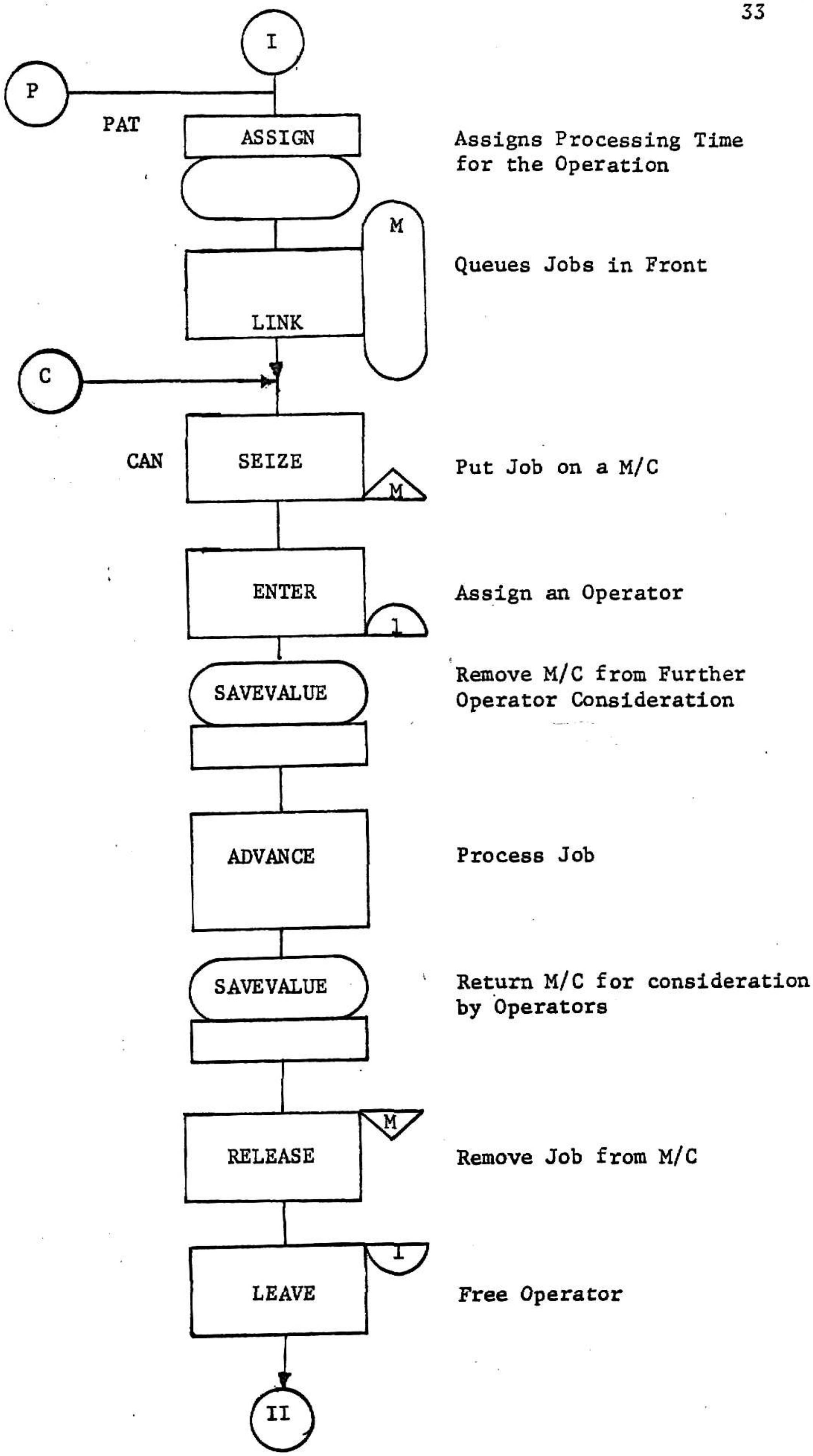


Figure 2 (contd.) Model I Flow Chart

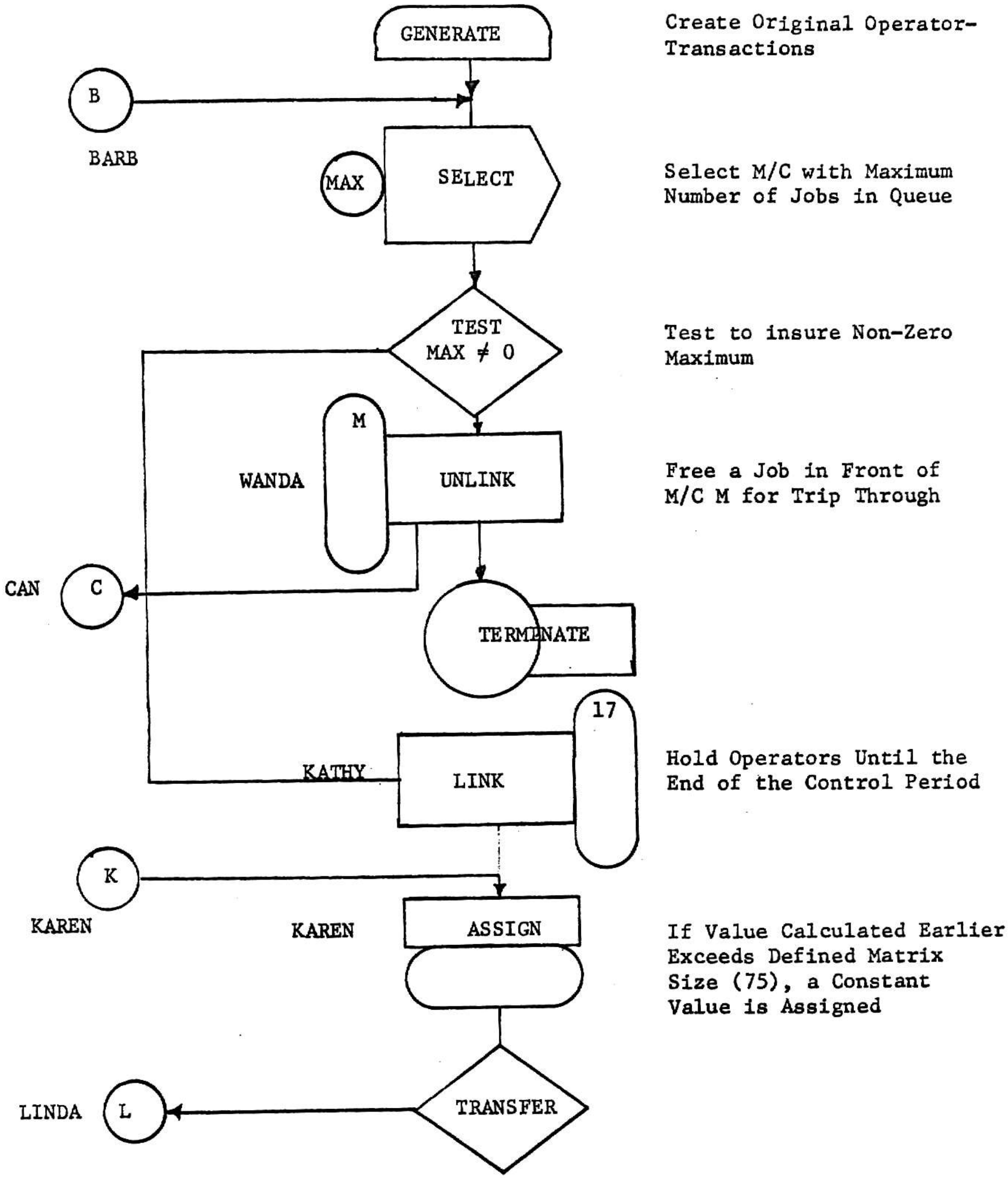


Figure 3(a) Machine-Operator Sub-Program Flow Chart

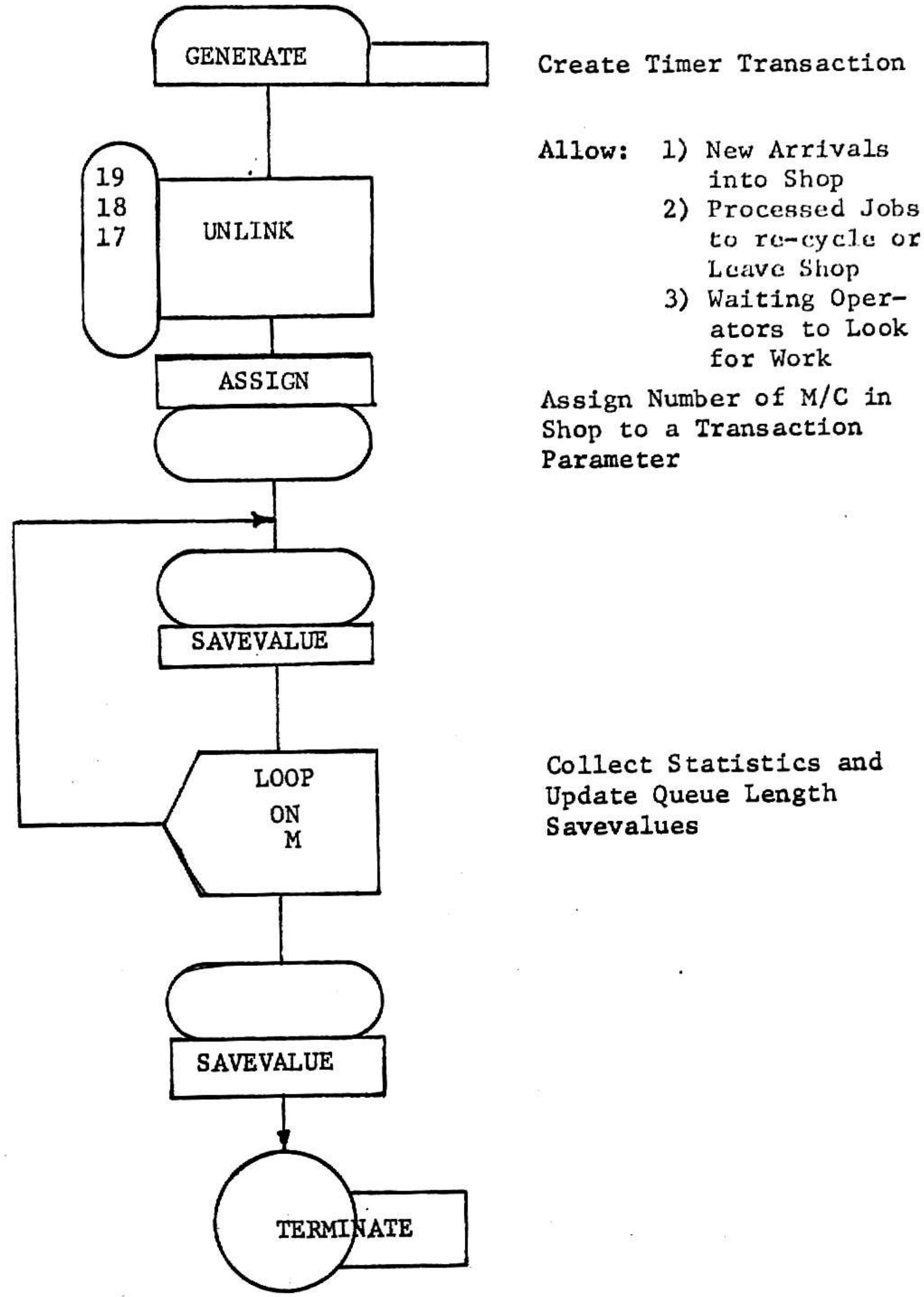


Figure 3(b) Timer Sub-Program Flow Chart

Once a job has been selected for processing the following sequence of operations occur:

1) The job is placed on a machine
2) An operator is assigned
3) The savevalue showing the number of jobs queued in front of the machine is set to zero (to remove that machine from further operator consideration)
4) Processing is begun.

