

JOB SHOP STUDY

BY

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CHAPTER I

INTRODUCTION

A production system may be defined as an orderly collection of elements of production which are combined and operated in a certain desired fashion to produce goods of economic use or to result into an efficient service. The basic elements of a production system are man, machine and materials.

The production system can be analyzed in terms of the nature of flow and the manner the jobs are handled in shop. The two broad categories into which a production system can be classified are batch production and continuous production systems. In a batch production system, the jobs each of which consists of a certain lot size are processed on the various machines. A job shop manufacturing electric motors is an example of batch production system. The distinguishing feature of such system is the multi-purpose nature of the machines used. All machines in the shop are universal and no machine is used for the specific purpose of a particular job. These machines may be arranged according to their types and each job may have different routing. Therefore, such a system is referred to as shop production system. In continuous production system, highly specialized nature of the machines characterizes such system. Car manufacturing industry is an example of continuous production system. The machines perform a specific operation on each product which form a line and approach individually towards a machine. Also the machines are arranged in a

particular order to conform to the order of operations to be performed on the job. Such a machine arrangement is commonly called an assembly-line and the system is referred to as line production system.

1.1 Job-Shop Scheduling

This thesis is concerned with the shop production system. In such a system, the shop consists of a set or group of working centers and a set of operations to be performed in a specified technological ordering at one or more working centers. Each center has a finite number of machines which are identical as far as the nature of work demanded at each working center is concerned. The complex behavior of a job shop can be described as follows:

After a customer order is received, the engineering department decides the nature of the work to be performed on different machines and specifies the technological ordering of machines to perform the work on the order, hereafter referred to as a job. Engineering department also sets the time limit by which each job has to be completed, known as the due-date of a job. In some cases, a job may have other attributes of interest such as monetary value or it may have a priority because of its regular potential customer. The information necessary for performing operations of a job is summarized on a paper generally termed as a job file and accompanies each job through the shop. After a job has arrived in the shop the machine on which the first operation is to be processed according to the corresponding routing, is checked for idleness. If that machine is processing another job, then the newly arrived job joins a queue before the work center. However, if the machine is idle and the information of

the next job to arrive is absent, the machine starts to prepare for the operation while the job waits at the work center. The time spent in the preparation of the machine for processing that job is known as set-up time of a job. After set-up time is over, a machine processes the job for a pre-specified operation. The time interval between end of the set-up and the completion of processing the job is called operation processing time. The job is then transported to another machine specified in the job file for performing its second operation. After all operations of a job are completed, it departs from the shop as a completed job.

Such a complex behavior of a job shop necessitates assumptions of some theoretical restrictions if experimental work is to be carried out on job-shop models. A simplified job-shop model is considered to have the following assumptions [2, 12, 23, 29, 40]:

I. Assumptions related to jobs

- 1.1 The arrival pattern of jobs in the shop is probabilistic in nature. The governing probability distribution remains unchanged through the length of an experiment and is not affected by shop conditions.
- 1.2 The arrival of a job to the shop includes the information necessary for processing such as processing times, job routing and due-date are known.
- 1.3 Even though a job may represent a lot consisting of several individual parts, no lot is processed on more than one machine at a time, i.e., no lot splitting is permitted, or overlapping of operations.

- 1.4 Job routing is fixed and no alternate routings are permissible.
- 1.5 Each job, once started, is processed until its completion; i.e., no order cancellation occurs.
- 1.6 Each job may wait between machines; i.e., in-process inventory is allowed.
- 1.7 No interaction is allowed among jobs at any work center. Jobs of nearly identical set-ups do not accumulate in order to save set-up times at given work center.

2. Assumptions related to productive elements (man and machine)

- 2.1 Each machine center has a single queue of jobs to be processed.
- 2.2 No machine may process more than one job at a time.
- 2.3 Each machine is continuously operating in time, i.e., time is not divided into shifts, days or weeks.
- 2.4 Machine breakdowns, manufacturing errors, employee absenteeism, material shortage, design changes and such interruptions are not permitted.
- 2.5 The system is either labor limited or machine limited.

3. Assumptions related to operations

- 3.1 An operation, once started, is performed to its completion; i.e., no pre-emptive priorities are allowed.
- 3.2 Each operation can be performed by only one machine at a time.
- 3.3 Operation processing times are independent of the order in which the operation are performed. In particular, set-up times, if any, are, are included in processing times and are sequence independent.

- 3.4 Each operation of a job must be completed before its succeeding operation can begin i.e., no phase-lapping is allowed.
- 3.5 Transportation times from one machine to another are not allowed or included in processing times.

In spite of the above simplifications it is presumed that the model still retains the essence of a realistic job-shop which is much more complex in nature than the one with assumptions.

Basically, the job-shop model may be viewed as a queueing system involving a network of two or more distinct work centers (servers). Each job is required to be processed by a finite number of machines according to the specified routing. The objective is to schedule the jobs such that a desired criterion is optimized.

The term industrial scheduling is used to refer to the planning of a limited manufacturing capacity to achieve certain goal over a period of time. Such a procedure of planning, a schedule is necessary in order to utilize the limited production capacity effectively. Scheduling can be classified into two categories depending on the time horizon used; namely long-term and short-term scheduling. Planning the gross number of workmen and number and type of machines required to manufacture, say, two turbo generators over a period of one year is an example of long-term scheduling. While planning a number of operators in a job shop on a day-to-day basis is an example of short-term scheduling. This type of scheduling forms the main topic of discussion for this thesis.

It is noted that the terms scheduling, dispatching and sequencing have been used interchangeably by many authors. Each of the above terms

is defined as considered in this thesis. Scheduling is the timing of the operations performed on each machine so as to optimize some desired criteria. However, dispatching is the sequencing of jobs on a facility without taking into consideration the effect of time. Dispatching is also called sequencing.

In order to run a shop effectively, some scheduling rules are required instead of the rules of thumb which have been used for years in actual shops. Scheduling rules help in selecting a job from a number of jobs waiting to be processed on a machine. These rules are also referred to as decision, dispatching, sequencing, loading or priority rules. Some of these rules are called heuristics. Scheduling rules are means of dispatching procedures to generate a schedule.

Scheduling of jobs in a single-channel queueing system has been investigated thoroughly by analytical methods but unfortunately no analytical solutions are reported for network configuration systems.

A number of investigators have therefore resorted to experimental investigations by digital computer simulation. Although simulation does not provide with the optimal solution, it provides some information which could motivate analytical work on network systems. Considerable amount of research along this line has been reported in a summary fashion in Chapter II.

1.2 Proposed Research

The purpose of this research is four-fold.

1. To provide a complete and comprehensive review of the most of the research on job-shop simulation. An effort has been made to form a tabulated summary of simulation experiments including shop characteristics, experimental conditions, scheduling rules, measures of performance and results obtained.

2. To develop a computational procedure for job due-date and evaluate it in comparison to the best procedure proposed by Conway [12].
3. To test the computational efficiency of GASP-II in handling simulation experiments for job-shop situations.
4. To study the effect of the change in the processing time distribution from exponential to Erlang with different parameters. The rules tested are those which have been found by Conway [12], in general, superior than others, namely, shortest imminent operation time [RUL105], remaining job slack time [RUL114], and remaining job slack to remaining number of operation [RUL226].

CHAPTER II

LITERATURE REVIEW

This chapter is devoted to a comprehensive review and summary of most of the research done so far on the performance of the various scheduling rules applicable to job-shop scheduling.

2.1 Scheduling Rules

Scheduling rule may be defined as the procedure by which a job is selected from a queue for scheduling. Although the term "scheduling rule" is used in this paper, the rules may be referred to as sequencing, loading, dispatching, priority, heuristic, or decision rules. Scheduling rules can be classified into various classes depending on the amount and type of information required. Four classes into which the rules can be grouped, are as follows [46]:

1. Local Rule: A local scheduling rule utilizes only the information associated with the jobs in the queue from which a job is to be scheduled next. The status of other machines is not considered while the selection is made.
2. Global Rule: While selecting a job from the queue, a global scheduling rule considers the information available in the queue as well as the status of other machines and also the attributes of jobs waiting in the various queues in the shop.
3. Static Rule: When the assigned priority index does not change with time, the rule is said to be static. For example, first-come first-served and shortest operation processing time rules are static.

4. Dynamic Rule: When the priority of jobs waiting in the queue changes with time, the rule is referred to as a dynamic rule. For example, the scheduling rule in which priority is given inversely proportional to the number of jobs waiting in the queue of the subsequent machine, according to machine ordering, is a dynamic rule.

Various scheduling rules (70 rules) which came to our attention while surveying the previous work, are listed in Appendix A. These rules have been carefully reviewed and defined including mathematical expressions except heuristics.

2.2 Measures of Performance.

Measures of performance are the basic criteria upon which the test of goodness of the rules is based. Two important categories into which these can be classified are [12]: (1) those which are related to the jobs; and (2) those which are related to the shop. However, when a measure of performance is a function of cost, it may be related to attributes of both shop and jobs together. The summary of the various measures of performance which have been most frequently considered in job-shop scheduling research is given below. For convenience, the notation used are summarized below

n	sample size
D_j	due-date of job j
C_j	completion time of job j
L_j	lateness of job j
\bar{L}	mean lateness of late jobs

V_L	variance of lateness
N	number of late jobs
T_j	tardiness of job j
T_c	conditional tardiness
\bar{T}	mean tardiness of jobs
Λ_j	delay factor of job j
\bar{W}	mean job waiting time
F_j	shop flow time of job j
\bar{F}	mean of shop flow times
V_F	variance of shop flow times
$M_b(t)$	number of machines busy at time t
$N(t)$	total number of jobs waiting in queues at time t
$\hat{N}(t)$	total number of jobs in shop at time t
$Q(t)$	total shop work at time t
$Q^*(t)$	total imminent operation work at time t
$\hat{Q}(t)$	total shop work not yet started at time t

I. Job Characteristics

Job characteristics are measures of performance which give information about attributes of jobs such as lateness, waiting time in queues, and shop flow time. The following 16 measures of performance, found mostly in [12, 23, 25], are given below.

NES101: JOB LATENESS

Job lateness is defined as algebraic difference between job completion time and job due-date.

$$l_j = C_j - D_j$$

MES102: JOB TARDINESS

Job tardiness is defined as the positive lateness

$$\begin{aligned} T_j &= \max [0, C_j - D_j] \\ &= \max [0, L_j] \end{aligned}$$

MES103: MEAN LATENESS OF JOBS

$$\bar{L} = \sum_{j=1}^n L_j / n$$

MES104: VARIANCE OF LATENESS OF JOBS

$$V_L = \sum_{j=1}^n \frac{(L_j)^2}{n} - (\bar{L})^2$$

MES105: CONDITIONAL TARDINESS

Conditional tardiness is defined as mean tardiness of all tardy (late) jobs.

$$T_c = \sum_{j=1}^N T_j / N$$

MES106: MEAN TARDINESS OF JOBS

$$\bar{t} = \sum_{j=1}^N T_j / n - \frac{NT_c}{n}$$

MES107: TOTAL NUMBER OF JOBS LATE

Total number of jobs for which lateness is positive.

$$N = \sum_{j \in n} X_j$$

where

$$\begin{aligned} X_j &= 1, & \text{if } L_j > 0 \\ &= 0, & \text{if } L_j \leq 0 \end{aligned}$$

MES108: SHOP FLOW TIME OF JOB

Shop flow time of a job is defined as the difference between the job completion time and the job release time.

$$F_j = C_j - r_{j1}$$

MES109: MEAN SHOP FLOW TIME OF JOBS

$$\bar{F} = \sum_{j=1}^n F_j / n$$

MES110: VARIANCE OF SHOP FLOW TIME OF JOBS

$$V_F = \sum_{j=1}^n F_j^2 / n - (\bar{F})^2$$

MES111: DELAY FACTOR

Delay factor is defined as the ratio of the shop flow time of a job to the sum of its operations processing times.

$$A_j = (C_j - r_{j1}) \sum_{k=1}^{K_j} t_{jk}$$

MES112: PENALTY COST FUNCTION

Penalty cost function is defined as weighted sum of the mean job lateness and the standard deviation of its lateness.

$$Z = a\bar{L} + b\sqrt{V_L}$$

where: a, b cost parameters (constant).

MES113: PENALTY COST FUNCTION BASED JOB LATENESS

Penalty cost function based on job tardiness is defined as the weighted job lateness.

$$P = c (C_j - D_j)$$

where c weighting factor such that

$$c = \begin{cases} c_E, & \text{if } D_j > C_j \\ c_L, & \text{if } D_j < C_j \end{cases}$$

MES114: MEAN JOB WAITING TIME

Mean job waiting time is defined as the time elapsed from the moment job arrives until its processing on a machine starts. This measure of performance is based on all jobs completed during the simulation run.

$$\bar{W} = \frac{1}{n} \sum_{j=1}^n \sum_{k=1}^{K_j} W_{jk}$$

MES115: COST FUNCTION BASED ON TARDINESS

Cost function based on tardiness is defined as the weighted sum of tardiness and the square of tardiness of all jobs.

$$Z = \sum_{j=1}^n K_1 + K_2 T_j + K_3 (T_j)^2$$

where

K_1 , K_2 and K_3 are constants.

MES207: TOTAL OUTSTANDING (REMAINING) SHOP WORK.