Upon completion of processing on a particular job, the sequence of operations is:

1) The value of the machine queue savevalue is updated
2) The job is removed from the machine
3) The operator is freed
4) A duplicate transaction is sent to the machine-operator sub-program
5) The job is placed in a pool until the end of the control period.

At the end of a control period, the jobs in the pool go through the following sequence:

1) The job is freed from the pool
2) The job is tested to see if all operations have been completed
3) If all operations are completed, the job leaves the shop
4) If further processing is required, the job has the next machine on its route assigned
5) A processing time for this operation is assigned

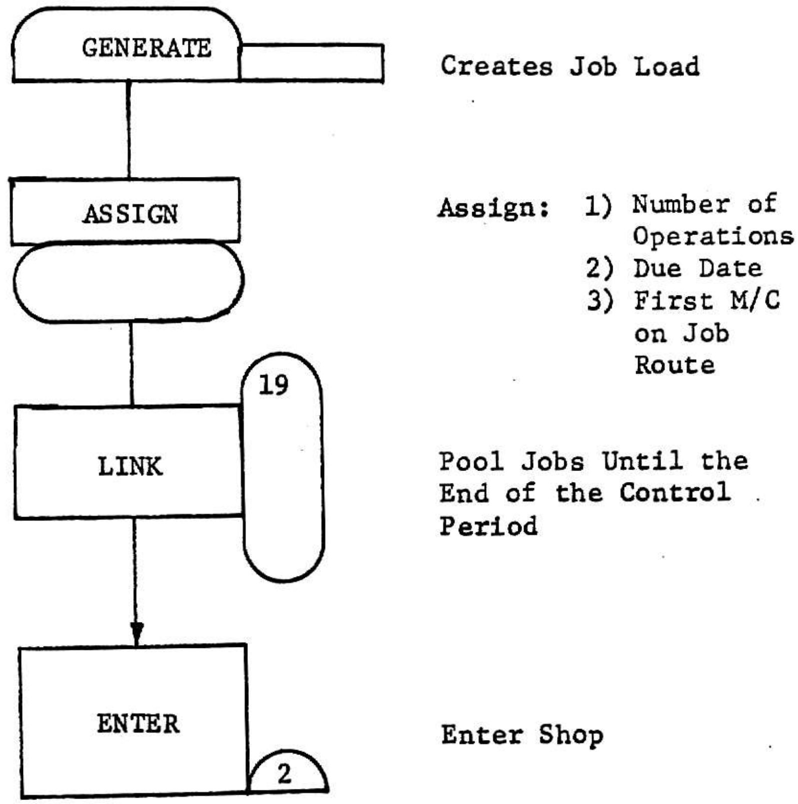
6) The job queues in front of the next machine to which it has been routed. Priority is given to the job with the shortest operation time.

The simulation timer generates a transaction every control period that: 1) allows new arrivals into the shop; 2) frees jobs that have undergone processing and have been pooled; and 3) allows waiting machine-operators to look for new assignments. In addition, the timer collects some statistics and updates the halfword savevalues (XHi;i=1,m) that keep track of the number of jobs queued in front of each free machine.

In the machine-operator sub-program, the operator-transaction selects the machine with the maximum number of jobs in front of it. This is done by looking for the maximum value of the halfword savevalues mentioned earlier. The GPSS program allows selection of zero as a maximum. If all savevalues are equal, the first value encountered will be chosen. The first trait mentioned above would result in a somewhat less than realistic model. Therefore, a test is made to insure that a non-zero maximum is selected before attempting to release a job. The second trait mentioned leads to a preference for lower numbered machines. However, no statistically significant imbalance is encountered. When a non-zero maximum is encountered, the first job in the queue in front of that machine is removed from the queue. The job then goes through the processing routine described earlier. The operator-transaction is terminated or removed from the system at this point. This does not result in a loss of operators. Immediately after a job-transaction frees the operator, a duplicate transaction is created. This duplicate is sent to the machine-operator sub-program. At this point the job-transaction ceases to act as a job-transaction and functions as an operator-transaction. If the maximum is zero, the operator-transaction is held until the end of a control period. This is reasonable since a system change can only occur at that time. The operator-transaction is then recycled.

3.4 Flow Chart of Model II

Model II functions, in all respects save one, in the same manner as Model I. The one exception is that no preloading or stochastic job arrivals occur. A fixed number of jobs, equal to the preset maximum number of jobs allowed in the shop, enter at the start of the second control period. This number has been set equal to four times the number of machines in the shop. In order to maintain a constant number of jobs in the shop, a duplicate job-transaction is created and allowed to "arrive" when a completed job leaves the shop. This duplicate transaction has all new parameters assigned. The rest of the shop model functions exactly like Model I. Figure 4 is a flow chart of the part of the job-transaction program that is different from Model I.



The Balance of the Model Duplicates Model I

Figure 4 Model II Flow Chart

CHAPTER 4

4.1 Model II Conclusion

To an extent, the validity of the whole thesis rests on the results obtained from Model II. Therefore, these will be examined first.

Recall that the purpose of this model was to show that the simulation of a relatively small shop would yield results valid for larger shops. It was decided that if results compatible with those of Conway and Maxwell (18) could be obtained, then their conclusion would be accepted. Only a portion of their experiment was reproduced. In this portion, shop capacity was limited by only allowing a number of jobs equal to four times the number of machines into the shop. This model was run for control period lengths of 25 and 50 simulation units. A run was made which only pooled newly arriving jobs.

The results of these runs are shown in Table III. Conway and Maxwell suggested that the expected idle time for their model could be obtained from:

$$\bar{T} = (N-1)/(XN+N-1)$$

where: $\bar{T}$ = Expected idle time

N = Number of machines

X = Constant in our model equal to four.

In order for this equation to be valid for a model, two requirements must be met. The shop must be a pure job shop, and a special (job) release mechanism be in use. This mechanism maintains a constant number of XN jobs distributed in a shop of N machines. Model II does

NUMBER OF OPERATIONS	PER CENT UTILIZATION	PER CENT IDLE EXPER.	PER CENT IDLE THEOR.	CONTROL PERIOD LENGTH
2	.932	.068	.111	50
3	.896	.104	.143	
4	.882	.118	.143	
5	.871	.129	.167	
6	.866	.134	.172	
7	.867	.133	.176	
8	.866	.134	.179	
9	.878	.122	.182	
10	.872	.128	.183	
2	.937	.063	.111	25
3	.908	.092	.143	
4	.900	.100	.143	
5	.888	.112	.167	
6	.881	.119	.172	
7	.882	.118	.176	
8	.882	.118	.179	
9	.855	.145	.182	
10	.881	.119	.183	
2	.942	.058	.111	25 (Only Newly Arrived Jobs Pooled)
3	.918	.082	.143	
4	.902	.098	.143	
5	.888	.112	.167	
6	.878	.122	.172	
7	.881	.119	.176	
8	.882	.118	.179	
9	.892	.108	.182	
10	.887	.113	.183	

Model II

Job Load = 4 x Number of M/C
Number of M/C = Number of Operators

Table III Mean Per Centage of Idle Machine Time for Model II not exactly fit this description. The control period length prevents the model from duplicating the job release mechanism that is necessary for the equation to be valid. The value was included for comparison purposes in Table III. Obviously, Model II does not approximate the operation of Conway and Maxwell's close enough for their equation to even approximate the actual idle time.

Figure 5 shows a plot of this data. There appears to be a significant indication that the shop response curve flattens very quickly. In fact, these curves are flatter than those obtained by Conway and Maxwell (13). From this data it would seem that a shop of six machines would yield quite valid results. One could conceivably simulate an even smaller shop and draw reasonably valid conclusions. But, a point of diminishing returns is reached in terms of money saved and confidence in the model. It seems safe to assume that general conclusions and interpretations of shop behavior can be made on the basis of small shop simulations. Here, a lower limit on shop size of six machines would be reasonable.

If a doubt still exists regarding the validity of the conclusion, it is very easy to increase the shop size and number of machine operators to, say, 15 or 20. However, the additional cost of running a larger shop simulation can be considerable. Figure 6 is a plot of the cost for model runs versus the size of the shop. Note how rapidly the costs increases. There is no reason to assume that the curve gets less steep for larger shop models.

4.2 Conclusions for Model I

Model I was used to investigate the effects of a fixed control period on a job shop operation. The initial model runs were made with

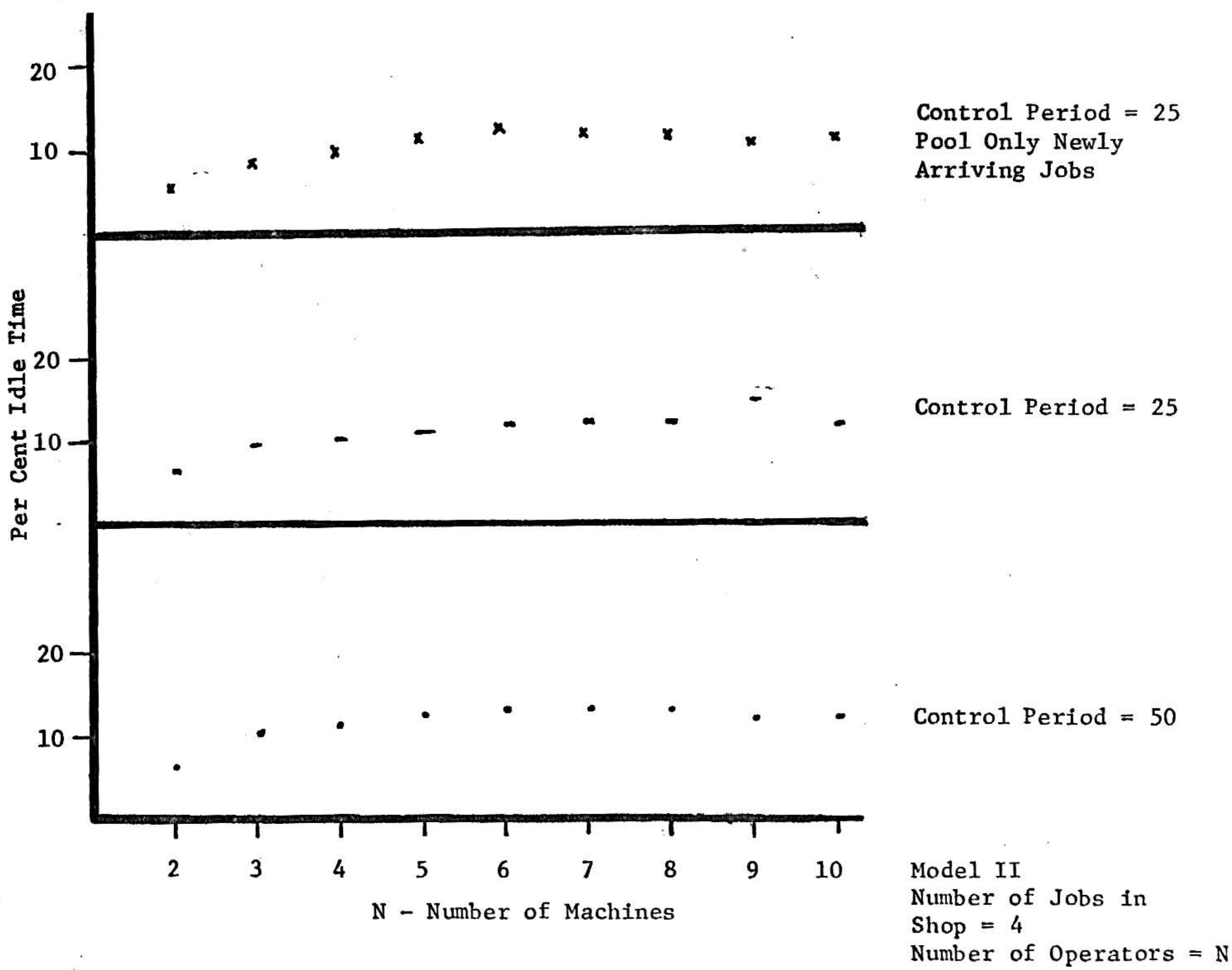


Figure 5 Model II - The Effect of Shop Size

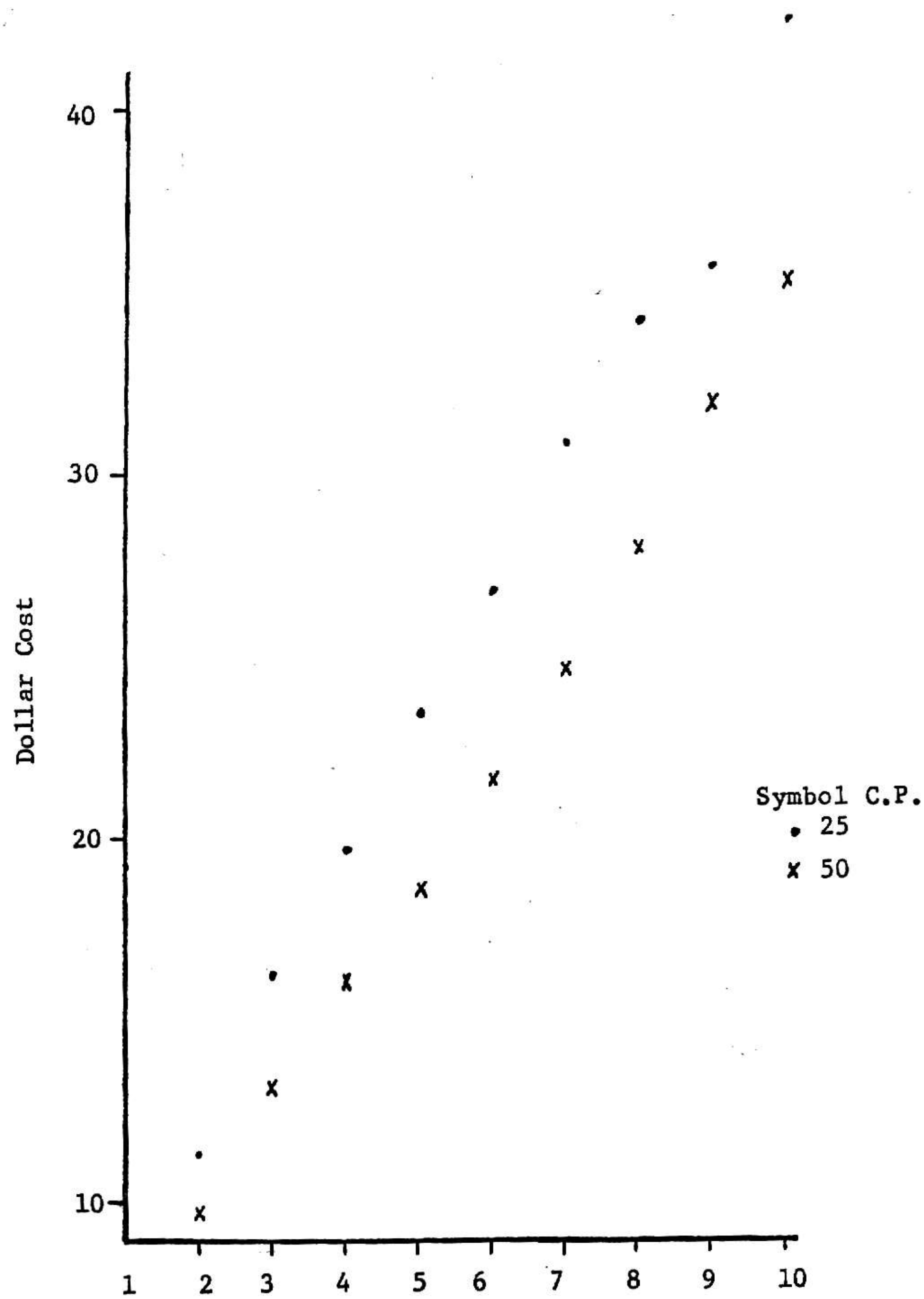


Figure 6 Cost of Model II Runs Versus Shop Size

a machine-limited shop of 9 machines and 9 operators. The mean inter-arrival time was 200 simulation units, the mean operation time was 100 units, the average number of operations per job was 4.5. Labor and machine utilization were equal to approximately 28 per cent.

Figure 7 shows the distribution of the time a job spends in the shop in terms of a control period length of 200 simulation units. Plots are presented for sets of jobs separated by number of operations. The minimum number of control periods a job could spend in the shop was equal to the number of operations for that job. The due date for each job was set equal to this minimum. The rightward movement of the distributions is to be expected. That no job with more than 3 operations was released on its due date was not expected. Consideration of possible causes for this suggests that the due date was set at a minimum value and it would unrealistic to expect very many jobs to meet it.

Figure 8 shows plots of mean time a job is in the shop. This is plotted for control period length and number of operations per job. Table IV lists the source data for these plots. The linearity of the plot makes it very easy to develop an equation for this family of lines. This equation can then be used to find a formula for K in the due date equation.

After performing the necessary calculations, the plot in Fig. 9 was made. This shows the slope of each line in Fig. 8(A) versus control period length. Using the slope of this line and the due date equation, the following formula for determining K was developed:

$$K = 1.35 + 135/C_{PL}$$

where: K = Constant for determining due date

Table IV lists theoretical versus observed mean time in the shop

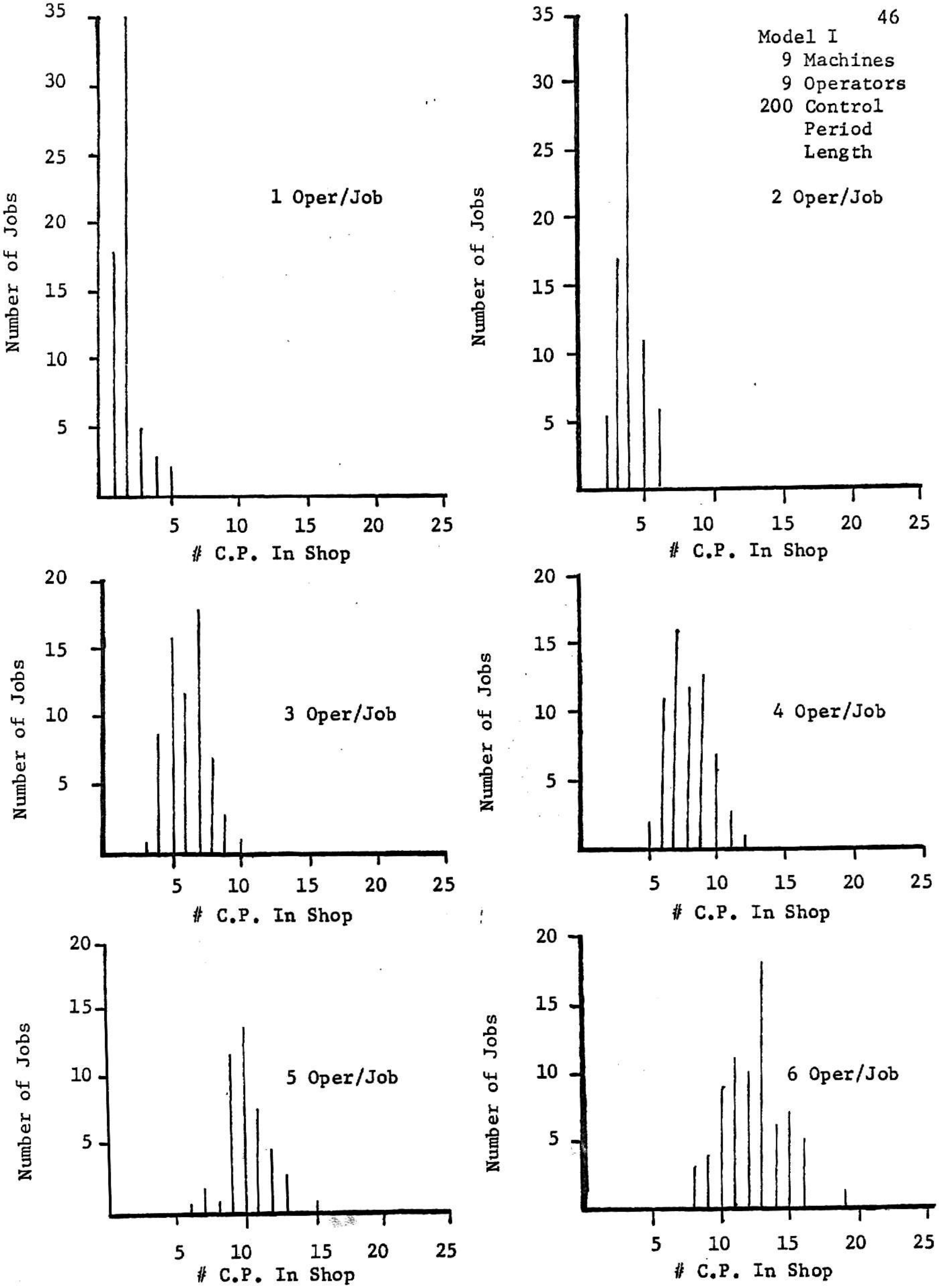
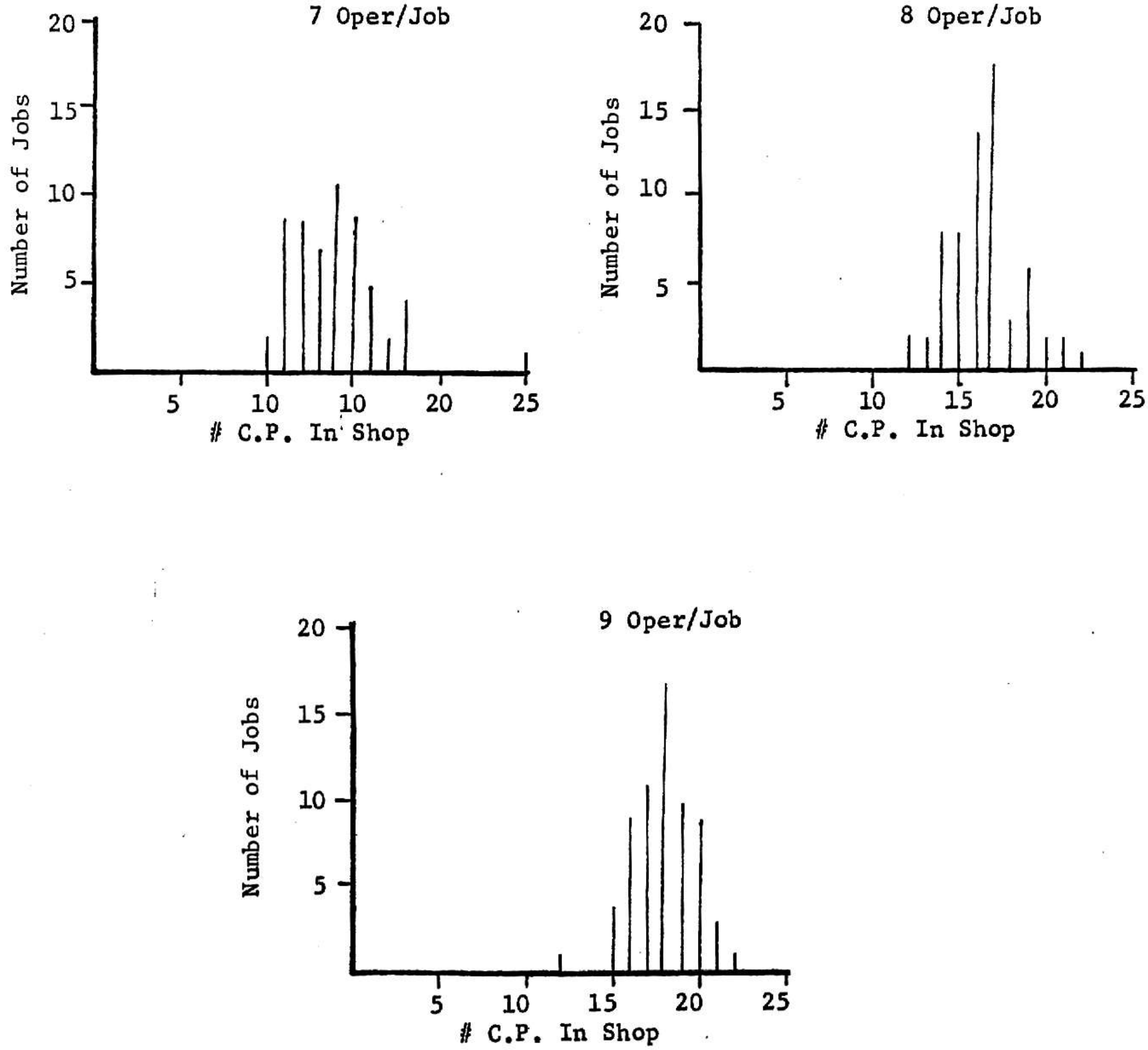