Total remaining shop work is defined as the sum of processing times of all operations which have not yet started for all jobs in the shop at time t .

$$\hat{Q}(t) = \sum_{j \in \text{shop}} \sum_{k=\hat{k}}^{K_j} t_{jk}$$

MES208: MEAN TOTAL OUTSTANDING SHOP WORK, $\bar{\hat{Q}}$

MES209: VARIANCE OF TOTAL OUTSTANDING SHOP WORK $V_{\hat{Q}}$

MES210: IMMINENT OPERATION WORK

Imminent operation work is defined as the sum of imminent operation processing times for all jobs in queue at time t .

$$Q^*(t) = \sum_{j \in \text{shop}} t_{j\hat{h}}$$

MES211: MEAN OF IMMINENT OPERATION WORK, \bar{Q}^*

MES212: VARIANCE OF IMMINENT OPERATION WORK V_{Q^*}

MES213: TOTAL NUMBER OF JOBS IN SHOP

Total number of jobs in shop is defined as the sum of all jobs waiting in queues and jobs being processed on machines (busy machine).

$$\hat{N}(t) = N(t) + M_D(t)$$

MES214: MEAN NUMBER OF JOBS IN SHOP, \bar{N}

MES215: VARIANCE OF NUMBER OF JOBS IN SHOP, V_N

MES216: MACHINE IDLE TIME

Machine idle time is defined as the machine time between the completion of an operation and the arrival of the next job for processing one of its operation. It is measured as percentage of total simulation time.

MES116: SUM OF TARDINESS

When the values of constants in the above measure of performance (MES115) are such that $K_1 = K_3 = 0$ and $K_2 = 1$, the above cost function becomes the sum of tardiness of all late jobs such that,

$$Z = \sum_{j=1}^n T_j$$

II Shop Characteristics

Shop characteristics are measures of performances which give information about conditions of the shop at any given time.

MES201: TOTAL NUMBER OF JOBS IN QUEUES

$$N(t) = \sum_{m=1}^M N_{jk}(t)$$

MES202: MEAN NUMBER OF JOBS, \bar{N} MES203: VARIANCE OF NUMBER OF JOBS, V_N MES204: TOTAL SHOP WORK

Total shop work is defined as the sum of processing times of all operations of jobs in the shop at time t .

$$Q(t) = \sum_{j \in \text{shop}} \sum_{k=1}^{K_j} t_{jk}$$

MES205: MEAN SHOP WORK, \bar{Q} MES206: VARIANCE OF SHOP WORK, V_Q

Machines utilization is defined as the ratio of working time of machines to the total available time.

2.3 Simulation Experiments

Considerable experimentations for testing the different scheduling rules have been conducted by several investigators. This section summarizes the experiments which are worth while for consideration before any new experiment should be designed.

The experiments consists mainly of two different natures; (1) machine limited systems; and (2) labor limited systems. Comparatively very little work has been done on labor limited systems. Rowe, Allen and, LeGrande [53, 1, 41] are those who, to the authors knowledge, have investigated such systems. Incidentally, the experiments have been conducted using actual shop settings of General Electric Company, and Hughes Aircraft Company. On the other hand, in the field of machine limited systems, Conway and his associates at Cornell University, have carried out several simulation experiments to study the effects of scheduling rules in job shop. An extensive study has been conducted by Conway [12] at Rand Corporation. In this work 92 scheduling rules has been tested in a maintainance shop of United States Air Force. Following is a list of 16 experiments which were carefully reviewed. The summary of each experiment together with results obtained are described hereunder.

Experiment Number	Investigator	Reference
1	Baker and Dzielinski (1960)	[4]
2	Conway, Johnson and Maxwell (1960)	[17]
3	Kurtani and Nelson (1960)	[40]
4	Conway and Maxwell (1962)	[15]
5	Gere (1962)	[29]
6	LeGrande (1963)	[41]
7	Conway (1964, 65)	[12,16]
8	Carrol (1965)	[11]
9	Orkin (1966)	[52]
10	Oldziej (1966)	[10]
11	Eilon and Hodgson (1967)	[23]
12	Moodie and Roberts (1967)	[45]
13	Neimeier (1967)	[50]
14	Thompson (1967)	[60]
15	Eilon and Cotteril (1968)	[22]

EXPERIMENT 1

INVESTIGATOR Baker and Dzielinski [4]

COMPUTER/PROG. LANG IBM 704/-

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|--------------------------|
| 1. Shop structure | Network of single queues |
| 2. Shop type | Job shop |
| 3. Number of groups | 9 - 30 |
| 4. Number of machines/group | 1 |
| 5. Shop utilization | 80% |

II EXPERIMENTAL CONDITIONS

- | | |
|--|---|
| 1. Distr. of job arrivals | - |
| 2. Distr. of job routings | Uniform |
| 3. Distr. of Number of operations/job. | Normal, \bar{c} = average no. of operations per job is 2 to 10. |
| 4. Distr. of processing time | Negative exponential, $1/\bar{c}$ = mean |
| 5. Number of runs | -- |
| 6. Initial Shop State | Empty |
| 7. Initial number of released jobs | - |
| 8. Run-in length | 10 and 20 unit loads (A unit load: aggregate of jobs involved requires one unit of expected processing time from each facility) |
| 9. Number of jobs considered for collecting statistics | - |
| 10. Run-out length | 5 unit loads |
| 11. Jobs/run or simulation time | -- |
| 12. Due-date multiplier | - |

EXPERIMENT 1 (cont.)

III Scheduling rules: RUL101, 102, 105, 109, 111, 120, 122, 123

IV Measures of performance: MES109

V Results:

1. Job's total expected processing time and the number of processing operations per job had a significant effect at 5% confidence level upon the job's total manufacturing time.
2. If the average of the job's manufacturing time is used as a measure of effectiveness, the simple shortest imminent processing time rule, is the best.

EXPERIMENT 2

INVESTIGATOR Conway, Johnson and Maxwell [17]

COMPUTER/PROG. LANG. IBM 650/-

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|--|
| 1. Shop structure | Network of single queues |
| 2. Shop type | Job shop |
| 3. Number of groups | 5 |
| 4. Number of machines/group | 1 |
| 5. Shop utilization | Light, medium and heavy load with average total processing time of 60, 120, and 200 time units respectively. |

II EXPERIMENTAL CONDITIONS

- | | |
|--|--|
| 1. Distr. of job arrivals | - |
| 2. Distr. of job routings | Expected number of operations on each machine is equal. |
| 3. Distr. of Number of operations/job. | Geometric, $p = \frac{1}{4}$, 7 operations maximum. |
| 4. Distr. of processing time | Total allowable processing time per job is normal |
| 5. Number of runs | - |
| 6. Initial Shop State | Non-empty, depending on shop load |
| 7. Initial number of released jobs | Function of shop load |
| 8. Run-in length | - |
| 9. Number of jobs considered for collecting statistics | 1. First 85 completed jobs
2. First 85 completed jobs + last 15 jobs forced out
3. All 100 jobs completed. |
| 10. Run-out length | 15 jobs |
| 11. Jobs/run or simulation time | 100 jobs |
| 12. Due-date multiplier | - |

EXPERIMENT 2 (cont.)

III Scheduling rules: RUL101, 109, 111, 119, 120, 122, 123
214, 215, 218

IV Measures of performance: MES103, 104, 109

V Results:

1. Next to shortest imminent operation rule (RUL105) least work remaining rule (RUL122) was the best as far as percentage utilization of shop capacity is concerned.
2. Shop capacity utilization is minimum for most work remaining rule (RUL123) at medium load.
3. Rules which depend on monetary value of jobs (RUL214, 215) are the poorest at light and medium load as far as percentage utilization of shop capacity is concerned. However, they were comparable at heavy loads.
4. It is expected that three-class monetary rule (RUL216) would be better than two-class monetary rule.
5. Mean lateness of jobs (MES103) is decreased as the work content of the subsequent queue increases before the queue becomes critical (RUL111). That is, the mean lateness decreases as parameter a increases.

EXPERIMENT 3

INVESTIGATOR Kurtani and Nelson [40]

COMPUTER/PROG. LANG IBM 709/--

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|--------------------|
| 1. Shop structure | Net work of queues |
| 2. Shop type | Job shop |
| 3. Number of groups | 4 and 8 |
| 4. Number of machines/group | 1 in each group |
| 5. Shop utilization | -- |

II EXPERIMENTAL CONDITIONS

- | | |
|--|---------------------------------------|
| 1. Distr. of job arrivals | Poisson and Erlang ($k = 2$) |
| 2. Distr. of job routings | Known probabilistic transition matrix |
| 3. Distr. of Number of operations/job. | -- |
| 4. Distr. of processing time | Exponential and Erlangs ($k = 2$) |
| 5. Number of runs | 256 runs |
| 6. Initial Shop State | Empty |
| 7. Initial number of released jobs | -- |
| 8. Run-in length | -- |
| 9. Number of jobs considered for collecting statistics | 1000 |
| 10. Run-out length | -- |
| 11. Jobs/run or simulation time | 1000 jobs |
| 12. Due-date multiplier | 1, 8 and 17 |

EXPPRIMENT 3 (cont.)

III Scheduling rules: RUL102, 105

IV Measures of performance: MES103, 109

V Results:

1. First in queue first served rule (RUL103) minimizes the maximum flow time of job.
2. Shortest imminent operation rule (RUL105) minimizes average flow time of jobs.

EXPERIMENT 4

INVESTIGATOR Conway and Maxwell [15]

COMPUTER/PROG. LANG.

I SHOP CHARACTERISTICS

1. Shop structure	Network of single queues
2. Shop type	Job shop and flow shop
3. Number of groups	2, 3, 6, and 9
4. Number of machines/group	1
5. Shop utilization	-

II EXPERIMENTAL CONDITIONS

1. Distr. of job arrivals	Number of jobs in shop were kept constant = 2, 4, 6 times number of machines
2. Distr. of job routings	Uniform
3. Distr. of Number of operations/job.	Geometric, mean = M, 9 maximum operations (Job shop)
4. Distr. of processing time	Exponential, mean = 10 time units
5. Number of runs	
6. Initial Shop State	Empty
7. Initial number of released jobs	-
8. Run-in length	-
9. Number of jobs considered for collecting statistics	2000
10. Run-out length	-
11. Jobs/run or simulation time	2000 jobs
12. Due-date multiplier	-

EXPERIMENT 4 (cont.)

III Scheduling rules: RUL106, 108, 111, 221

IV Measures of performance: MES108, 109, 110, 213, 216

V Results:

1. There is little difference between performance in pure job shop and that in pure flow shop.
2. The transition matrix, which determines the probability of subsequent operation of a job on a specific machine, is not a principal determinant of priority rule performance.
3. Longest imminent operation rule (RUL109) maximizes what the shortest imminent operation rule (RUL105) minimizes; however, both the rules have high variance of flow time.
4. Subsequent operation rule (RUL111) exhibited considerably better performance than the random rule but it did not surpass the shortest imminent operation rule.
5. Advantage secured in mean shop flow time of job is directly proportional to the fraction of time the shortest-operation time rule is used in the compound rule of alternating shortest operation and first come first served rule (RUL221).
6. In a system consisting of a network of queues, there is a considerable experimental support to the conjectures that:
 - 6.1 All local priority rules such that each priority class has some expected processing time, are equivalent.
 - 6.2 The shortest operation rule (RUL105) is optimal with respect to the set of all local priority rules.
7. The shortest operation rule (RUL105) appeared to be highly insensitive to errors of estimating processing times.

EXPERIMENT 5

INVESTIGATOR Gere [29]

COMPUTER/PROG. LANG. IBM 709/Fortran

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|---------------------------------|
| 1. Shop structure | Network of single server queues |
| 2. Shop type | Job shop |
| 3. Number of groups | 4 to 16 |
| 4. Number of machines/group | 1 |
| 5. Shop utilization | - |

II EXPERIMENTAL CONDITIONS

- | | |
|--|---|
| 1. Distr. of job arrivals | - |
| 2. Distr. of job routings | - |
| 3. Distr. of Number of operations/job. | - |
| 4. Distr. of processing time | Rectangular, 1 to 10 hrs. per operation |
| 5. Number of runs | - |
| 6. Initial Shop State | Empty |
| 7. Initial number of released jobs | - |
| 8. Run-in length | - |
| 9. Number of jobs considered for collecting statistics | 1. 25 files each having 6-20 jobs.
2. 16 files each having 20-60 jobs. |
| 10. Run-out length | - |
| 11. Jobs/run or simulation time | 1. Static case: 25 files each with 6-20 jobs, 1-16 operations
2. Dynamic case: 16 files each with 20-60 jobs, 1-16 operations. |
| 12. Due-date multiplier | 2 to 4 |

EXPERIMENT 5 (cont.)

III Scheduling rules: RUL101, 103, 105, 114, 207, 208, 209-212, 226, 228, 229

IV Measures of performance: MES102, 105, 115, 116

V Results:

1. Priority rules which considered job slack time (RUL114, 226, 228 and 229) were more effective than the rules in which priority is given at random (RUL101 and 103).
2. If all the jobs have different number of operations, remaining job slack time rule (RUL114) was somewhat better than remaining job slack per operation rule (RUL226). However, when each job has same number of operations there is no significant difference between the two rules.
3. Ratio of modified job slack time to time until due date rule (RUL229) was no more effective than RUL114, for different machine loading.
4. For both static and dynamic problems job slack time rule (RUL114) was significantly more effective than shortest imminent operation rule (RUL105).
5. Non-random rules are significantly more effective than random rules.
6. There is little difference in effectiveness between the rules which use some property of job slack time.
7. The alternate operation and look ahead heuristics are effective, both individually and collectively.

EXPERIMENT 6

INVESTIGATOR LeGraude [41]
 COMPUTER/PROG. LANG. IBM 7090/-

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|---|
| 1. Shop structure | Labour restricted fabrication shop. |
| 2. Shop type | Job shop |
| 3. Number of groups | 115 machine groups & 47 labour classes. |
| 4. Number of machines/group | Total 1000 machines & 400 to 500 men. |
| 5. Shop utilization | Labour utilization of 60-70% |

II EXPERIMENTAL CONDITIONS

- | | |
|--|--|
| 1. Distr. of job arrivals | Known historic data |
| 2. Distr. of job routings | - |
| 3. Distr. of Number of operations/job. | - |
| 4. Distr. of processing time | Negative exponential, mean = mean processing time of machine group concerned |
| 5. Number of runs | - |
| 6. Initial Shop State | - |
| 7. Initial number of released jobs | - |
| 8. Run-in length | - |
| 9. Number of jobs considered for collecting statistics | 3000 jobs |
| 10. Run-out length | - |
| 11. Jobs/run or simulation time | 3000 jobs |
| 12. Due-date multiplier | - |

EXPERIMENT 6 (cont.)

III Scheduling rules: RUL101, 103, 105, 115, 116, 226

IV Measures of performance: MES110,
202, 214, 217

V Results:

1. The order in which the rules were effective, starting with the 'best' rule, was as follows:
 1. Shortest imminent operation (RUL105)
 2. Ratio of remaining job slack to total remaining number of operation (RUL226)
 3. First in queue first served (RUL103)
 4. Earliest start date (RUL115)
 5. Earliest job due date (RUL116)
 6. Random rule (RUL101)
2. The above rating was made under the weighting systems which assigned weights to the different measures of effectiveness. The job completion measures were given the highest weighting factors.

EXPERIMENT 7

INVESTIGATOR Conway [12,16]
 COMPUTER/PROG. LANG. IBM 7090/Simsript

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|---------------------------------|
| 1. Shop structure | Network of single-server queues |
| 2. Shop type | Job shop |
| 3. Number of groups | 9 |
| 4. Number of machines/group | 1 |
| 5. Shop utilization | 90% . |

II EXPERIMENTAL CONDITIONS

- | | |
|--|-----------------------------|
| 1. Distr. of job arrivals | Poisson |
| 2. Distr. of job routings | Uniform (1,M) |
| 3. Distr. of Number of operations/job. | Geometric, $p = 1/M$ |
| 4. Distr. of processing time | Exponential, $\mu = 1$ |
| 5. Shop utilization | 130 |
| 6. Initial Shop State | Empty shop |
| 7. Initial number of released jobs | 50 |
| 8. Run-in length | 400 |
| 9. Number of jobs considered for collecting statistics | 8700 (401 to 9100 serially) |
| 10. Run-out length | 900 |
| 11. Jobs/run or simulation time | 10,000 jobs |
| 12. Due-date multiplier | -- |

EXPERIMENT 7 (cont.)

III Scheduling rules: RUL101 - 106, 108 - 130,
204, 214 - 219, 221 - 226, 231 - 236

IV Measures of performance: MES201, 204, 207, 210

V Results:

1. The shortest imminent operation rule (RUL105) clearly dominates all the other rules. Combination of shortest operation rule with any other rules seems always beneficial.
2. Shortest imminent operation rule is not the best rule with any of the work content measures (MES204 to MES212).
3. The work content measures rules involving processing time factor are the best.
4. For three out of the four methods considered for setting due dates, shortest imminent operation rule caused fewer jobs to be late than any other procedure.
5. The variance of distribution of shop times is smaller for shortest imminent operation rule than for any other basic rule, except first in shop first served rule (RUL102).
6. Shortest imminent operation rule is not sensitive to errors in estimating processing times.
7. Rule in which priority is assigned according to the ratio of remaining slack to remaining number of operations (RUL226) was clearly superior to the other due date dependent rules.
8. Where due dates are assigned at the time of job arrival, an allowance proportional to the total processing time appeared to be better than the other methods.

EXPERIMENT 8

INVESTIGATOR Carrol [11]

COMPUTER/PROC. LANG. -

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|--|
| 1. Shop structure | Assembly shop |
| 2. Shop type | Job shop having single and multiple component jobs |
| 3. Number of groups | 8 |
| 4. Number of machines/group | 1 |
| 5. Shop utilization | 80% |

II EXPERIMENTAL CONDITIONS

- | | |
|--|---|
| 1. Distr. of job arrivals | Poisson |
| 2. Distr. of job routings | -- |
| 3. Distr. of Number of operations/job. | -- |
| 4. Distr. of processing time | Exponential |
| 5. Number of runs | -- |
| 6. Initial Shop State | - |
| 7. Initial number of released jobs | - |
| 8. Run-in length | - |
| 9. Number of jobs considered for collecting statistics | - |
| 10. Run-out length | -- |
| 11. Jobs/run or stimulation time | 1. Single component runs: 3000 orders involving 40,000 tasks
2. Multiple components runs: 2000 orders involving 30,000 to 60,000 tasks |
| 12. Due-date multiplier | - |

EXPERIMENT 8 (cont.)

III Scheduling rules: RUL102, 103, 105, 108,
226, 230

IV Measures of performance: MES103

V Results:

1. Mean job tardiness (MES106) for COVERT rule was less as compared to truncated shortest imminent operation rule (RUL108)
2. With COVERT the distribution of job lateness is skewed such that jobs completed on the due dates are the mode of the distribution with very few late jobs.
3. At different shop utilization levels and with different flow allowance there was no significant difference in the performance of COVERT rule.

EXPERIMENT 9

INVESTIGATOR Orkin [52]

COMPUTER/PROG. LANG. CDC - 1604/Fortran 63, Codap - 1

I SHOP CHARACTERISTICS

1. Shop structure	Network of single server queues
2. Shop type	Job shop
3. Number of groups	8
4. Number of machines/group	1
5. Shop utilization	90%

II EXPERIMENTAL CONDITIONS

1. Distr. of job arrivals	Interarrival: Geometric
2. Distr. of job routings	Uniform
3. Distr. of Number of operations/job.	Geometric, $p = 1/8$
4. Distr. of processing time	Geometric, $p = 1/4$
5. Number of runs	-
6. Initial Shop State	Empty
7. Initial number of released jobs	15
8. Run-in length	215
9. Number of jobs considered for collecting statistics	6000
10. Run-out length	-
11. Jobs/run or simulation time	6215 jobs
12. Due-date multiplier	5 and 9

EXPERIMENT 9 (cont.)

III Scheduling rules: RUL103, 105, 113, 116, 117,
203, 226, 239

IV Measures of performance: MES105, 106, 107, 109, 110

V Results:

1. Setting operation due dates proportional to processing time results significantly lower values of mean job tardiness than setting equally spaced operation due dates.

EXPERIMENT 10

INVESTIGATOR Oldziej [51]

COMPUTER/PROG. LANG. CDC - 1604/LPF, Codap 1

I SHOP CHARACTERISTICS

- 1. Shop structure Network of single server queueing process
- 2. Shop type Job shop
- 3. Number of groups 8
- 4. Number of machines/group 1
- 5. 90%

II EXPERIMENTAL CONDITIONS

- 1. Distr. of job arrivals Geometric interarrival
- 2. Distr. of job routings Uniform
- 3. Distr. of Number of operations/job. Geometric, $p = 1/8$; max of 63 operations per job.
- 4. Distr. of processing time Geometric, $p = 1/4$
- 5. Number of runs
- 6. Initial Shop State Empty
- 7. Initial number of released jobs 15 (for sample size of 6000), 50 (for sample size of 2000)
- 8. Run-in length 200
- 9. Number of jobs considered for collecting statistics 2000 (201st to 2200th) and 6000 (201st to 6200th)
- 10. Run-out length 300
- 11. Jobs/run or simulation time 2500 jobs (flow factor = 6), 6500 (flow factor = 5)
- 12. Due-date multiplier 4,5,6

EXPERIMENT 10 (cont.)

- III Scheduling rules: RUL101, 103, 105, 116,
201, 202, 203, 206, 237, 238
- IV Measures of performance: MES103, 104, 106, 107, 110
- V Results:

1. Sum of operation slack time and weighted operation processing time rule (RUL238) with weighting factor of 15 reduced mean job tardiness to half that of shortest operation rule (RUL105) while reducing variance of lateness of jobs to less than 1/3 the value obtained with shortest operation rule.
2. RUL201 improved the measure of mean tardiness marginally over that of RUL238.
3. RUL239 showed better performance over RUL201 and RUL238 by the inclusion of load smoothing factor, $c_{j,k+1}^0(t)$.

EXPERIMENT 11

INVESTIGATOR Eilon and Hodgson [23]

COMPUTER/PROG. LANG. -

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|--|
| 1. Shop structure | A queing system of two identical servers in parallel |
| 2. Shop type | Parallal processor shop with single queue |
| 3. Number of groups | Two in parallal |
| 4. Number of machines/group | 1 |
| 5. Shop utilization | $\rho = 0.5, 0.6, 0.7, 0.8, 0.9$ |

II EXPERIMENTAL CONDITIONS

- | | |
|--|-----------------------------------|
| 1. Distr. of job arrivals | Poisson |
| 2. Distr. of job routings | - |
| 3. Distr. of Number of operations/job. | Each job requires one operation |
| 4. Distr. of processing time | Negative exponential distribution |
| 5. Number of runs | - |
| 6. Initial Shop State | Empty |
| 7. Initial number of released jobs | - |
| 8. Run-in length | 100 |
| 9. Number of jobs considered for collecting statistics | 1300 |
| 10. Run-out length | 100 |
| 11. Jobs/run or simulation time | 2000 jobs |
| 12. Due-date multiplier | - |

EXPERIMENT 11 (cont.)

III Scheduling rules: RUL101, 103, 105, 109, 116

IV Measures of performance: MES101, 107, 108, 111, 113, 114, 117,
201, 216

V Results:

1. With respect to the measure of mean and standard deviation of job waiting times, it was shown that shortest imminent operation rule performed the best and longest imminent operation rule (RUL109) performed the poorest.
2. For job due date multiplier of 8, the results of job due date rule (RUL116) was close to shortest operation rule.
3. The performance measures of job flow time, facility idle time and job delay factor are independent of loading rules but dependent on the load ratio (ρ) of the system.
4. Shortest operation rule was considered the best for minimizing measures of job waiting times, flow times, machine idle time, delay factor and queue lengths.

EXPERIMENT 12

INVESTIGATOR Moodie and Roberts [45]

COMPUTER/PROC. LANG. IBM 7094/GPSS III

I SHOP CHARACTERISTICS

1. Shop structure	Identical servers with single queue
2. Shop type	Parallal processor shop
3. Number of groups	24
4. Number of machines/group	1
5. Shop utilization	-

II EXPERIMENTAL CONDITIONS

1. Distr. of job arrivals	Known historic distribution, arrival rate = 10, 11, 12
2. Distr. of job routings	-
3. Distr. of Number of operations/job.	Number of operations per job is consistant
4. Distr. of processing time	Known historic distribution
5. Number of runs	
6. Initial Shop State	Empty
7. Initial number of released jobs	-
8. Run-in length	-
9. Number of jobs considered for collecting statistics	-
10. Run-out length	-
11. Jobs/run or simulation time	480 minutes per day; 365 days
12. Due-date multiplier	-

EXPERIMENT 12 (cont.)

III Scheduling rules: RUL103, 105, 114, 116, 240

IV Measures of performance: MES102, 103, 104, 106, 107

V Results:

1. Job due date rule (RUL116) failed to minimize the maximum lateness in a parallal processor shop.
2. The weighted objective rule (RUL240) showed remarkable consistency for changing shop loads.
3. Mean job tardiness seemed to be best minimized by remaining job slack time rule (RUL114) and weighted objective rule, but for highly loaded shop shortest operation (RUL105) and weighted objective rule were the best.

EXPERIMENT 13

INVESTIGATOR McIner [50]

COMPUTER/PROG. LANG. CDC 1604/CIP (Cornell list processor)

I SHOP CHARACTERISTICS

1. Shop structure	Network of single queues
2. Shop type	Job shop with alternating routing
3. Number of groups	9
4. Number of machines/group	1
5. Shop utilization	90%

II EXPERIMENTAL CONDITIONS

1. Distr. of job arrivals	Poisson, mean interarrival = 1.09
2. Distr. of job routings	Uniform
3. Distr. of Number of operations/job.	Geometric, $p = 1/9$
4. Distr. of processing time	Exponential, mean = 0.96
5. Number of runs	-
6. Initial Shop State	Empty
7. Initial number of released jobs	50 jobs
8. Run-in length	40, 200, 400 time units corresponding to short, medium and long run
9. Number of jobs considered for collecting statistics	After every 30 time units
10. Run-out length	-
11. Jobs/run or simulation time	1200, 5000, 10000 time units corresponding to short, medium and long run
12. Due-date multiplier	-

EXPERIMENT 13 (cont.)

III Scheduling rules: RUL102, 105

IV Measures of performance: MES108,
201, 216

V Results:

1. Alternative routing could be profitably employed in a job shop under first in queue first served rule.
2. There was greater improvement in performance under the first come first served rule (RUL103) than under shortest operation rule (RUL105), with introduction of alternative routing.
3. Alternative routing with the selection of machine with least number of waiting jobs had slightly better performance than that of selecting the machine with least amount of work in queue.