Figure 7 Number of Control Periods a Job Spends in the Shop as a Function of the Mean Number of Operations Per Job



Model I

9 Machines
9 Operators
200 Control Period Length

Figure 7 (contd.) Number of Control Periods a Job Spends in the Shop as a Function of the Mean Number of Operations Per Job

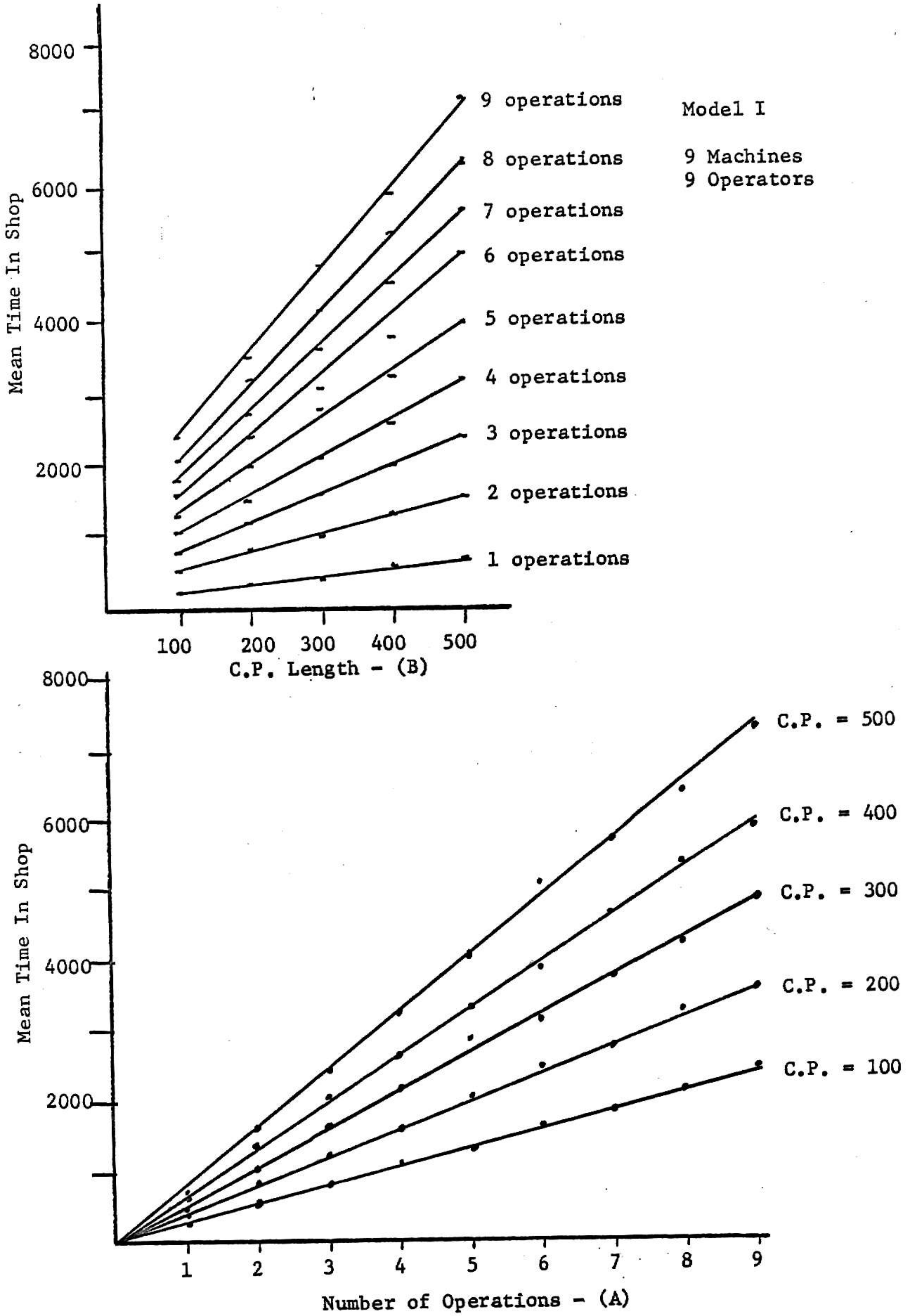


Figure 8 Mean Time in Shop as a Function of Control Period Length and Number of Operations

CONTROL PERIOD	NUMBER OF OPERATIONS								
LENGTH	1	2	3	4	5	6	7	8	9
100	297 (270)	549 (540)	813 (810)	1104 (1080)	1319 (1350)	1621 (1620)	1844 (1890)	2109 (2160)	2433 (2430)
200	396 (405)	886 (810)	1222 (1215)	1588 (1620)	2034 (2025)	2466 (2430)	2772 (2835)	3284 (3240)	3578 (3645)
300	432 (540)	1035 (1080)	1650 (1620)	2187 (2160)	2850 (2700)	3129 (3240)	3702 (3780)	4239 (4320)	4866 (4860)
400	628 (675)	1380 (1350)	2084 (2025)	2644 (2700)	3304 (3375)	3880 (4050)	4648 (4725)	5340 (5400)	5896 6075
500	755 (810)	1615 (1620)	2475 (2430)	3275 (3240)	4080 (4050)	5085 (4860)	5680 (5670)	6320 (6480)	7295 (7290)

(   ) Theoretical Value

Table IV Theoretical and Observed Time a Job Spends in the Shop

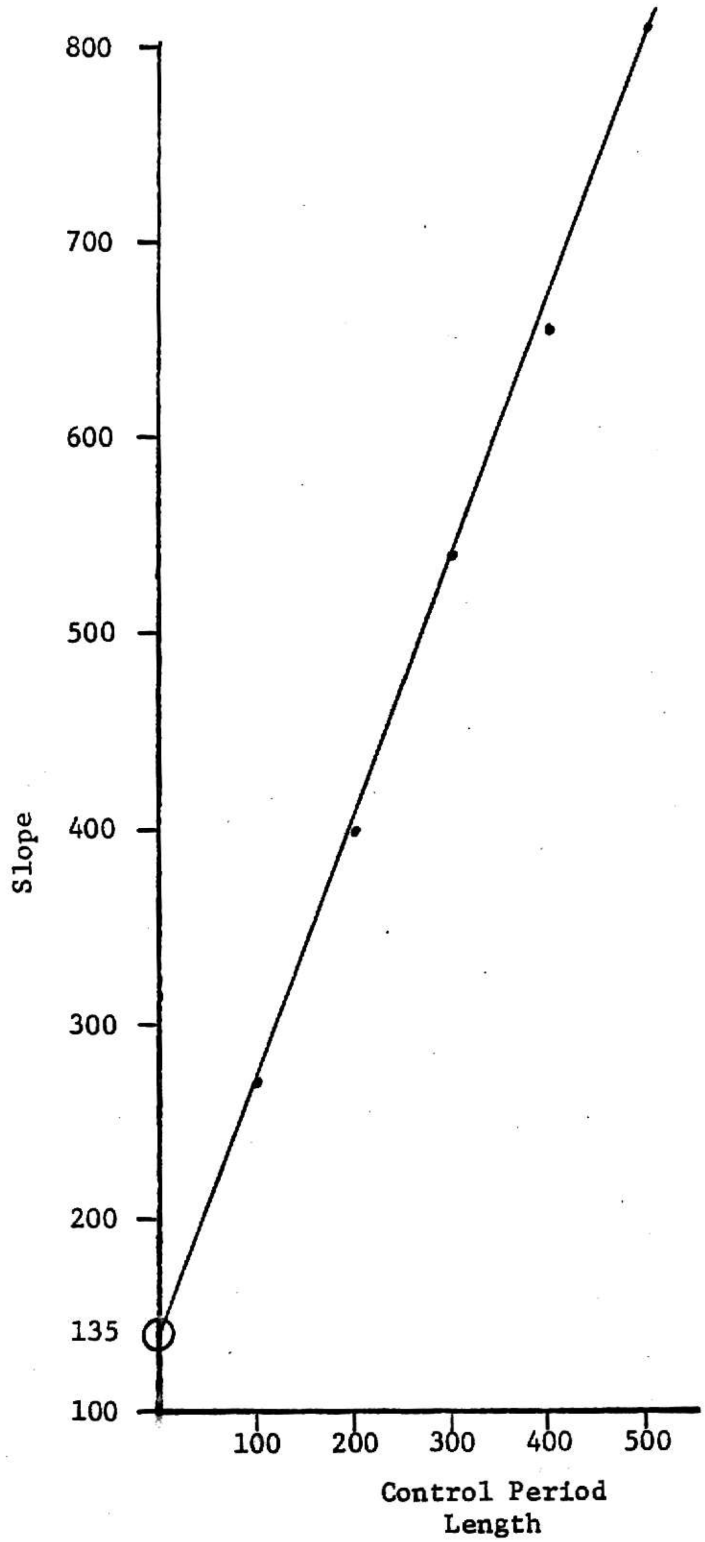


Figure 9 Plot of Slope of Line in Fig. 8(A) Versus Control Period Length

for selected control period lengths and number of observations. It would be interesting to see how well this formula holds for other control period lengths.

One common measure of shop performance is the number of jobs out on or before their due dates. Using a K value calculated from the above equation should improve shop performance.

In Fig. 10, the mean and standard deviation of the time spent in the shop for all jobs is plotted. The value of the mean increases linearly with control period length. This should not be surprising. Each job must stay in the shop at the very least, for the same number of control periods as it has operations. If each job was released on its due date, a graph of mean time in shop versus control period length would be a straight line. The fact that a straight line results with the completion of the jobs as it is, merely implies that the linearity built into the model is preserved. There is little evidence of any other direct interaction between control period length and job or shop parameters.

One reason for the lack of interaction is the low level of utilization in the shop. For a machine-limited shop, the utilization of the operators and machines is the same. This is identified then as shop utilization. Because of the low shop utilization, there may be enough slack in the system to obscure the effects of various control period lengths. On the other hand, there may not be any significant effects due to control period length at very low levels of utilization. In order to investigate these possibilities, the shop utilization was increased by steps.

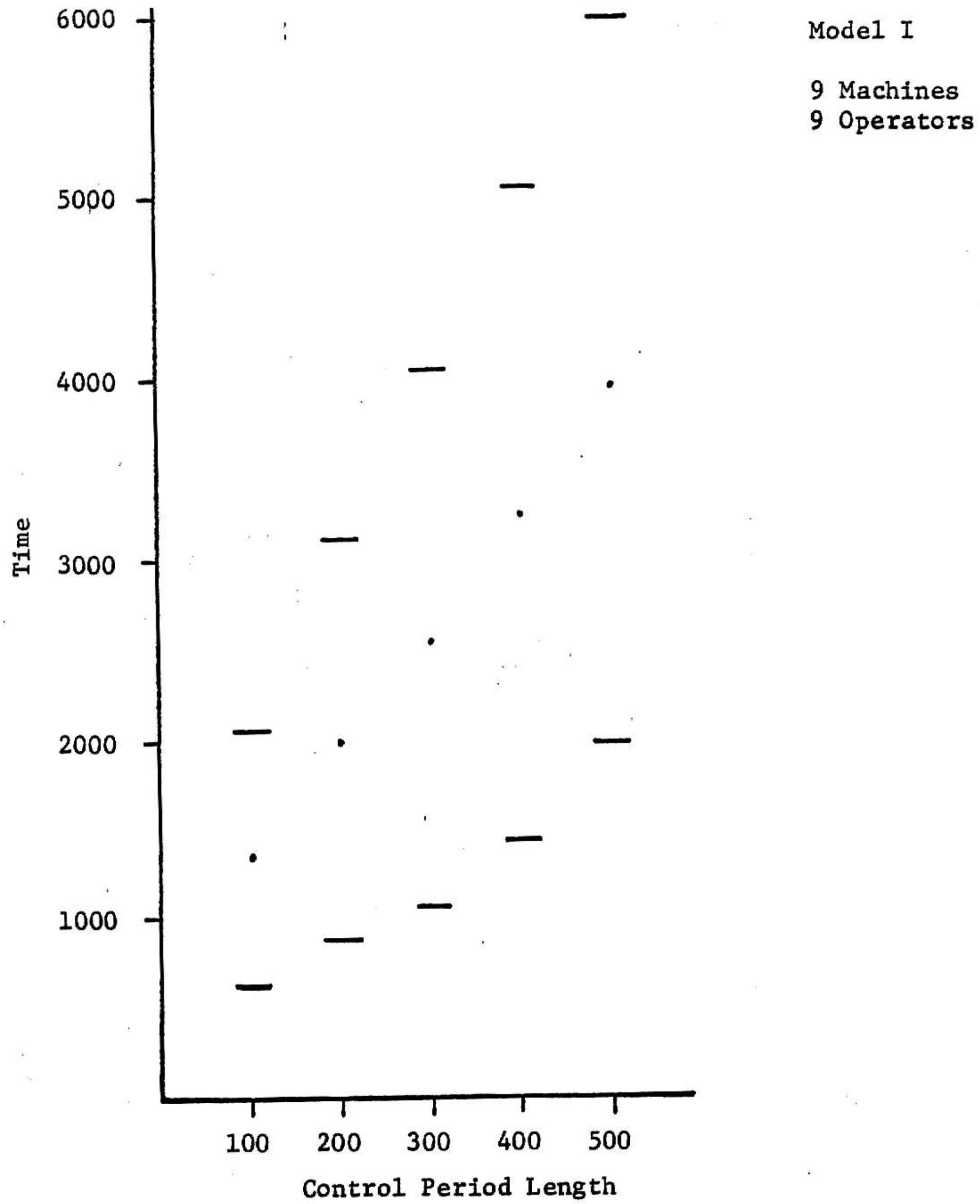


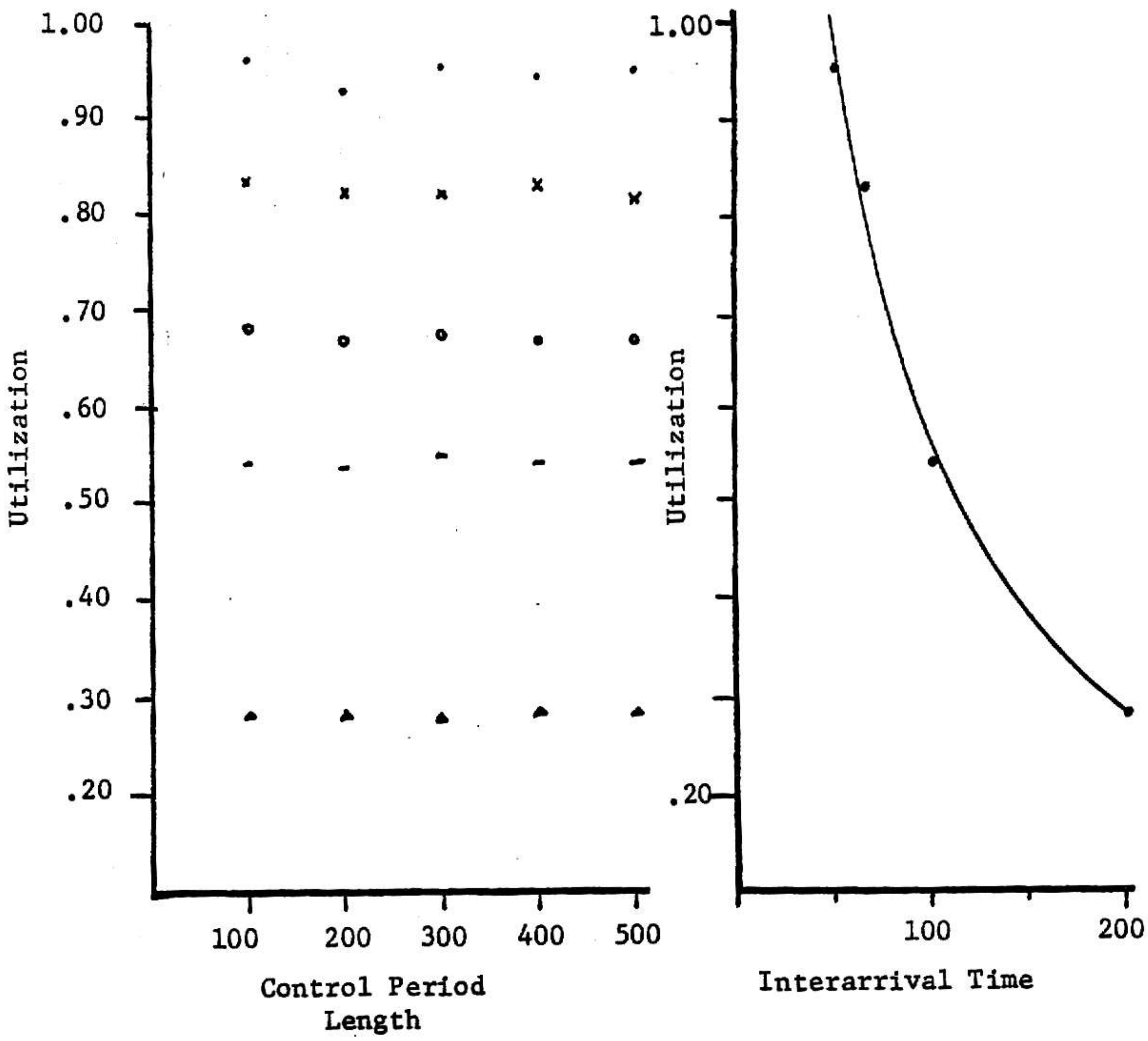
Figure 10 Mean and Standard Deviation of Time a Job Spends in the Shop

By reducing the interarrival time between stochastically arriving jobs, more and more jobs could crowd into the shop. The demand for services would increase and shop utilization would go up. Thus it was determined to decrease mean interarrival time for 5 sets of model runs. The results are shown in Figure 9 and 10.

Figure 11 shows how shop utilization increases with decreased interarrival time. Included with this graph is a plot of mean utilization versus interarrival time. Early in the research considerable difficulty was experienced in calculating a theoretical shop utilization. This plot serves as a convenient guide to predicting a theoretical utilization and appears to be quite accurate.

In Fig. 12, the mean time a job is late is related to control period length. A job is late when it leaves the shop past its due date. The same equation was used to set the due dates for this model. But notice that at 83% shop utilization there is a significant dip in the curve. At 96% utilization there is a very significant effect on mean time late due to control period length. From this, it can be hypothesized that a "threshold" effect is exhibited by the shop with respect to utilization. That is, shop behavior is not affected by control periods of different lengths until a specific threshold utilization is reached. Once this threshold utilization level is passed, considerable influence is exerted by the control period.

The final model studied was that of a labor-limited shop. The shop had the same parameters as the earlier models except that the number of machine operators was varied. Figure 13 depicts graphs of the mean time a job is in the shop versus the number of operations per job. Results are shown for various control period lengths and for shops with 3, 4 and



Model I

9 Machines
9 Operators

Symbol	Inter.
•	50
X	65
o	80
—	100
▲	200

Figure 11 Utilization vs. Control Period Length for Model I with Various Interarrival Times

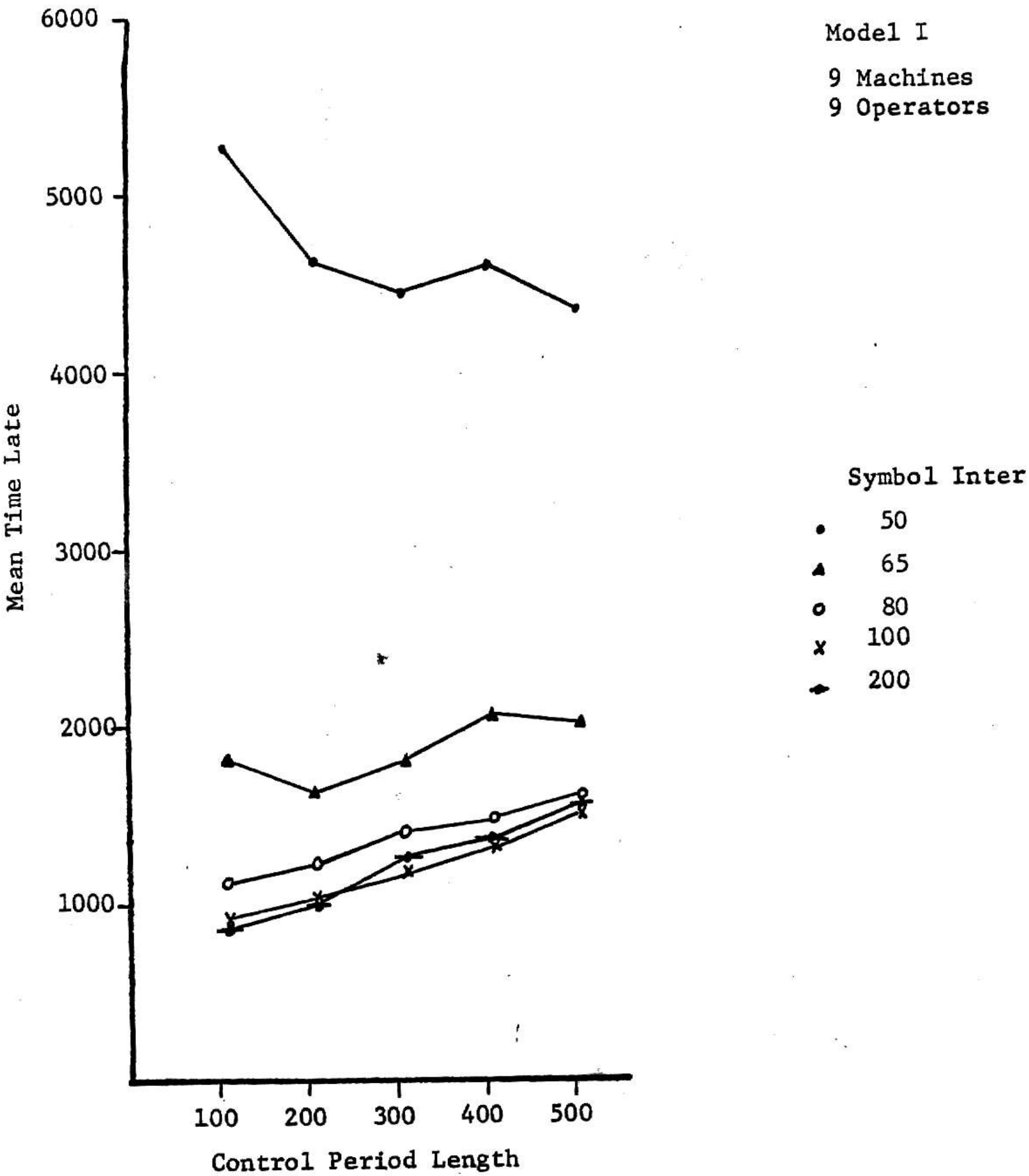
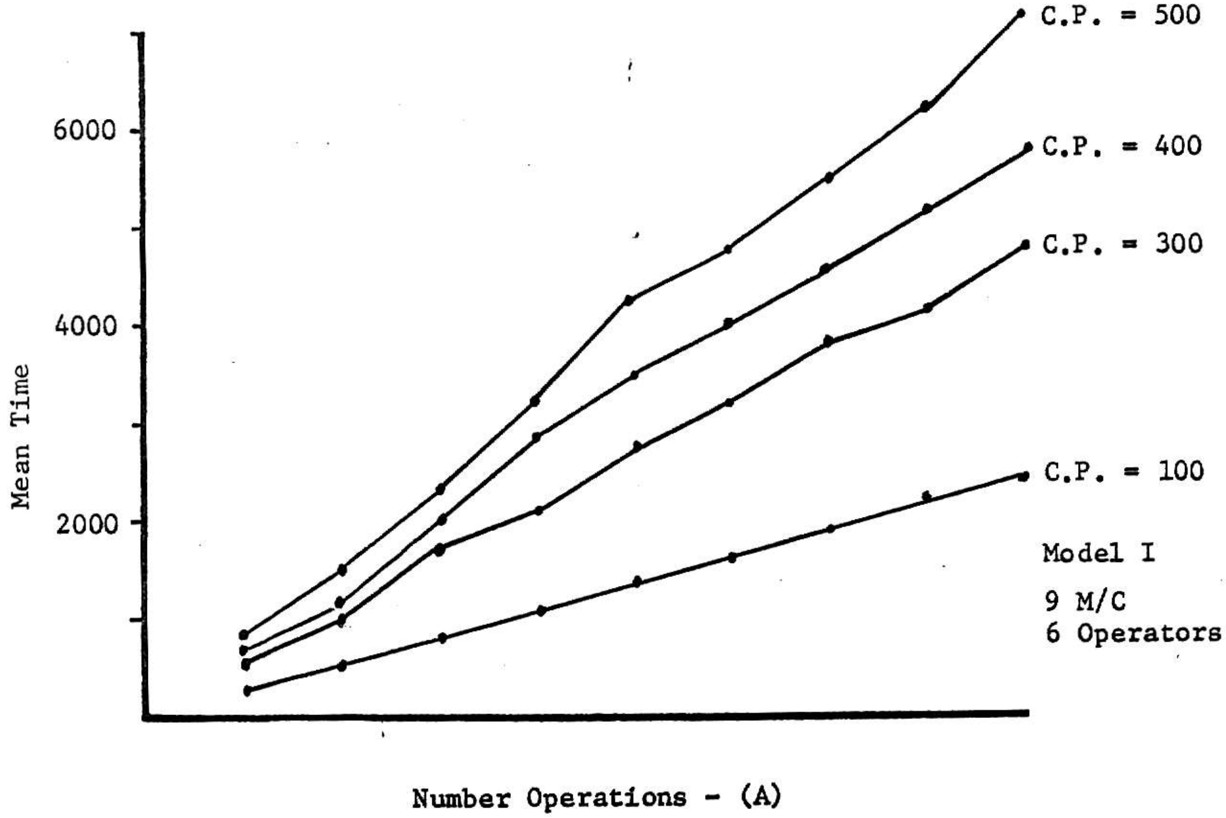