EXPLRIMENT 14

INVESTIGATOR Thompson [60]
 COMPUTER/PROG. LANG. CDC 3400/CASP LI

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|-------------------|
| 1. Shop structure | Assembly job shop |
| 2. Shop type | Job shop |
| 3. Number of groups | 20 |
| 4. Number of machines/group | 1 |
| 5. Shop utilization | 75% |

II EXPERIMENTAL CONDITIONS

- | | |
|--|---|
| 1. Distr. of job arrivals | Poisson $\lambda = 20$ products per day |
| 2. Distr. of job routings | |
| 3. Distr. of Number of operations/job. | Triangular, mean = 15, range = 10 to 20 |
| 4. Distr. of processing time | Exponential, mean = 0.1 day |
| 5. Number of runs | 37 |
| 6. Initial Shop State | Empty |
| 7. Initial number of released jobs | - |
| 8. Run-in length | 100 |
| 9. Number of jobs considered for collecting statistics | 300 |
| 10. Run-out length | - |
| 11. Jobs/run or simulation time | 400 jobs |
| 12. Due-date multiplier | - |

EXPERIMENT 14 (cont.)

III Scheduling rules: RUL102, 105, 119, 206

IV Measures of performance: MES108

V Results:

1. Performance of maximum number of operation remaining rule (RUL119) was as well or better than any of the rules tested for assembly job shop, however no optimality can be guaranteed.

EXPRIMENT 15

INVESTIGATOR Eilon and Cotterill [22]

COMPUTER/PROG. LANG. IBM 7090/-

I SHOP CHARACTERISTICS

1. Shop structure	Network of queues
2. Shop type	Job shop
3. Number of groups	4
4. Number of machines/group	1
5. Shop utilization	$\rho = 0.4, 0.5, 0.6, 0.7, 0.8$

II EXPERIMENTAL CONDITIONS

1. Distr. of job arrivals	Poisson
2. Distr. of job routings	Random
3. Distr. of Number of operations/job.	Rectangular distribution number of operation
4. Distr. of processing time	Negative exponential per job two to four
5. Number of runs	-
6. Initial Shop State	Empty
7. Initial number of released jobs	-
8. Run-in length	-
9. Number of jobs considered for collecting statistics	5000 jobs
10. Run-out length	-
11. Jobs/run or simulation time	5000 completed jobs
12. Due-date multiplier	-

EXPERIMENT 15 (cont.)

III Scheduling rules: RUL103, 105, 107-109, 116, 122-124
206, 210, 220

IV Measures of performance: MES101, 108, 111, 113, 114

V Results:

1. The difference between performance of various loading rules become increasingly pronounced as the load ratio increases, the shortest operation rule (RUL105) being more effective than first come first served (RUL103) and longest operation rule (RUL107).
2. The shortest operation rule performs best with several criteria, but not for minimizing the variance of flow times or lateness of jobs.
3. The total simulation run time (for completing 5000 jobs) and machine idle time depend on the load ratio (ρ) but not on the loading rules.

CHAPTER III

SIMULATION MODEL

This chapter deals with the discussion of the job-shop model on which our experiments are based. The system description, experimental conditions, scheduling rules and the measures of performance are described in detail below. The simulation computer program together with the purpose of the subroutines and the definition of the program variables is presented in Appendix C. A general, flow chart of the job-shop simulation is given in Figure 3.1.

3.1 Model Description

The job-shop considered in this paper is a network of single-server queues in which a job may join all or a subset of queues, waiting to be served at different machine groups. Each machine group is an independent work center. All machines in a particular group are identical as far as the type of work to be performed on a job is concerned. In other words, jobs waiting at any machine group form a single queue and are processed on any of the machine which becomes idle first.

In operating such system, the utilization of the shop may be assured. The utilization of the shop may be discussed as follows. Each time a job is processed on a machine, its services are utilized and the machine is said to be busy, otherwise it remains idle. Hence, the utilization of a machine can be defined as the ratio of the total busy time of that machine to the total time for which it has been available. The utilization of the shop, as a whole, is the average of the utilizations

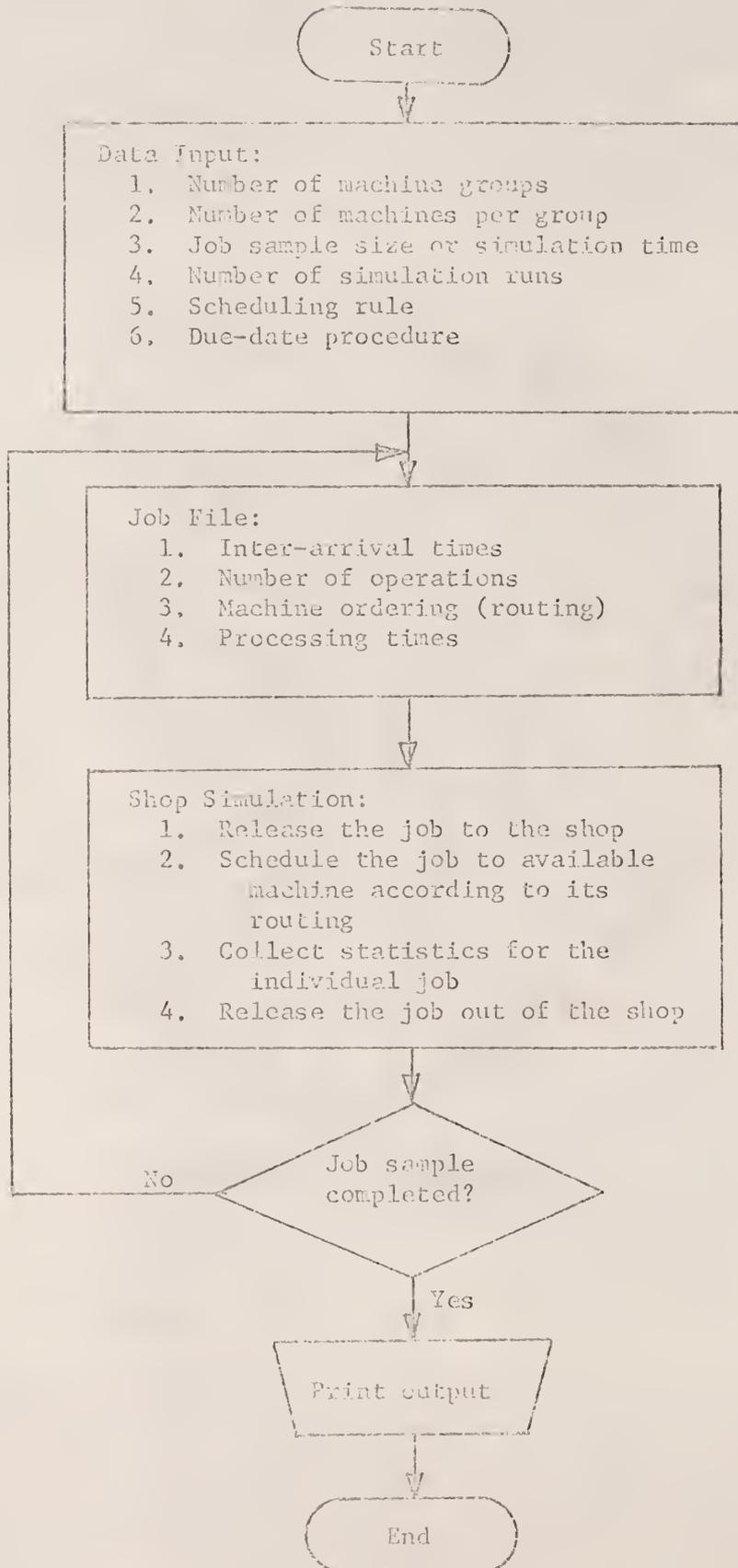


Figure 3.1 General simulation flow chart

of individual machines. For a network system of job-shop, the utilization, called load ratio in [22], can be defined such that

$$U = \frac{n\bar{t}}{MT}$$

where

- U utilization of the shop
- n job sample size
- \bar{t} mean processing time per job
- M total number of machines in the shop
- T total simulated run time

In summary, the shop characteristics considered in this investigation are:

- | | |
|---------------------------------|--------------------------|
| 1. Shop structure: | Network of single-queues |
| 2. Shop type: | Job-shop |
| 3. Number of machine groups: | 9 |
| 4. Number of machine per group: | 1 |
| 5. Utilization of shop: | $\approx 93\%$ |

3.2 Experimental Conditions

In order to perform a simulation experiment, certain conditions have to be specified. The following conditions are considered in our experiments.

1. Job Arrivals: At a time, only one job is released to the shop. The inter-arrivals of jobs are obtained from an exponential distribution. However, Erlang distributions with different parameters are also used in other experiments. The exponential mean inter-arrival time was fixed at 1.0 time units, similar to [12] so that comparison of the results can be made.

2. Job Routing: On arrivals, each job is equally likely to start its first operation on any of the machines in the shop. Furthermore, if the job has more than one operation, it has equal probability of starting its next operation on any of the remaining machines in the shop. Therefore, the machine ordering of each job is generated randomly from a uniform distribution [1,9]. In other words, all elements of the machine ordering matrix have equal probability value $1/9$.

3. Number of Operations Per Job: Since each job may be processed more than once on a certain machine, the number of operations for each job has to be determined. In our experiments, the distribution of the number of operations per job j is governed by the following distribution:

$$P(K_j) = p(1-p)^{K_j-1}, \quad K_j = 1, 2, \dots$$

The above probability function represents a geometric distribution with mean equal to $1/p$ or 9, where 9 is the total number of machines in the shop. Each job is allowed to have at the most 12 operations.

4. Processing Times: In some experiments the processing times of operations are obtained from an exponential distribution. The mean of the distribution is such that the desired shop utilization is obtained. However, Erlang distributions with different parameters are also used in other experiments.

5. Number of Runs: Each rule is tested for one simulation run. To gain more knowledge about the effectiveness of any rule, it is preferred to have more runs each of which has different sets of jobs. The lack of computer time available is the main factor for considering only one run per rule.

6. Initial Shop State: Before conducting any simulation experiment, it is necessary to place the shop in some more realistic initial state. In initiating an experiment, one of the methods is to assume an empty shop. However, this directly affects the length of the run, which should be long enough to obtain representative results of the steady state conditions. A more desired procedure would be to start the shop with steady state conditions, after they have been known from some initial experimental results. For the sake of simplicity, the shop considered here starts empty as has been assumed in [22, 23, 25].

7. Initial Number of Release Jobs: There are no released jobs when the shop is started; however, the loading of the shop could be accelerated. Eilon and Cotteril [22] has reported that the initial number of release jobs has very little effect on reaching the steady state conditions.

8. Run-In Length: Since the shop starts in an empty state, a certain time period is necessary before it reaches the steady state. Any statistics collected during this transient period are likely to be not representative. Unfortunately, there is no practical analytical method available by which steady state condition could be determined beforehand. Hence one has to depend on the initial experiments which have to be conducted mainly in order to gain an insight in the stability of the system. For determining the steady state conditions for our experiments, the absolute differences between mean inter-arrivals and mean inter-departures are computed sequentially. The steady state is considered to have started when such difference is nearly vanished. The number of jobs after which the steady state

condition can be started is determined for each experiment by plotting the graph of inter-arrival and inter-departure times of the jobs, see Chapter IV.

9. Number of Jobs Considered for Collecting Statistics: As mentioned earlier, for consistent results one should run the simulation experiment for long runs. A long run neutralizes the effects of assuming wrong initial shop conditions. To compromise between the computer time and the consistency desired in results, statistics are collected at every 100 jobs departed from the shop. The final statistics are also collected at the end of the run.

10. Run-Out Length: Run-out length is necessary to remove the effect of uncompleted jobs, specially in the rules which give preference to the last operation of the jobs. Performance of such rules is greatly affected, if at the end of the experiment there are many jobs waiting for their last operations. Since the rules considered do not fall into the above category, no run-out length is allowed in this investigation. Also this is supported by previous investigations [22, 25] which have showed that assumptions of no run-out period are not serious to affect the accuracy of the analysis.

11. Jobs Per Run: To limit the computer time within 30 minutes for each run, the sample size of each run is 1300 departed jobs.

12. Due-Date Multiplier: Before a job is released to the shop, a due-date is determined. Four methods of assigning such due-date have been proposed by Conway [12]. These are:

1. Allowance proportional to the total work to be done on the job

$$D_j = r_{j1} + 9 \sum_{k=1}^{K_j} t_{jk}$$

Although Conway has not mentioned the reason for determining the value of the constant 9, we believe that it is the total number of machines in the shop.

2. Allowance proportional to the number of operations on the job.

$$D_j = r_{j1} + 8.883 K_j$$

3. Constant allowance

$$D_j = r_{j1} + 78.7985$$

4. Random allowance

$$D_j = r_{j1} + 157.597X_j$$

where

- D_j due date of job j
- r_{j1} ready time of job j for operation 1
- K_j the number of operations on job j
- t_{jk} the processing time of job j for operation k
- X_j a random variable for job j

It has been found in [12] that assigning due-dates by the first method is superior to any other methods. In this paper, a new method of assigning due-date is proposed which is expressed such that

$$D_j = r_{j1} + K_j \sum_{k=1}^{K_j} t_{jk}$$

It differs from the first method in the sense that the allowance is proportional to the number of operations as well as the total work to be done on the job. In method 1., the allowance is computed by multiplying the total work content of the jobs by the number of machine groups regardless to the number of operations to be performed on the job. This proposed method is considered to be more logical, since for the same total work content; the job which has a greater number of operations is more likely to be late than the one which has fewer operations. Accordingly, the job with the larger number of operations should be given the greater allowance.