Figure 12 Mean Time Late vs. Control Period Length for Various Interarrival Times



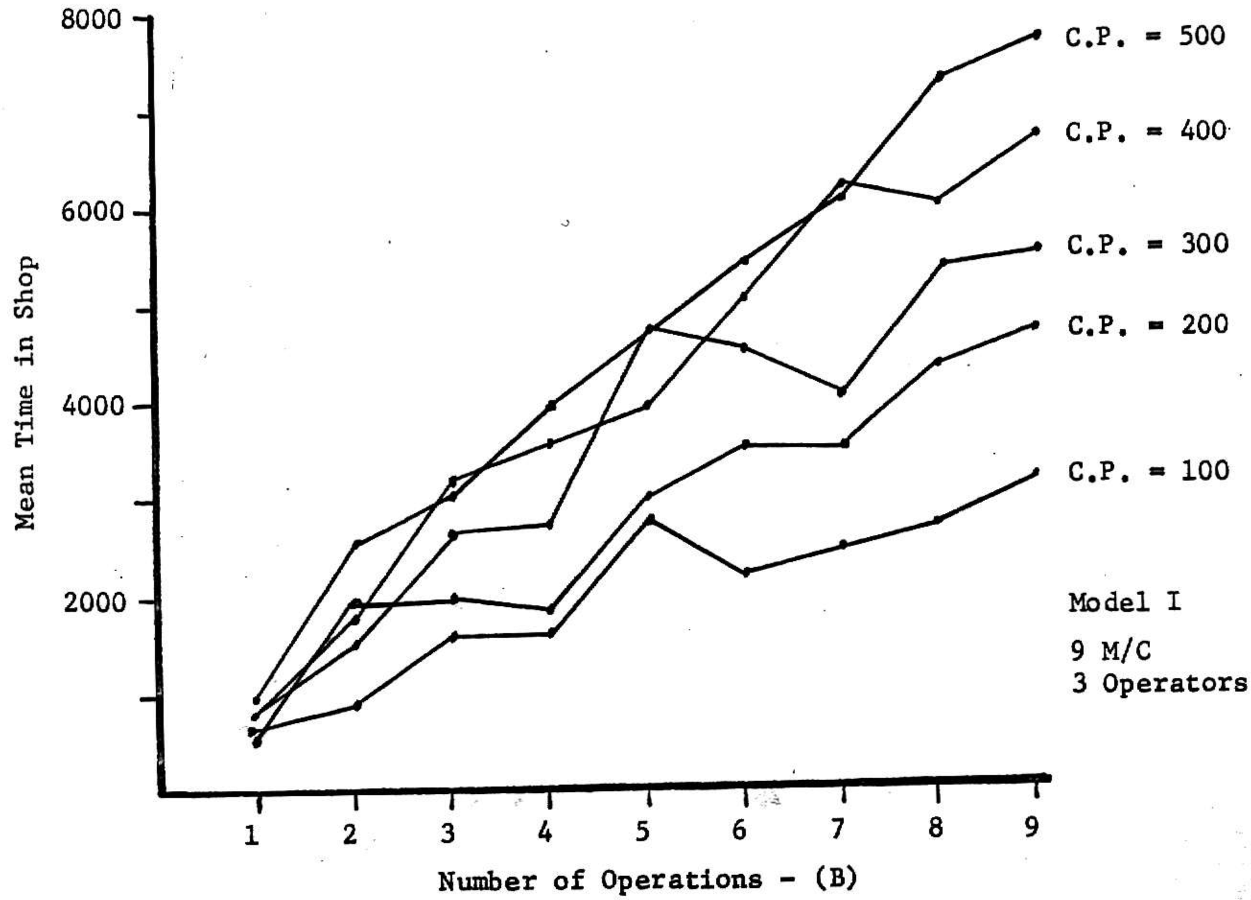


Figure 13 Mean Time in Shop vs. Number of Operations in Labor Limited Shops

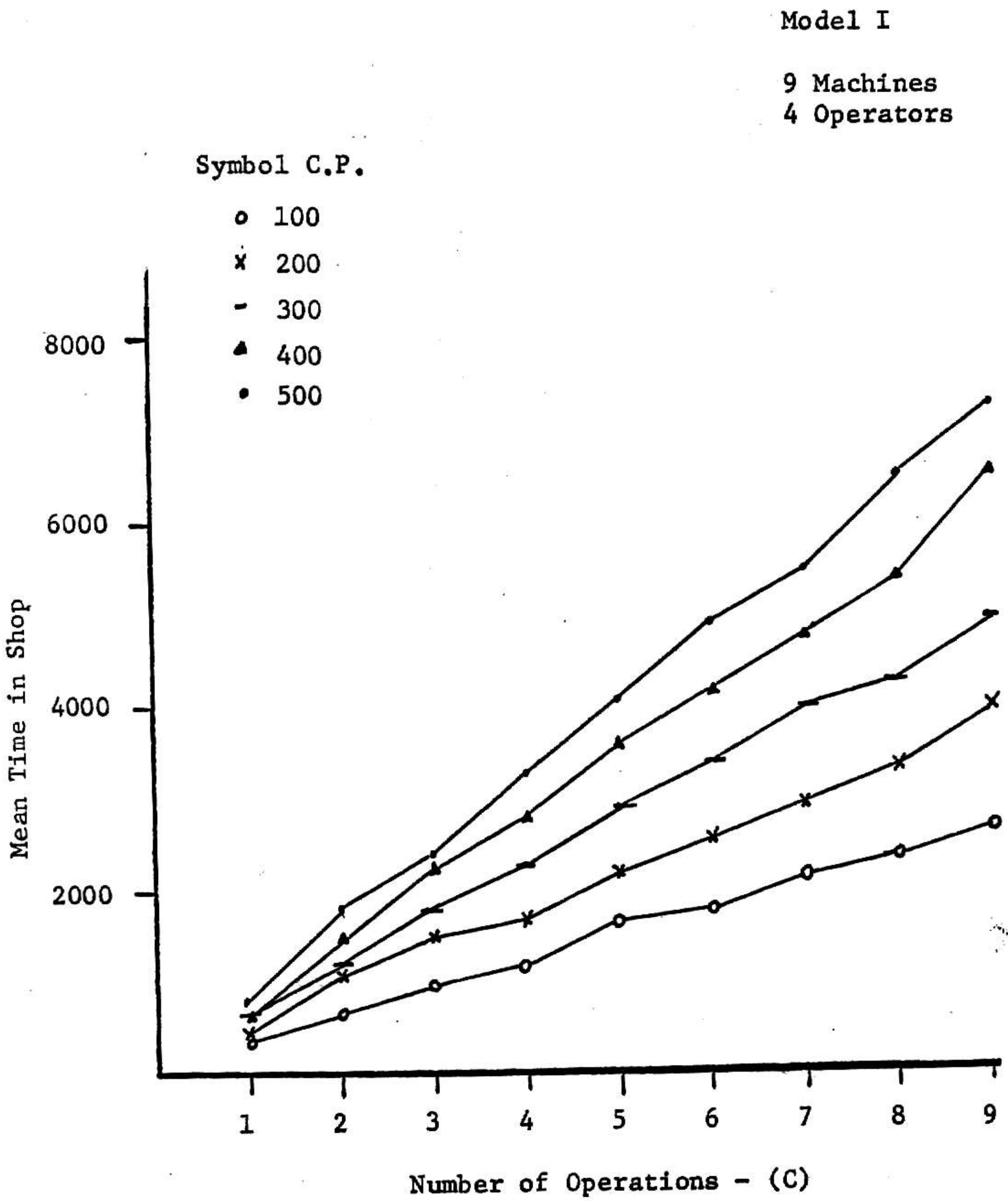


Figure 13 Mean Time in Shop vs Number of Operations (contd.)

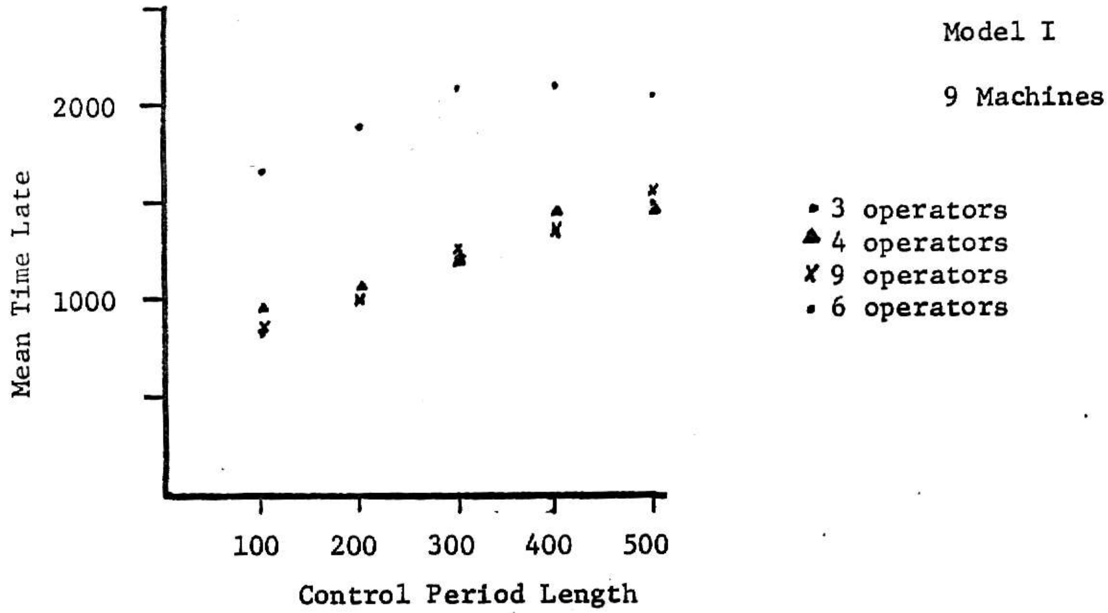
6 operators. From earlier runs with the machine-limited shop, a linear plot was expected. The plots for 4 and 6 operators were pretty much as expected. But when only 3 operators are working, all semblance of linearity disappears. Considerable interaction between number of operations and control period length is exhibited. A definite preference for jobs with a specific number of operations is shown by each control period.

Figure 14 shows plots of the mean time a job is late and operator utilization for each labor-limited shop. Once again a threshold effect is exhibited. When operator utilization reaches about 86%, the length of the control period exerts a discernible influence on shop performance. There isn't the clear cut preference for a specific control period length shown when the mean time in the shop was examined. Operator utilization shows a marked decrease for a control period length of 500 simulation units and a dip occurs at 200 simulation units. The decrease in utilization at a control period length of 200 units could be the result of an interaction between shop parameters and the control period length. The marked decrease with control period length of 500 simulation units is partly due to interaction with parameters and partly to operators sitting waiting for work.

4.3 Summary

The research reported here raised considerably more questions than it answered. The major conclusions that can be drawn from this work are:

1) The influence of a control period on shop performance is subject to a threshold effect. No interactions occur until a threshold utilization level is exceeded.



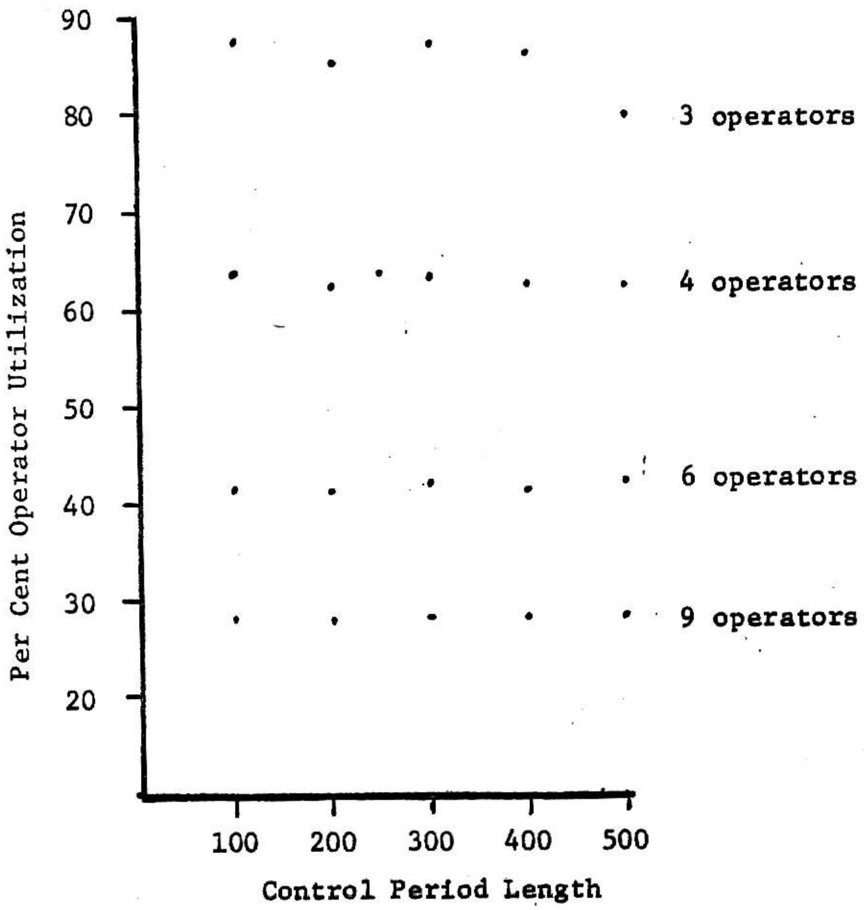


Figure 14 Per Cent Utilization and Mean Time Late in Labor Limited Shops

2) At low levels of utilization, the major effect of changing control period lengths is to linearly change the mean time of a job in the shop and mean time a job is late in the same direction as the control period.

3) A threshold effect with respect to a labor-limited shop is also exhibited. There seems to be no significant effect on mean job lateness and time in shop as a function of the number of job operations until a specific level of operator utilization is reached.

These conclusions serve more to indicate areas of further research, than as absolute ends in themselves. Some of the areas for further research that come to mind are:

1) An investigation into the effects of control period length on priority rules.

2) Investigate the performance of priority rules in a labor-limited shop.

3) Find the exact threshold point in terms of utilization for both control period and labor-limited shop effects.

4) Is there an actual threshold or is it a gradual increase in the influence of control period length as utilization increases?

5) Determine an "optimal" value for K in the due date equation.

These areas and those mentioned in connection with Rohr Corporation system, should provide fertile fields for further investigation.

A possible explanation for the threshold nature of shop response can be inferred from Fig. 11. The exponential-like curve suggests a very sensitive system at higher levels of utilization. At low levels of utilization, considerable slack exists in the system. There are free machines, waiting operators and few, if any, jobs in machine queues. Thus, significant changes can be made in shop parameters, with little or no obvious effect on shop performance. At higher levels of utilization, the system is much tighter. Increased demands for service, more jobs waiting in queues and larger in-process inventory remove much of the slack that was in the system. At this time, any changes in shop parameters, such as control period length, will effect significant changes in shop performance. This would explain our observed threshold effects. A gradual increase in the effects of any particular change rather than an absolute threshold utilization would seem to be suggested. At any rate, further research in this area would definitely be informative.

APPENDIX A

```
BLOCK
NUMBER   *LOC    OPERATION   A,B,C,D,E,F,G                      COMMENTS
                 RMULT       ,3,5,7,9,11,13,15
                 SIMULATE
          1      FUNCTICN    RN2,C2
         0,1/1,10
          2      FUNCTICN    RN6,C2
         0,1/1,10
          3      FUNCTICN    RN7,C2
         0,1/1,10
          4      FUNCTICN    RN5,C2
         0,1/1,10
          5      FUNCTICN    RN8,C2
         0,1/1,10
          6      FUNCTICN    RN2,C2
         0,1/1,10
          7      FUNCTICN    RN6,C2
         0,1/1,10
          8      FUNCTICN    RN7,C2
         0,1/1,10
          9      FUNCTICN    RN5,C2
         0,1/1,10
          10     FUNCTICN    RN4,C2
         0,1/1,10
          11     FUNCTICN    RN3,C31
         .001,-3.09/.0C5,-2.58/.01,-2.33/.02,-2.05/.03,-1.88/.04,-1.75
         .05,-1.645/.100,-1.28/.15,-1.04/.20,-.84/.25,-.70/.30,-.52/.35,-.40
         .40,-.25/.45,-.15/.50,0.00/.55,.15/.60,.25/.655,.40/.70,.52/.758,.70
         .80,.84/.85,1.04/.90,1.28/.95,1.645/.96,1.75/.97,1.88/.98,2.05
         .990,2.33/.995,2.58/.999,3.09
          12     FUNCTICN    RN5,C2        ASSIGNS DIST. FOR NO. OF OPER.
         0,1/1,10
          13     FUNCTICN    RN4,C2
         0,1/1,10
          14     FUNCTICN    RN3,D8
         .222,1/.415,2/.582,3/.720,4/.831,5/.914,6/.968,7/1.0,8
          1      TABLE       M1,300,300,100 TABULATES MEAN TIME IN SHOP
          2      TABLE       V3,0,300,100 TABULATES MEAN TIME LATE
                 INITIAL     X11,9/X12,4/X13,6/X14,100/X15,10/X16,10
                 INITIAL     X17,200/X18,50/X19,300
          1      VARIABLE    P1*X19         SETS DUE DATE
          2      FVARIABLE   X14+X15*FN11   OPERATION TIME DETERMINED
          3      VARIABLE    M1-P5          DETERMINES JOB LATENESS
          4      VARIABLE    CH*1(1-F*1)    ADJUSTS QUEUE LENGTH AT END OF C. P.
          5      VARIABLE    M1/X19         DETERMINES NUMBER OF C. P. IN SHOP
          6      VARIABLE    FR*1           GETS M/C UTILIZATION FO M/C *1
          7      VARIABLE    10(X1)/X11     DETERMINES MEAN M/C UTILIZATION
          1      MATRIX      H,100,9
          1      STORAGE     4              TELLS NUMBER OF OPERATORS
3 1              GENERATE    ,,5000,X16,,X13
  2              TRANSFER    ,BETSY
  3              GENERATE    ,,4C00,X16,,X13
  4              TRANSFER    ,BETSY
  5              GENERATE    ,,3000,X16,,X13
  6              TRANSFER    ,BETSY
2 7              GENERATE    ,,2C00,X16,,X13
  8              TRANSFER    ,BETSY
```

```
            GENERATE    ,,X19,X16,,X13
      BETSY ASSIGN      4,FN14        ASSIGNS NO. OF OPERATIONS FOR A JOB
            ASSIGN      1,*4          RE-LOCATES P4 FOR STATISTIC COLLECTING
            ASSIGN      5,V1          ASSIGNS EARLIEST DUE DATE
            ASSIGN      2,FN13        ASSIGNS FIRST M/C FOR JOB
            SAVEVALUE   *2+,K1,H      UPDATES QUEUE LENGTH
            TRANSFER    ,ANN
            GENERATE    X17,X18,X19,,,X13  DYNAMIC SHOP ARRIVALS
            ASSIGN      4,FN12        ASSIGNS NO. OF OPERATIONS FOR A JOB
            ASSIGN      1,*4          RE-LOCATES P4 FOR STATISTIC COLLECTING
            ASSIGN      5,V1          ASSIGNS EARLIEST DUE DATE
            ASSIGN      2,FN13       ASSIGNS FIRST M/C FOR THE JOB
      ANN   LINK        19,FIFO        HOLD ARRIVALS UNTIL END OF CONT. PER.
      DEE   ENTER       2             ENTERS SHOP
            MARK
            TRANSFER    ,PAT
      NXTOP ASSIGN      2,FN*2       ASSIGNS M/C FOR SECOND OPER. AND ON
      PAT   ASSIGN      3,V2          GIVES OPERATION TIME FOR THIS RUN
            LINK        *2,P3        SIO QUEUE DISCIPLINE
      CAN   SEIZE       *2            PUT A JOB ON A M/C
            ENTER       1            ASSIGN AN OPERATOR TO A JOB
            SAVEVALUE   *2,K0,H       REMOVES M/C FROM AVAILABILITY
            ADVANCE     *3            PROCESS JOB
            SAVEVALUE   *2,CH*2,H     GIVES PREFERENCE TO LARGEST QUEUE
            RELEASE     *2            REMOVE JOB FROM THE M/C
            LEAVE       1            FREE OPERATOR
            SPLIT       1,BARB
            LINK        18,FIFO       HOLD JOBS UNTIL THE END OF C. P.
      MARY  LOOP        4,NXTOP
            LEAVE       2
            ASSIGN      6,V5
            TEST L      P6,K100,KAREN
      LINDA MSAVEVALUE  1+,P6,*1,K1,H
            TABULATE    1
            TABULATE    2
            TERMINATE
            GENERATE    ,,,X12,,2     M/C OPERATOR SUB-PROGRAM
      BARB  SELECTMAX   2,1,X11,,XH
            TEST NE     CH*2,K0,KATHY
      WANDA UNLINK      *2,CAN,1
            TERMINATE
      KATHY LINK        17,FIFO
      KAREN ASSIGN      6,K100
            TRANSFER    ,LINDA
            GENERATE    X19,,,,,1     CONTROL PERIOD TIMER
            UNLINK      19,DEE,ALL
            UNLINK      18,MARY,ALL
            UNLINK      17,BARB,ALL
            ASSIGN      1,X11
            SAVEVALUE   1,K0
      FIX   SAVEVALUE   *1,V4,H
            SAVEVALUE   1+,V6
            LOOP        1,FIX
            SAVEVALUE   2,V7
            TERMINATE   1
            START       3
            END
```