3.3 Scheduling Rules:

Since one of the purpose of this investigation is to test the method of assigning due-dates as described earlier, due-date rules are considered. The following due-date rules are tested together with the first-in-queue first-served and shortest imminent operation time rules.

1. Shortest imminent operation time rule (RUL105): Select from the queue of waiting jobs, the job which will occupy the machine for the minimum period of time,

$$R_j(t) = t_{jk}^{\wedge}$$

2. First-in-queue first-served rule (RUL103): Select the job which has the earliest arrival time at the queue,

$$R_j(t) = r_{jk}^{\wedge}$$

3. Earliest job due-date rule (RUL116): Select first the job which has the earliest job due-date,

$$r_j(t) = D_j .$$

4. Remining job slack time rule (RUL114): Select first the job which has the minimum free time left after all its remaining operation times are deducted from its due-date,

$$R_j(t) = D_j - t - \sum_{k=\hat{k}}^{K_j} t_{jk} .$$

5. Remaining job slack time per remaining operations (RUL226): Select first the job which has minimum free time left per operation,

$$R_j(t) = \frac{D_j - t - \sum_{k=\hat{k}}^{K_j} t_{jk}}{K_j - \hat{k} + 1} .$$

3.4 Measures of Performance:

The choice of measures of performance depends mainly on the rules to be evaluated. As the last three rules considered are job due-date rules, the measures of performance adopted should indicate the deviation of jobs completion time from the pre-planned due-date. Lateness of job, job flow time and number of jobs which were behind their due-date are examples of such measures which are considered in our experiments. Shop characteristics such as utilization of shop and average number of jobs in the shop are also computed. To summarize, the following measures of performance are considered:

1. Job lateness
2. Average shop flow time of job
3. Number of jobs late
4. Average number of jobs in the shop
5. Utilization of the shop

The next chapter is devoted to the discussion of the results and their analyses.

CHAPTER IV

SIMULATION RESULTS

This chapter is devoted to the results of three different experiments totalling 14 simulation runs. A representative results of a particular simulation run is presented in Appendix B along with the graphs which show the convergence of the inter-arrivals and inter-departures in order to determine the steady state condition for each run. The results of all the simulation runs pertaining to each experiment are summarized separately in a tabular form.

4.1 Experiment I

The purpose of this experiment is to compare the results of this investigation to the results obtained by Conway [12] under nearly the same set of experimental conditions. The two main differences are (1) the consideration of a sample size of 1000 jobs instead of 10,000 jobs; and (2) the setting of the upper limit of the number of operations per job as 12 instead of 39. Experiment I is necessary in order to compare the results of experiment II in which the new procedure of determining the job due-date is evaluated. For convenience, the results obtained from Conway [12] for the five scheduling rules under test in this paper are displayed in Table 4.1.

In order to determine the number of departed jobs at which the shop reaches the steady state conditions, the grand averages of the inter-arrivals and inter-departures of the jobs are plotted in Figures 5-1 through 5-5 for each rule tested. It is found that regardless of the rule, the shop reaches the steady state conditions

Table 4.1

Results Obtained from Conway's Experiment

Scheduling rule	Lateness		Shop flow times		Number of jobs late	Average number of jobs in queues
	Mean	Std. Dev.	Mean	Std. Dev.		
FCFS (RUL103)	-4.49	41.1	74.43	75.8	3898	58.87
S/OPN (RUL105)	-44.9	53.7	34.02	48.2	437	23.25
SLACK (RUL114)	-13.13	20.8	65.79	80.8	1916	51.25
DDATE (RUL116)	-15.53	20.8	63.72	82.4	1544	49.45
S/OPN (RUL226)	-12.79	15.0	66.13	73.8	323	51.65

after approximately 300 jobs have departed from the shop. Hence the statistics are collected after the departure of 299th job and until 1300 jobs have departed from the shop. Table 4.2 presents the results of the five rules tested in this experiment.

Table 4.2

Results of Experiment I

Scheduling rule	Lateness		Shop flow times		Number of jobs late	Average number of jobs in the shop
	Mean	Std. Dev.	Mean	Std. Dev.		
FCFS (RUL103)	-36.34	25.82	9.26	5.72	7	11.30
S/OPN (RUL105)	-37.30	25.22	8.39	6.17	0	10.35
SLACK (RUL114)	-35.38	23.12	8.12	6.89	0	10.06
DDATE (RUL116)	-35.34	25.41	8.01	6.72	0	9.90
S/OPN (RUL226)	-34.79	24.48	8.51	5.98	10	10.46

Note that the last column in both tables is different.

Significant results have been obtained from the above experiment. These are summarized as below:

1. The shortest imminent operation rule (RUL105) is no doubt the best of all the rules tested in reducing the lateness of a job. The negative value of lateness indicates that the job is completed earlier than the due-date, see Table 4.2.
2. The slack time rule (RUL114) and the earliest job due-date rule (RUL116) are equally good in reducing the lateness. The difference between the mean lateness is negligible to conclude the superiority of one over the other, see Table 4.2.
3. In comparing the results of Tables 4.1 and 4.2, it is revealed that the numbers of jobs late under all rules tested are much larger in Conway's experiment than those in ours. This is because the maximum number of operations per job is 39 compared to ours which is 12. Hence due to this truncation the mean number of operations per job is approximately 4.2 instead of the theoretical mean of 9.
4. The mean shop flow time of the jobs under first-come first-served rule (RUL103) is much higher than that of the shortest imminent operation rule (RUL105) as has also been shown by Conway [12]. However in this respect the earliest job due-date rule (RUL116) surpassed all the rules tested. Furthermore, the mean shop flow time under the job slack time rule (RUL114) is very close to that obtained by the earliest job due-date rule.
5. The standard deviation of shop flow times is not proportional to the mean of the shop flow time. This is also shown by Conway [12].

6. Even though the shortest imminent operation rule is the best in minimizing the mean job lateness, it keeps long jobs waiting for much longer times in the queues than most of the other rules tested. This is evident from the fact that the maximum shop flow time encountered under this rule is the second highest (the first being under the slack time per remaining number of operations). The reason for this is that the shortest operation rule selects the shortest job first from the queue of waiting jobs. The maximum time that a job waits in the shop is shown below for each rule tested:

Scheduling rule	Maximum time in shop
FCFS(RUL103)	27.43
SHOPN(RUL105)	36.67
SLACK(RUL114)	35.51
DDATE(RUL116)	35.38
S/OPN(RUL226)	38.18

7. As mentioned earlier, the condition of the shop is reflected by the measure of the average number of jobs in the shop. The due-date rule is the best of all rules tested in having few jobs in the shop. The shortest imminent operation rule ranks the third; however, the difference is insignificant to conclude that it is inferior to the due-date rule. The first-come first-served rule has on the average the maximum number of jobs waiting in the shop. This is in agreement with the results obtained in [12].

4.2 Experiment II

The purpose for conducting Experiment II is to test the new procedure of assigning due-dates as proposed in Chapter III. All the experimental conditions of this experiment are exactly the same as those of Experiment I, which serves as the basis for comparison of the results obtained.

As before, the graphs of inter-arrivals and inter-departures are plotted separately for each rule in Figures B-6 through B-10, Appendix B. These graphs show that the new procedure of assigning due-dates have no effect on the shop in reaching the steady state conditions. The shop is completely free from the initial transient effects when approximately 300 jobs have departed from the shop. Table 4.3 displays the results obtained from this experiment.

Table 4.3

Results of Experiment II

Scheduling rule	Lateness		Shop flow times		Number of jobs late	Average number of jobs in the shop
	Mean	Std. Dev.	Mean	Std. Dev.		
FCFS (RUL103)	-35.33	40.08	8.22	5.22	185	10.13
SHOPN (RUL105)	-36.04	39.64	7.60	5.49	78	9.47
SLACK (RUL114)	-35.63	38.23	8.23	7.13	40	10.19
DDATE (RUL116)	-35.51	38.15	8.19	7.05	44	10.12
S/OPN (RUL226)	-35.02	39.87	8.53	5.92	178	10.49

A summary of conclusions drawn is given below:

1. In general, the mean lateness of jobs under the new procedure of assigning due-dates has very little effect, an increase of less than 2% on all the rules tested.
2. In comparing the results in Tables 4.2 and 4.3, it is observed that the numbers of jobs completed late are larger in Experiment II than those in Experiment I. This shows that the new procedure proposed produces the condition of tight job due-dates in comparison to the procedure in which the allowance is computed as fixed multiple (equal to number of machine) of work content of job, see Experiment I.
3. The standard deviation of job lateness is increased by 60% more than that obtained in Experiment I.
4. The mean shop flow times for the non-due-date rules is reduced by 10% than those obtained in Experiment I.
5. The due-date rules are not significantly affected by the new procedure of assigning due-dates. The mean of shop flow times are increased by less than 1%.
6. The due-date rules are not much sensitive to the new procedure as far as standard deviation of shop flow times is concerned. The slack per remaining number of operation rule (RUL226) is the least sensitive among all due-date rules.
7. The non-due-date rules gained much in reducing the standard deviation of the distribution of shop flow times. The reduction is approximately 10% in both rules.

4.3 Experiment III

The purpose of this experiment is to study the effect of different processing time distributions on the performance of the above rules. The two different distributions selected are Erlang 4 and Erlang 8. Due to the lack of the computer time, it was necessary to collect the final statistics after 600 jobs had departed from the shop. The remaining experimental conditions are the same as those of Experiment I. The graphs of inter-arrivals and inter-departures are plotted in Figures B-11 through B-14. It is observed that under the shortest operation rule, the shop reaches steady state condition at approximately the same stage as it did in the previous two experiments. However, the steady state can not be predicted in the case of the slack per remaining operation rule. This is mainly because of small job sample. The results of this experiment are summarized below:

Table 4.4

Results of Experiment III

Scheduling rule	Lateness		Shop flow time		Number of jobs late	Average number of jobs in the shop
	Mean	Std. Dev.	Mean	Std. Dev.		
SHOPN(ERL.4)	17.81	29.99	92.08	63.18	273	89.01
SHOPN(ERL.8)	1.5	20.34	72.92	48.87	196	72.11
S/GPN(ERL.8)	365.3	115.2	447.1	127.8	500	374.68

The interesting results are summarized below.

1. The graphs of inter-arrivals and inter-departures show that even after 600 jobs have departed from the shop, the curves are not as close as they are in the case of Experiment I. This is logical since with the increase of the value of the parameter K of Erlang distribution, the processing times are increased. Hence more jobs arrive in the shop than those departed. Consequently an explosion could take place in the shop.

2. The shortest imminent operation rule is more effective in the case of Erlang 8 than that of Erlang 4.

3. In general, the performances of the rules are poorer than those obtained when the exponential processing times are assumed.

CHAPTER V

SUMMARY AND CONCLUSIONS

The job-shop simulation is a process in which different scheduling rules under different experimental conditions are evaluated. A simulation model can nearly duplicate the conditions prevailing in real time job-shops. The purpose of this thesis is to (1) present a consistent and more comprehensive review of the most important job-shop simulation experiments conducted since 1960; (2) develop a method of assigning job due-dates, and testing it; (3) evaluate the efficiency of GASP-II in handling simulation experiments; and (4) study the effect of different processing time distribution on the performance of the rules.

The design of the simulation model is influenced by the work of Conway [12], since it is necessary to compare the results on the basis of same experimental conditions. However, limitation of computer times has been a deciding factor which influenced the experimental conditions in the present investigation. A summary of this experimental investigation, referred to as Experiment 16, along with the results obtained are presented in the next page.

GASP-II can efficiently handle job-shop problems of the size as big as 1500 jobs and 9 machines. The average computer execution time for a simulation run of 1300 departed jobs (corresponding to 1500 arrived jobs) is approximately 20 minutes.

EXPERIMENT 16

INVESTIGATOR Present Thesis
 COMPUTER/PROG. LANG. IBM System 360/50 - GASP-II

I SHOP CHARACTERISTICS

- | | |
|-----------------------------|--------------------------|
| 1. Shop structure | Network of single queues |
| 2. Shop type | Job shop |
| 3. Number of groups | 9 |
| 4. Number of machines/group | 1 |
| 5. Shop utilization | ≈93% |

II EXPERIMENTAL CONDITIONS

- | | |
|--|---|
| 1. Distr. of job arrivals | Exponential inter-arrivals, mean = 1.0 |
| 2. Distr. of job routings | Uniform [1,9] |
| 3. Distr. of Number of operations/job. | Geometric [4,12] with mean = 9, |
| 4. Distr. of processing time | Erlang (K=1,4,8), mean = 0.8 |
| 5. Shop utilization | 1 |
| 6. Initial Shop State | Empty |
| 7. Initial number of released jobs | - |
| 8. Run-in length | -- |
| 9. Number of jobs considered for collecting statistics | Intermediate statistics are collected after every 100 jobs are departed. Final statistics are collected after 1300 departed jobs; however, in the case of Erlang 4 and 8 it is 600 departed jobs. |
| 10. Run-out length | - |
| 11. Jobs/run or simulation time | 1300 and 600 departed jobs |
| 12. Due-date multiplier | 1. Proportional to work content of job
2. Proportional to work content and number of operations/job. |

EXPERIMENT 16 (Contd.)