APPENDIX B

Model I
9 Machines
5 Operators
Control Period = 1000 Simulation Time Units

TIME	UTILIZATION		TIME	UTILIZATION	
	Mean Machine	Operator		Mean Machine	Operator
2000	.071	.099	52000	.277	.499
4000	.174	.314	54000	.279	.502
6000	.223	.402	56000	.280	.504
8000	.264	.476	58000	.279	.502
10000	.273	.493	60000	.279	.502
12000	.277	.500	62000	.278	.500
14000	.271	.487	64000	.277	.500
16000	.267	.479	66000	.277	.499
18000	.268	.483	68000	.277	.499
20000	.267	.479	70000	.275	.496
22000	.265	.476	72000	.275	.496
24000	.264	.475	74000	.274	.494
26000	.260	.469	76000	.276	.497
28000	.257	.463	78000	.276	.499
30000	.258	.465	80000	.279	.502
32000	.262	.472	82000	.279	.503
34000	.263	.474	84000	.278	.501
36000	.266	.480	86000	.277	.499
38000	.270	.487	88000	.276	.497
40000	.272	.490	90000	.275	.495
42000	.274	.493	92000	.276	.497
44000	.275	.495	94000	.276	.498
46000	.275	.496	96000	.275	.496
48000	.275	.495	98000	.275	.495
50000	.275	.495	100000	.274	.493

Table VI 40 Jobs at Once: Pre-Load

Model I
9 Machines
5 Operators
Control Period = 1000 Simulation Time Units

TIME	UTILIZATION		TIME	UTILIZATION	
	Mean Machine	Operator		Mean Machine	Operator
2000	.071	.099	52000	.273	.492
4000	.279	.503	54000	.273	.493
6000	.283	.510	56000	.274	.494
8000	.281	.507	58000	.274	.494
10000	.286	.516	60000	.273	.491
12000	.292	.527	62000	.271	.490
14000	.283	.510	64000	.271	.488
16000	.283	.510	66000	.272	.491
18000	.280	.505	68000	.273	.491
20000	.277	.499	70000	.274	.494
22000	.276	.498	72000	.274	.494
24000	.275	.496	74000	.274	.494
26000	.270	.486	76000	.277	.499
28000	.267	.481	78000	.279	.502
30000	.271	.488	80000	.279	.502
32000	.276	.497	82000	.277	.499
34000	.279	.502	84000	.275	.496
36000	.278	.500	86000	.274	.494
38000	.276	.496	88000	.273	.493
40000	.276	.497	90000	.273	.493
42000	.275	.496	92000	.275	.495
44000	.275	.495	94000	.275	.495
46000	.274	.494	96000	.275	.496
48000	.274	.493	98000	.276	.496
50000	.273	.493	100000	.277	.499

Table VII 50 Jobs at Once: Pre-Load

Model I
9 Machines
5 Operators
Control Period = 1000 Simulation Time Units

TIME	UTILIZATION		TIME	UTILIZATION	
	Mean Machine	Operator		Mean Machine	Operator
2000	.071	.099	52000	.262	.473
4000	.098	.196	54000	.262	.472
6000	.151	.272	56000	.262	.472
8000	.177	.320	58000	.264	.475
10000	.190	.342	60000	.265	.477
12000	.197	.356	62000	.266	.478
14000	.202	.364	64000	.266	.479
16000	.209	.377	66000	.267	.480
18000	.211	.379	68000	.267	.482
20000	.221	.398	70000	.267	.482
22000	.228	.412	72000	.267	.482
24000	.236	.426	74000	.267	.482
26000	.242	.436	76000	.269	.484
28000	.245	.442	78000	.270	.487
30000	.246	.443	80000	.270	.487
32000	.249	.449	82000	.270	.485
34000	.252	.454	84000	.269	.485
36000	.256	.461	86000	.270	.486
38000	.258	.465	88000	.271	.488
40000	.262	.473	90000	.272	.490
42000	.263	.474	92000	.272	.489
44000	.264	.475	94000	.271	.489
46000	.264	.475	96000	.271	.489
48000	.263	.473	98000		
50000	.263	.474	100000		

Table VIII 20 Jobs Over Time: Pre-Load

Model I
9 Machines
5 Operators
Control Period = 1000 Simulation Time Units

TIME	UTILIZATION		TIME	UTILIZATION	
	Mean Machine	Operator		Mean Machine	Operator
2000	.071	.099	52000	.258	.465
4000	.156	.282	54000	.261	.471
6000	.202	.365	56000	.263	.474
8000	.219	.395	58000	.264	.475
10000	.231	.416	60000	.264	.476
12000	.232	.419	62000	.263	.474
14000	.238	.430	64000	.262	.472
16000	.242	.437	66000	.262	.471
18000	.244	.440	68000	.263	.474
20000	.243	.438	70000	.264	.476
22000	.243	.437	72000	.267	.481
24000	.243	.437	74000	.267	.482
26000	.241	.435	76000	.267	.481
28000	.242	.437	78000	.266	.480
30000	.240	.432	80000	.267	.482
32000	.246	.443	82000	.268	.483
34000	.249	.449	84000	.269	.484
36000	.252	.454	86000	.268	.482
38000	.253	.456	88000	.267	.481
40000	.253	.457	90000	.267	.482
42000	.255	.460	92000	.268	.482
44000	.258	.464	94000	.267	.482
46000	.258	.466	96000	.268	.484
48000	.258	.464	98000	.269	.485
50000	.259	.466	100000	.269	.484

Table IX 30 Jobs Over Time: Pre-Load

Model I
9 Machines
5 Operators
Control Period = 1000 Simulation Time Units

TIME	UTILIZATION		TIME	UTILIZATION	
	Mean Machine	Operator		Mean Machine	Operator
2000	.055	.099	52000	.269	.484
4000	.156	.282	54000	.270	.487
6000	.232	.417	56000	.271	.488
8000	.256	.462	58000	.271	.489
10000	.262	.472	60000	.272	.489
12000	.258	.465	62000	.271	.489
14000	.254	.458	64000	.272	.482
16000	.254	.457	66000	.270	.487
18000	.256	.460	68000	.269	.485
20000	.257	.463	70000	.270	.486
22000	.258	.465	72000	.270	.486
24000	.260	.468	74000	.270	.486
26000	.259	.467	76000	.270	.486
28000	.259	.467	78000	.270	.486
30000	.259	.467	80000	.270	.487
32000	.263	.474	82000	.270	.486
34000	.264	.475	84000	.268	.483
36000	.266	.480	86000	.269	.484
38000	.268	.483	88000	.269	.484
40000	.269	.485	90000	.269	.485
42000	.268	.483	92000	.268	.483
44000	.268	.482	94000	.267	.482
46000	.267	.482	96000	.267	.481
48000	.266	.480	98000	.267	.481
50000	.267	.481	100000	.267	.482

Table X 40 Jobs Over Time: Pre-Load

Model I
9 Machines
5 Operators
Control Period = 1000 Simulation Time Units

TIME	UTILIZATION		TIME	UTILIZATION	
	Mean Machine	Operator		Mean Machine	Operator
2000	.071	.099	52000	.272	.489
4000	.156	.282	54000	.273	.491
6000	.262	.472	56000	.275	.496
8000	.281	.506	58000	.276	.497
10000	.286	.515	60000	.277	.498
12000	.285	.513	62000	.277	.498
14000	.282	.507	64000	.277	.499
16000	.278	.500	66000	.277	.500
18000	.279	.503	68000	.278	.501
20000	.276	.498	70000	.279	.503
22000	.275	.495	72000	.279	.503
24000	.274	.493	74000	.280	.504
26000	.269	.484	76000	.281	.505
28000	.265	.478	78000	.281	.506
30000	.266	.480	80000	.281	.506
32000	.269	.485	82000	.280	.505
24000	.271	.489	84000	.280	.504
36000	.271	.488	86000	.279	.503
38000	.271	.487	88000	.278	.501
40000	.272	.489	90000	.278	.500
42000	.269	.485	92000	.277	.500
44000	.270	.486	94000	.276	.498
46000	.270	.487	96000	.276	.497
48000	.271	.489	98000	.276	.498
50000	.270	.487	100000	.277	.498

Table XI 50 Jobs Over Time: Pre-Load

Model I
9 Number of Machines
9 Number of Operators

CONTROL PERIOD LENGTH	MEAN TIME LATE	% UTIL-IZATION	INTERARRIVAL TIME
100	875	.284	
200	1032	.281	
300	1261	.281	200
400	1387	.283	
500	1584	.285	
100	926	.547	
200	1048	.542	
300	1207	.551	100
400	1345	.546	
500	1555	.545	
100	1139	.689	
200	1228	.675	
300	1403	.681	80
400	1477	.675	
500	1638	.675	
100	1842	.838	
200	1636	.829	
300	1816	.823	65
400	2070	.836	
500	2017	.821	
100	5270	.962	
200	4830	.960	
300	4474	.962	50
400	4630	.959	
500	4370	.961	

Table XII Mean Time Late and % Utilization for Different Interarrival Times

Mode I
Number of Machines 9

MEAN TIME LATE	UTILIZATION MIC	UTILIZATION OPERATOR	NUMBER OF OPERATORS	CONTROL PERIOD LENGTH
1698	.292	.877	3	100
1903	.285	.855	3	200
2101	.291	.873	3	300
2128	.287	.861	3	400
2070	.266	.800	3	500
961	.284	.639	4	100
1089	.279	.629	4	200
1279	.283	.636	4	300
1465	.277	.624	4	400
1519	.277	.623	4	500
853	.279	.419	6	100
1051	.272	.416	6	200
1249	.281	.421	6	300
1398	.279	.418	6	400
1519	.281	.421	6	500
875	.284	.284	9	100
1032	.281	.281	9	200
1261	.281	.281	9	300
1387	.283	.283	9	400
1584	.285	.285	9	500

Table XIII Mean Time Late and Per Cent Utilization in Labor-Limited Shops

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THE EFFECTS OF A FIXED CONTROL

PERIOD ON THE JOB SHOP SEQUENCING PROBLEM

by

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B.S., Kansas State University, 1969

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

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The effect of an imposed control period on the operation of a job shop was examined. Control period lengths of 100, 200, 300, 400 and 500 simulation time units were tried. The operation of a job shop in a labor-limited situation was also examined. Shop size was set at nine machines. Model runs were made with the 3, 4 and 6 machine operators. It was concluded that:

1) Control period length does not effect shop performance below some threshold utilization.
2) At low levels of utilization the major effect of changing control period lengths is to linearly change mean time late and mean time a job is in the shop.
3) A threshold effect is also experienced in a labor-limited shop with no effects exhibited below a minimum level of operator utilization.