III. Scheduling rules: RUL103, 105, 114, 116, 226

IV. Measures of performance: MES101, 104, 109, 110, 201

V. Results:

1. The shortest imminent operation rule (RUL105) is superior to others in reducing job lateness and shop flow time.
2. The procedure in which the due-date allowance is proportional to the number of operations and work content of the jobs has proved to be beneficial in the case of the non-due-date rules such as first-come first-served and shortest imminent operation time rules. However, there is no effect on the performance of due-date rules (RUL114, 116, 226).
3. The performance of the shortest imminent operation time and slack per remaining number of operations rules are affected badly with the use of the processing time distributions of Erlang with parameter K equaling 4 and 8. However, the performances under Erlang 8 are better than those obtained under Erlang 4.
4. The GASP-II works equally good for large size of shop problems. The simulation computer execution time of runs; ranging from 600 to 1300 departed jobs, varies from 18 to 23 minutes depending on the rules tested.

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APPENDIX A

SCHEDULING RULES

This appendix includes almost a comprehensive list of scheduling rules along with the corresponding definitions and mathematical expressions. An effort has been made to classify these rules into local static (LS), local dynamic (LD), global static (GS), and global dynamic (GD) types; however, it is very difficult to be conclusive.

NOTATION

j	job index; $j = 1, 2, \dots, J$
\hat{j}	particular job
K_j	total number of operations for job j
k	operation index for a job j , $k = 1, 2, \dots, K_j$
\hat{k}	particular operation
M	total number of machines
m	machine index; $m = 1, 2, \dots, M$
n	sample size
$R_j(t)$	priority index of job j at time t
t_{jk}	processing time of job j for operation k
D_j	due date of job j
D_{jk}	due date of job j for operation k
r_{jk}	ready time of job j for operation k
r_{j1}	time at which job j arrived at shop
$N_{jk}(t)$	number of jobs in queue while job j is ready for its operation k at time t
$Q_{jk}(t)$	total work content of a queue while job j is ready for its operation k at time t
$\bar{Q}_{jk}(t)$	total expected work content of a queue while job j is ready for its operation k at time t

- s_j slack time of job j
- X_{jk} random variable assigned to job j for operation k
- W_{jk} expected waiting time of job j for operation k
- V_j monetary value of job j

RUL101: RANDOM RULE (LS)

Schedule next the job which has the lowest value of a random priority index. The priority value are assigned randomly as each new job joins the queue before a machine.

$$R_j(t) = X_{jk} \hat{k}$$

RUL102: FIRST IN SHOP FIRST SERVED (LS)

Schedule next the job which has the earliest arrival date at the shop. The priority numbers are given in increasing order as the job arrive in the shop. The job which has the lowest priority number is scheduled next.

$$R_j(t) = r_{j1}$$

RUL103: FIRST IN QUEUE FIRST SERVED (LS)

Schedule next the job which entered the queue first. The priority numbers are given in increasing order as each job arrives at machine. The job having lowest value of priority number is scheduled first.

$$R_j(t) = r_{jk} \hat{k}$$

RULE 104: FIRST COME IN QUEUE FIRST SERVED WITH SHORTEST OPERATION
OVERLOAD PROTECTION (LS)

Schedule next the job which arrived first in the queue unless the number of jobs waiting in the queue has not crossed the value a . If the number of jobs in the queue is equal to or greater than a , the job with the shortest operation processing time is scheduled first.

$$R_j(t) = \begin{cases} r_{jk}^{\wedge} , & N_{jk}(t) < a \\ t_{jk}^{\wedge} , & \text{otherwise} \end{cases}$$

RULE 105: SHORTEST IMMINENT OPERATION TIME (LS)

Schedule next the job which has the shortest imminent operation processing time. In other words, the job with short operation is given first preference.

$$R_j(t) = t_{jk}^{\wedge}$$

RUL106: TWO-CLASS SHORTEST OPERATION (LS)

Schedule next the job from short operation class. Jobs being classified into two classes: short job class and long job class. Preference is given to short job class. A job is called a short job if its imminent operation processing time is less than the specified parameter a which is measured in units of time. Within each class the tie is resolved by first come first served rule.

$$R_j(t) \begin{cases} r_{jk}^{\hat{}} & , \quad t_{jk}^{\hat{}} < a \\ b+r_{jk}^{\hat{}} & , \quad t_{jk}^{\hat{}} \geq a \end{cases}$$

RUL107: THREE-CLASS SHORTEST OPERATION (LS)

Schedule next the job according to the shortest operation rule from a set of jobs which will arrive at the queue of size equal to or greater than a constant a . All waiting jobs are divided into three classes: the first class consists of jobs having their next operation on a machine with a queue of size equal to or greater than a . The second class consists of jobs whose subsequent operation is to be processed on a machine with a queue of size less than b , where $b > a$. The third class consists of the remaining jobs. The first class has preference over the second one which has, in turn, preference over the third class.

$$R_j(t) = \begin{cases} t_{jk}^{\hat{}} & , \quad N_{j,k+1}(t) \leq a \\ t_{jk}^{\hat{}} & , \quad N_{j,k+1}(t) < b \\ t_{jk}^{\hat{}} & , \quad N_{j,k+1}(t) \geq b \end{cases}$$

where a and b are positive integers such that $b > a$.

RUL108: TRUNCATED SHORTEST OPERATION (LD)

Schedule next the job which has the shortest imminent operation processing time unless there is a job in the queue which has waited more than or equal to certain time units, a . When $a = 0$, this rule becomes same as first in queue first served rule.

$$R_j(t) = \begin{cases} t_{jk}^{\wedge}, & (t - r_{jk}^{\wedge}) < a \\ 0, & (t - r_{jk}^{\wedge}) \geq a \end{cases}$$

RUL109: LONGEST IMMINENT OPERATION TIME (LS)

Schedule next the job which has the longest imminent operation processing time.

Priority number is given inversely proportional to the operation processing time.

$$R_j(t) = 1/t_{jk}^{\wedge}$$

RUL110: LONGEST OPERATION WITH SHORTEST OPERATION OVERLOAD PROTECTION (LS)

Schedule next the job with the longest operation processing time unless the number of jobs waiting in the queue has not reached a certain number equal to or greater than a . If the number of jobs waiting is equal to or greater than a , schedule the job with the shortest operation processing time.

$$R_j(t) = \begin{cases} 1/t_{jk}^{\wedge}, & N_{jk}^{\wedge}(t) < a \\ t_{jk}^{\wedge}, & \text{otherwise} \end{cases}$$

RULE111: SUBSEQUENT OPERATION (CS)

Schedule next the job whose subsequent operation is to be processed on a machine with a critical queue and has shortest operation processing time among the jobs which are qualifying for the next critical queue. A critical queue is the one with less than a certain time units of work waiting to be processed, a . If there is no critical queue, select the job in order of their arrival.

$$R_j(t) = \begin{cases} t_{j\hat{k}} & , \quad Q_{j,\hat{k}+1} < a \\ r_{j\hat{k}} & , \quad \text{otherwise} \end{cases}$$

RULE112: LONGEST SUBSEQUENT OPERATION TIME (LS)

Schedule next the job whose next operation has the longest processing time. Priority numbers for the current operations are assigned inversely proportional to the subsequent operation processing time. Preference is given to jobs on their last operation by assigning a very low value of priority index.

$$R_j(t) = \begin{cases} 1/t_{j,\hat{k}+1} & , \quad \hat{k} < K_j \\ 1/\max[t_{j\hat{k}}] & , \quad \hat{k} = K_j \end{cases}$$

RUL113: OPERATION SLACK TIME (LS)

Schedule next the job which has the minimum operation slack time. The operation slack time is the difference between the present and previous operation due dates minus the operation processing time. Operation slack time is the time for the operation to make up if it is already late.

$$R_j(t) = D_{jk} - D_{j,k-1} - t_{jk}$$

RUL114: REMAINING JOB SLACK TIME (LD)

Schedule next the job which has the minimum job allowance or free time before the job due date. The job allowance is the time left after all the operation processing times of a job are deducted from the due date minus the present time.

$$R_j(t) = D_j - t - \sum_{k=1}^{K_j} t_{jk}$$

RUL115: EARLIEST START DATE (LS)

Schedule next the job which has the earliest planned start date. A planned start date on which a job should start in order to be completed on time is determined by multiplying the total number of operations by arbitrary allowance.

RULE 116: EARLIEST JOB DUE DATE (LS)

Schedule next the job which has the earliest job due date. Priority numbers are assigned proportional to job due date. Jobs which are supposed to be completed early, receive a higher priority.

$$R_j(t) = D_j$$

RULE 117: OPERATION DUE DATE (LS)

Schedule next the job which has the earliest operation due date. The operation due date is computed as the sum of the job arrival time at the shop and equally spaced job due date per operation.

$$R_j(t) = r_{j1} + (D_j - r_{j1}) \hat{k}/K_j$$

RULE 118: EARLIEST OPERATION DUE DATE AND PROPORTIONAL SLACK TIME (LS)

Schedule next the job which has the earliest operation due date. The operation due date is computed as the sum of the previous operation due date and the assigned shop time of job proportional to the operation processing time.

$$R_j(t) = D_{j,k-1} + (D_j - r_{j1}) \frac{t_{jk} \hat{k}}{\sum_{k=1}^K t_{jk}}$$

RUL119: FEWEST REMAINING OPERATIONS (LS)

Schedule next the job which has the least number of operations still to be performed before being departed from the shop. The priority number of operations remaining including the present operation for which it is waiting. Hence jobs on their last operations are scheduled first.

$$R_j(t) = K_j - \hat{k} + 1$$

RUL120: MOST REMAINING OPERATIONS (LS)

Schedule next the job which has the most number of the unscheduled operations before being departed from the shop. Priority numbers are assigned inversely proportional to the number of operations remaining.

$$R_j(t) = 1/(K_j - \hat{k} + 1)$$

RUL121: GREATEST TOTAL WORK (LS)

Schedule next the job which has the most amount of work on its routing. Priority numbers are assigned to the jobs on their arrival in the shop. The jobs which has the maximum total operations processing time is given highest priority. The priority remains static, i.e. does not change with time

$$R_j(t) = 1 / \sum_{k=1}^{K_j} t_{jk}$$

RUL122: LEAST WORK REMAINING (LS)

Schedule next the job which has the least amount of remaining work to be performed including the present operation. The amount of work to be performed on a job is the sum of all of its operations processing times.

$$R_j(t) = \sum_{k=\hat{k}}^{K_j} t_{jk}$$

RUL123: MOST WORK REMAINING (LS)

Schedule next the job which has the most remaining work to be performed. In other words the job whose total remaining operation processing times is a maximum, receives highest priority.

$$R_j(t) = 1 / \sum_{k=\hat{k}}^{K_j} t_{jk}$$

RUL124: FEWEST JOBS IN NEXT QUEUE (GD)

Schedule next the job whose subsequent operation is going to be processed on a machine with a queue having the least number of jobs waiting. If two or more jobs qualify, the tie is resolved by the shortest operation rule.

$$R_j(t) = N_{j, \hat{k}+1}(t)$$

RULL25: LEAST WORK IN NEXT QUEUE (GD)

Schedule next the job whose subsequent operation is going to be processed on a machine with a queue having the minimum sum of processing times of all waiting jobs.

$$R_j(t) = Q_{j, \hat{k}+1}(t)$$

RULL26: LEAST EXPECTED WORK IN NEXT QUEUE (GD)

Schedule next the job whose subsequent operation is going to be performed on the machine of which the queue has the minimum sum of work waiting and work expected to arrive soon. Expected work is the sum of operations processing time of all those jobs which at present being processed on different machines and will arrive soon in the queue under consideration.

$$R_j(t) = Q_{j, \hat{k}+1}(t) + \bar{Q}_{j, \hat{k}+1}(t)$$

RULL27: FIRST HALF PREFERENCE (LS)

Schedule next the job which is yet to be processed on more than half its total number of operations. This rule divides the jobs which are waiting for processing into two classes depending on the corresponding number of operations. A tie, if exists, is broken by first in queue first served rule.

$$R_j(t) = \begin{cases} 1 & , \quad (K_j - \hat{k}+1) \leq K_j/2 \\ 0 & , \quad (K_j - \hat{k}+1) > K_j/2 \end{cases}$$

RUL128: LAST HALF PREFERENCE (LS)

Schedule next the job which is yet to be processed on less than or equal to half of its total number of operations. If a tie exists, schedule the job which arrived earlier in the queue. If there is no job to qualify the above condition, schedule the jobs according to first in queue first served rule.

$$R_j(t) = \begin{cases} 0, & (K_j - \hat{k} + 1) \leq K_j/2 \\ 1, & (K_j - \hat{k} + 1) > K_j/2 \end{cases}$$

RUL129: LATE OPERATION PREFERENCE WITH SHORTEST IMMINENT OPERATION TIME (LS)

Schedule next the job which is behind operation due date. If there is no such job in the queue then the job which has the shortest imminent operation processing time is selected next.

$$R_j(t) = \begin{cases} t_{j\hat{k}}, & r_{j\hat{k}} < r_{j1} + (D_j - r_{j1}) \hat{k}/K_j \\ 0, & \text{otherwise.} \end{cases}$$

RUL130: LAST OPERATION OF LATE JOBS PREFERENCE WITH SHORTEST IMMINENT OPERATION TIME (LS)

Schedule next the job which has the shortest imminent operation processing time unless there is a late job waiting in the queue for its last operation whose lateness can be avoided by scheduling it first.

$$R_j(t) = \begin{cases} U_j & , \quad G < P \quad \text{for } \hat{k} = K_j \text{ and } U_j > 0 \\ t_{j\hat{k}} & \quad G \geq P \end{cases}$$

where,

$$U_j = D_j - t - t_{j\hat{k}}$$

$$P = \min_j [t_{j\hat{k}}]$$

$$G = \min [U_j] \text{ for all jobs with } \hat{k} = K_j \text{ and } U_j > 0$$

RUL201: LAST OPERATION PREFERENCE WITH POSITIVE OPERATION SLACK TIME (LS)

Schedule next the job which has the minimum sum of weighted remaining job slack time and weighted imminent operation processing time. The weighting factor for processing time is the function of work content of the queue. The weighting factor of job slack time gives preference to the last operation of the job.

$$R_j(t) = a^c (D_{j\hat{k}} - D_{j,\hat{k}-1} - t_{j\hat{k}}) + (b \sum_j t_{jk}) t_{j\hat{k}}$$

where

$$a \geq 1$$

$$c = \begin{cases} 0, & \hat{k} \neq K_j \\ -1, & \hat{k} = K_j \text{ and } (D_{j\hat{k}} - D_{j,\hat{k}-1} - t_{j\hat{k}}) > 0 \\ 1, & \hat{k} = K_j \text{ and } (D_{j\hat{k}} - D_{j,\hat{k}-1} - t_{j\hat{k}}) \leq 0 \end{cases}$$

RUL202: LAST OPERATION PREFERENCE WITH JOB SLACK TIME FACTOR (LS)

Schedule next the job with the smallest sum of imminent operation slack time and weighted work in the queue minus a value, v which takes a positive number if the current operation is the last operation and its operation slack time is less than u , otherwise v has value equal to 1.

$$R_j(t) = (D_{j\hat{k}} - D_{j,\hat{k}-1} - t_{j\hat{k}}) + (b \sum_j t_{j\hat{k}}) t_{j\hat{k}} - v$$

where

$$v > 0, \quad \hat{k} = K_j \text{ and } (D_{j\hat{k}} - D_{j,\hat{k}-1} - t_{j\hat{k}}) < u$$

$$v = 0, \quad \hat{k} \neq K_j \text{ or } (D_{j\hat{k}} - D_{j,\hat{k}-1} - t_{j\hat{k}}) \geq u$$

RUL203: LAST OPERATION PREFERENCE WITH OPERATION SLACK TIME AND PROCESSING TIME FACTORS (LS)

Schedule next the job which has the minimum sum of imminent operation slack time and weighted imminent operation processing time. The weighting factor is a function of work content of the queue and assigns a higher priority to a job which is waiting for its last operation.

$$R_j(t) = (D_{j\hat{k}} - D_{j,\hat{k}-1} - t_{j\hat{k}}) + [xb \sum_j t_{j\hat{k}}] t_{j\hat{k}}$$

where

$$x = \begin{cases} 0, & \hat{k} = K_j \\ 1, & \text{otherwise} \end{cases}$$

RUL204: LAST OPERATION PREFERENCE WITH DIFFERENCE BETWEEN PROCESSING TIME AND SUBSEQUENT PROCESSING TIME (LS)

Schedule next the job which is waiting for its last operation. If no such job is waiting, select the job with the least difference between its weighted current processing time and weighted subsequent operation processing time where a is a weighting factor. When a = 1, this rule becomes the shortest operation rule; however, when a = 0, it becomes the longest subsequent operation rule.

$$R_j(t) = \begin{cases} at_{jk} - (1-a) t_{j,k+1}, & \hat{k} < K_j \\ at_{jk} - (1-a) \max [t_{jk}], & \hat{k} = K_j \end{cases}$$

RUL205: SHORTEST OPERATION WITH PREFERENCE TO ARRIVING JOBS WITH SHORTER PROCESSING TIME (GS)

Schedule next the job with the shortest operation processing time with a 'hold' if there are few jobs in the queue and a job with shorter processing time will arrive soon.

$$R_j(t) = t_{jk}$$

No assignment is made, i.e. the machine is held idle, if $Q_{jk} \leq a$ and if there is a job j now being processed for its $(\hat{k} - 1)$ operation that will come to this queue for its \hat{K} -th operation with:

$$t_{j,\hat{k}-1} < \min_j [t_{jk}] - b$$

where b is a constant.

RUL206: DIFFERENCE BETWEEN AVAILABLE TIME UNTIL DUE DATE AND IMMINENT OPERATION TIME (LS)

Schedule next the job with the minimum difference of weighted remaining flow time (job due date minus present time) and imminent operation time.

$$R_j(t) = w(D_j - t) - t_{jk}$$

where w is waiting factor.

RUL207: ALTERNATE OPERATION HEURISTIC (LS)

Schedule next the job which becomes critical as a result of scheduling another job according to a specific priority rule. If processing of the critical job first create another critical job in the queue, schedule next a job according to the specific priority rule. A critical job is the one which is already late or soon will be late.

RUL208: LOOK AHEAD HEURISTIC (GS)

Schedule next the job which is critical (late or near late) and is due to join the present queue at some future time before the completion of the operation of the job which has been selected by a priority rule. If the processing of this future critical job create another critical jobs in the present queue, apply the current priority rule and neglect future critical job.

RUL209: INSERT HEURISTIC (LS)

Schedule next the job whose operation processing time can fit into the idle time created by look ahead rule. Due to look ahead rule the jobs at the present machine are withheld from being processed, since critical job is due to arrive at the queue soon. This causes an idle time of the corresponding machine.

RUL210: TIME-TRANSCENDING SCHEDULE HEURISTIC (LD)

Schedule next the job with the top priority. Re-evaluate the priorities every time a job joins the queue.

RUL211: SUBSET OF CRITICAL JOBS HEURISTIC (LS)

Schedule next the job from a subset of critical jobs according to a priority rule or set of rules, then schedule the remaining jobs around them. In this rule schedule is laid out by jobs instead of job operations.

RUL212: RE-DO WITH ADJUSTED DUE DATES HEURISTIC (LD)

Schedule next the job according to the priority rule. When the schedule is completed check for late jobs, decrease their due dates by the time the job was late and schedule again. This will give chance to the previously late jobs to be completed in time.

RUL213: MANIPULATION HEURISTIC (LD)

Schedule next the job as determined by the Gantt chart until a better schedule is obtained. This heuristic is similar in nature to the heuristic of re-do with adjusted due dates.

RUL214: ONE CLASS MONETARY VALUE OF THE JOB (LS)

Schedule next the job with the highest monetary value among jobs waiting in the queue. Priority index is inversely proportional to the value of job.

$$R_j(t) = 1/v_j$$

RUL215: TWO-CLASS MONETARY VALUE OF THE JOB (LS)

Schedule next the job from higher monetary value class. Jobs in queue are divided into two classes depending on their monetary value. All jobs with higher monetary value have higher priority. Within each class, the job which arrived first in queue is selected first.

$$R_j(t) = \begin{cases} t_{jk}^{\wedge}, & v_j > a \\ t_{jk}^{\wedge} + \max [t_{jk}^{\wedge}], & v_j \leq a \end{cases}$$

where a is a specified parameter measured in monetary value.

RUL216: THREE-CLASS MONETARY VALUE OF THE JOB (LS)

Schedule next the job which arrived first in the highest monetary value class. Jobs are classified into three classes: high, medium and low depending on their monetary values. Within each class jobs are selected with first come first served rule. In other words jobs are selected from the highest monetary value queue first.

$$R_j(t) = \begin{cases} r_{jk}^{\wedge}, & v_j > a \\ p + r_{jk}^{\wedge}, & b \leq v_j \leq a \\ q + r_{jk}^{\wedge}, & v_j < b \end{cases}$$

where a and b are specified parameters measured in monetary values, $a > b$, and p and q are constants such that $q > p$.

RUL217: EARLIEST DUE DATE AND SUBSEQUENT QUEUE SIZE (GD)

Schedule next the job which has the earliest job due date and whose subsequent operation is going to be processed on a machine with a queue having less than a certain number of waiting jobs, a . If such a job does not exist, apply the simple earliest due date rule. This compound rule divides waiting jobs into two groups: one consisting of jobs whose subsequent operation is to be performed on a machine with queue of a size less than a . The second group consists of jobs whose subsequent operation is to be processed on a machine with a queue of a size greater than a . The jobs in the first group are given preference over those in the second group. Furthermore, the jobs in both groups are scheduled according to the earliest due date rule.

$$R_j(t) = \begin{cases} D_j, & \hat{k} = K_j \text{ or } N_{j,\hat{k}+1}(t) < a \\ D_j + n, & \text{otherwise} \end{cases}$$

RUL218: FEWEST JOBS IN NEXT QUEUE AND SHORTEST OPERATION (GD)

Schedule next the job whose subsequent operation is going to be processed on a machine with a queue having a number of jobs less than a , i.e., a short queue is available. If all the queues have a number of jobs more than a , i.e., no short queue is available, then select the job by applying the shortest operation rule.

$$R_j(t) = \begin{cases} N_{j,\hat{k}+1}(t), & N_{j,\hat{k}+1}(t) < a \\ t_{j\hat{k}}, & \text{otherwise} \end{cases}$$

RUL219: REMAINING JOB SLACK TIME AND SHORTEST OPERATION WITH CONTROL
OVER JOB DELAYS IN SHOP (LS)

Schedule next the job with the shortest operation processing time from the set of jobs having $F \leq 0$ where:

$$F = (D_j - t) - \sum_{k=\hat{k}}^{K_j} t_{jk} - c$$

and c is a control parameter. If no such job is waiting, simply schedule a job according to the shortest operation rule.

$$R_j(t) = \begin{cases} t_{j\hat{k}}, & F \leq 0 \\ t_{j\hat{k}}, & \text{otherwise} \end{cases}$$

RUL220: MODIFIED REMAINING JOB SLACK TIME AND SHORTEST OPERATION WITH
CONTROL OVER DELAYS (LS)

Schedule next the job with the minimum value of F from set of waiting jobs having $F \leq 0$ where:

$$F = (D_j - t) - \sum_{k=\hat{k}}^{K_j} t_{jk} - c$$

and c is a control parameter. If no such a job is waiting, schedule a job according to the shortest operation rule.

$$R_j(t) = \begin{cases} F, & F \leq 0 \\ t_{j\hat{k}}, & \text{otherwise} \end{cases}$$

RUL221: ALTERNATING SHORTEST OPERATION AND FIRST COME FIRST SERVED (LD)

Schedule next the job according to shortest operation rule for certain fixed period of time, a , and then schedule those according to first come first served rule.

$$R_j(t) = \begin{cases} \hat{t}_{jk} & \text{for certain period of time, } a \\ \hat{t}_{jk} & \text{otherwise} \end{cases}$$

RUL222: RATIO OF PROCESSING TIME TO NUMBER OF OPERATIONS REMAINING (LS)

Schedule next the job which has the minimum ratio of its processing time to the weighted number of operations remaining including the current operation. Hence for the same operation processing time, the job which has more remaining operations is given higher priority. When a , the weighting factor is such that $a \rightarrow \infty$, this rule becomes the most operation rule; however, when $a = 0$, this rule becomes shortest operation rule.

$$R_j(t) = \hat{t}_{jk} / (K_j - \hat{k} + 1)^a$$

RUL223: RATIO OF PROCESSING TIME TO WORK REMAINING (LS)

Schedule next the job which has the minimum ratio of processing time to work remaining raised to power a , where a is a weighting factor. When $a = 0$, this rule becomes shortest operation rule; however, when $a \rightarrow \infty$, this rule becomes the most work remaining rule.

$$R_j(t) = \hat{t}_{jk} / \left(\sum_{k=\hat{k}}^{K_j} \hat{t}_{jk} \right)^a$$

RUL224: RATIO OF PROCESSING TIME TO TOTAL JOB WORK (LS)

Schedule next the job which has the smallest ratio of processing time to the total job work. Total work of a job is the sum of all operations processing time.

$$R_j(t) = t_{jk} / \sum_{k=1}^{K_j} t_{jk}$$

RUL225: RATIO OF SUM OF PROCESSING TIME AND WORK IN NEXT QUEUE TO PROCESSING TIME OF NEXT OPERATION (GD)

Schedule next the job which has the minimum ratio of sum of its weighted processing time and weighted work content of the next queue to processing time of its next operation. The work content of the next queue is the sum of the processing times of jobs waiting in queue.

$$R_j(t) = \frac{at_{jk} + (1-a) Q_{j,k+1}(t)}{(t_{j,k+1})^b}$$

RUL226: RATIO OF REMAINING JOB SLACK TIME TO REMAINING NUMBER OF OPERATION (LS)

Schedule next the job which has the smallest ratio of remaining job slack time to the remaining operations including the one for which the job is waiting. The remaining slack time is computed as the difference of job due date and the sum of remaining operation processing time minus the present time.

$$R_j(t) = (D_j - t - \sum_{k=k}^{K_j} t_{jk}) / (K_j - k + 1)$$

RUL227: RATIO OF TIME ELAPSED SINCE COMPLETION OF PREVIOUS OPERATION
TO REMAINING NUMBER OF OPERATIONS (LS)

Schedule next the job which has maximum ratio of the time elapsed since completion of previous operation minus a weighting factor a, to remaining number of operations. The weighting factor a is a function of job flow allowance.

$$R_j(t) = \frac{(t - r_{j,k}) - a}{(K_j - k + 1)^b}$$

where a and b are positive integers

RUL228: RATIO OF REMAINING JOB SLACK TIME TO REMAINING TIME UNTIL
JOB DUE DATE (LS)

Schedule next the job which has the smallest ratio of free time available before the job due date and time remaining until job due date.

$$R_j(t) = (D_j - t - \sum_{k=1}^{K_j} t_{jk}) / (D_j - t)$$

RULE 229: RATIO OF MODIFIED JOB SLACK TIME TO REMAINING TIME UNTIL JOB DUE DATE (LS)

Schedule next the job which has the minimum ratio of free time available before due date, after expected delay time for the remaining operations have been deducted, to the time remaining until job due date.

$$R_j(t) = \frac{D_j - t - \sum_{k=\hat{k}}^{K_j} (t_{jk} + t'_{jk})}{(D_j - t)}$$

where

t'_{jk} delay time of job j for operation k

RULE 230: RATIO OF COST TO PROCESSING TIME (COVERT RULE) (LS)

Schedule next the job with the largest ratio of delay cost to imminent operation processing time. It is assumed that the cost of delay, c is simply the incremental change in tardiness of the job order.

$$R_j(t) = \frac{1/c}{t_{jk}}$$

where

$$c = \frac{\sum_{k=1}^{K_j} W_{jk} - S_j}{\sum_{k=1}^{K_j} W_{jk}}$$

RULE 231: SUM OF PROCESSING TIME AND REMAINING SLACK TIME PER REMAINING OPERATIONS (LS)

Schedule next the job which has the minimum sum of weighted processing time and weighted remaining slack time per remaining operations.

Weighting factor a , is a function of the number of operations remaining.

$$R_j(t) = ct_{j\hat{k}} + (1-c) \frac{D_j - t - \sum_{k=\hat{k}}^{K_j} t_{jk}}{(K_j - \hat{k} + 1)^b}$$

where

$$c = a + \min [(1-a), (K_j - \hat{k} + 1)/b]$$

a and b are positive integers.

RULE 232: SUM OF PROCESSING TIME AND REMAINING SLACK TIME PER REMAINING OPERATION (LS)

Schedule next the job having minimum ratio of weighted processing time and weighted remaining slack time per remaining operations including the one for which job is waiting.

$$R_j(t) = a t_{j\hat{k}} + (1-a) \frac{D_j - t - \sum_{k=\hat{k}}^{K_j} t_{jk}}{(K_j - \hat{k} + 1)}$$

where a is a weighting factor.

RUL233: SUM OF PROCESSING TIME AND WORK REMAINING (LS)

Schedule next the job which has the minimum sum of weighted processing time and weighted work remaining. When $a = 1$, where a is the weighting factor, this rule becomes the shortest operation processing time rule; however, when $a = 0$, this rule becomes the least work remaining rule.

$$R_j(t) = at_{jk} + \left(\sum_{k=k}^{K_j} t_{jk} \right) (1-a)$$

RUL234: SUM OF PROCESSING TIME AND NUMBER OF JOBS IN THE SUBSEQUENT QUEUE (GD)

Schedule next the job which has the minimum sum of weighted processing time and weighted number of jobs in the next queue. When $a = 1$, where a is a weighting factor, this rule becomes the shortest imminent operation processing time rule, and when $a = 0$, the job which will be processed for its subsequent operation at the smallest queue size is scheduled next.

$$R_j(t) = at_{jk} + (1-a) N_{j,k+1}(t)$$

RUL235: SUM OF PROCESSING TIME AND WORK IN NEXT QUEUE (GD)

Schedule next the job which has the smallest sum of weighted processing time and weighted work in the next queue. Work in the next queue is the sum of operation processing time of jobs waiting in that queue.

$$R_j(t) = at_{j\hat{k}} + (1-a) Q_{j,\hat{k}+1}(t)$$

RUL236: SUM OF PROCESSING TIME AND WEIGHTED EXPECTED WORK IN SUBSEQUENT QUEUE (GD)

Schedule next the job which has the smallest sum of its weighted processing time and weighted expected work in the subsequent queue. The expected work is the work content of the jobs waiting and those which will arrive soon in the queue. The weighting factors being complement of each other.

$$R_j(t) = at_{j\hat{k}} + (1-a)[Q_{j,\hat{k}+1}(t) + \bar{Q}_{j,\hat{k}+1}(t)]$$

RUL237: SUM OF OPERATION SLACK TIME, PROCESSING TIME AND WORK CONTENT IN THE SUBSEQUENT QUEUE WITH PREFERENCE FOR LAST OPERATION (GD)

Schedule next the job with the smallest sum of imminent operation slack time, weighted imminent operation time and weighted work content in the subsequent queue minus the last operation indicator, y which takes value greater than zero if the job is waiting for its last operation.

$$R_j(t) = \{D_{j\hat{k}} - D_{j,\hat{k}-1} - t_{j\hat{k}}\} + \left\{b \sum_j t_{j\hat{k}}\right\} t_{j\hat{k}} + cQ_{j,\hat{k}+1}(t) - y$$

where,

$$y = 0, \quad \hat{k} \neq K_j$$

$$0 < y < c \quad \hat{k} = K_j$$

RUL233: SUM OF PROCESSING TIME AND WORK REMAINING (LS)

Schedule next the job which has the minimum sum of weighted processing time and weighted work remaining. When $a = 1$, where a is the weighting factor, this rule becomes the shortest operation processing time rule; however, when $a = 0$, this rule becomes the least work remaining rule.

$$R_j(t) = at_{jk} + \left(\sum_{k=k}^{K_j} t_{jk} \right) (1-a)$$

RUL234: SUM OF PROCESSING TIME AND NUMBER OF JOBS IN THE SUBSEQUENT QUEUE (GD)

Schedule next the job which has the minimum sum of weighted processing time and weighted number of jobs in the next queue. When $a = 1$, where a is a weighting factor, this rule becomes the shortest imminent operation processing time rule, and when $a = 0$, the job which will be processed for its subsequent operation at the smallest queue size is scheduled next.

$$R_j(t) = at_{jk} + (1-a) N_{j,k+1}(t)$$

RUL235: SUM OF PROCESSING TIME AND WORK IN NEXT QUEUE (GD)

Schedule next the job which has the smallest sum of weighted processing time and weighted work in the next queue. Work in the next queue is the sum of operation processing time of jobs waiting in that queue.

$$R_j(t) = at_{jk} + (1-a) Q_{j,\hat{k}+1}(t)$$

RUL236: SUM OF PROCESSING TIME AND WEIGHTED EXPECTED WORK IN SUBSEQUENT QUEUE (GD)

Schedule next the job which has the smallest sum of its weighted processing time and weighted expected work in the subsequent queue. The expected work is the work content of the jobs waiting and those which will arrive soon in the queue. The weighting factors being complement of each other.

$$R_j(t) = at_{jk} + (1-a)[Q_{j,\hat{k}+1}(t) + \bar{Q}_{j,\hat{k}+1}(t)]$$

RUL237: SUM OF OPERATION SLACK TIME, PROCESSING TIME AND WORK CONTENT IN THE SUBSEQUENT QUEUE WITH PREFERENCE FOR LAST OPERATION (GD)

Schedule next the job with the smallest sum of imminent operation slack time, weighted imminent operation time and weighted work content in the subsequent queue minus the last operation indicator, y which takes value greater than zero if the job is waiting for its last operation.

$$R_j(t) = (D_{jk} - D_{j,\hat{k}-1} - t_{jk}) + (b \sum_j t_{jk}) t_{jk} + cQ_{j,\hat{k}+1}(t) - y$$

where,

$$y = 0, \quad \hat{k} \neq K_j$$

$$0 < y < c \quad \hat{k} = K_j$$

RUL238: SUM OF IMMINENT OPERATION SLACK TIME AND WEIGHTED OPERATION
PROCESSING TIME (LS)

Schedule next the job which has the smallest sum of imminent operation slack time and weighted imminent operation processing time. The weighting factor is the function of the work content in the present queue.

$$R_j(t) = (D_{jk}^{\hat{}} - D_{j,k-1}^{\hat{}}) + b \sum_j t_{jk}^{\hat{}}$$

where b is a positive integer

RUL239: SUM OF OPERATION SLACK TIME, PROCESSING TIME AND WORK CONTENT
IN THE SUBSEQUENT QUEUE (GD)

Schedule next the job which has the minimum sum of imminent operation slack time, weighted imminent, operation processing time and weighted work content in the subsequent queue. The weighting factor of operation processing time is the function of the work content of the present queue

$$R_j(t) = (D_{jk}^{\hat{}} - D_{j,k-1}^{\hat{}} - t_{jk}^{\hat{}}) + (b \sum_j t_{jk}^{\hat{}}) t_{jk}^{\hat{}} + cQ_{j,k+1}(t)$$

where b and c are positive integers.

RUN 240: WEIGHTED OBJECTIVE RULE

Schedule next the job with maximum value of priority index as calculated by

$$R_j(t) = \sum_{r=1}^R a_j R_{rj}^*, \quad \sum_{r=1}^R a_j = 1 \text{ and } R_{rj}^* \leq 1$$

where

R = number of rules combined

a_j = weighting factor of job j

R_{rj}^* = ratio of the 'best' value for the rule r to the value of job j for rule r .

Hence, when the rule considered is, say, shortest processing time, the job with minimum processing time will have ratio of $R_{rj}^* = 1.00$ and all other jobs will have $R_{rj}^* \leq 1.0$ depending on the relation of their processing time to the processing time of the 'best' job.

APPENDIX B

This appendix includes the graphs of inter-arrivals and inter-departures for all the experiments conducted in this investigation. Figures B-1 through B-5, B-6 through B-10, and B-11 through B-14 correspond to Experiments I, II, and III, respectively.

In addition to the above, a computer output of sample results is included. These results belong to the shortest imminent operation rule tested in Experiment II.

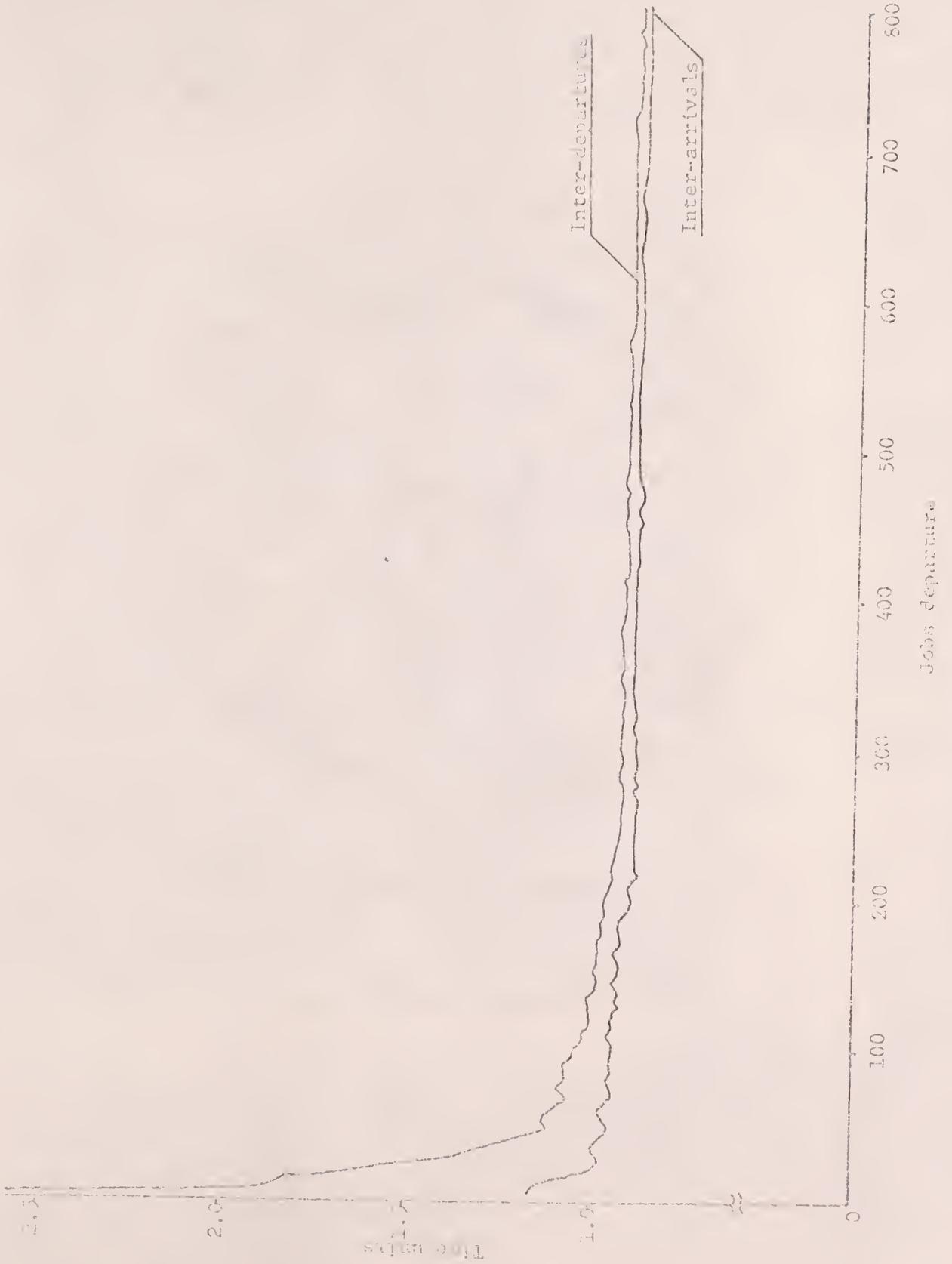


Figure P-1. Inter-arrivals and inter-departures of first come first served rule

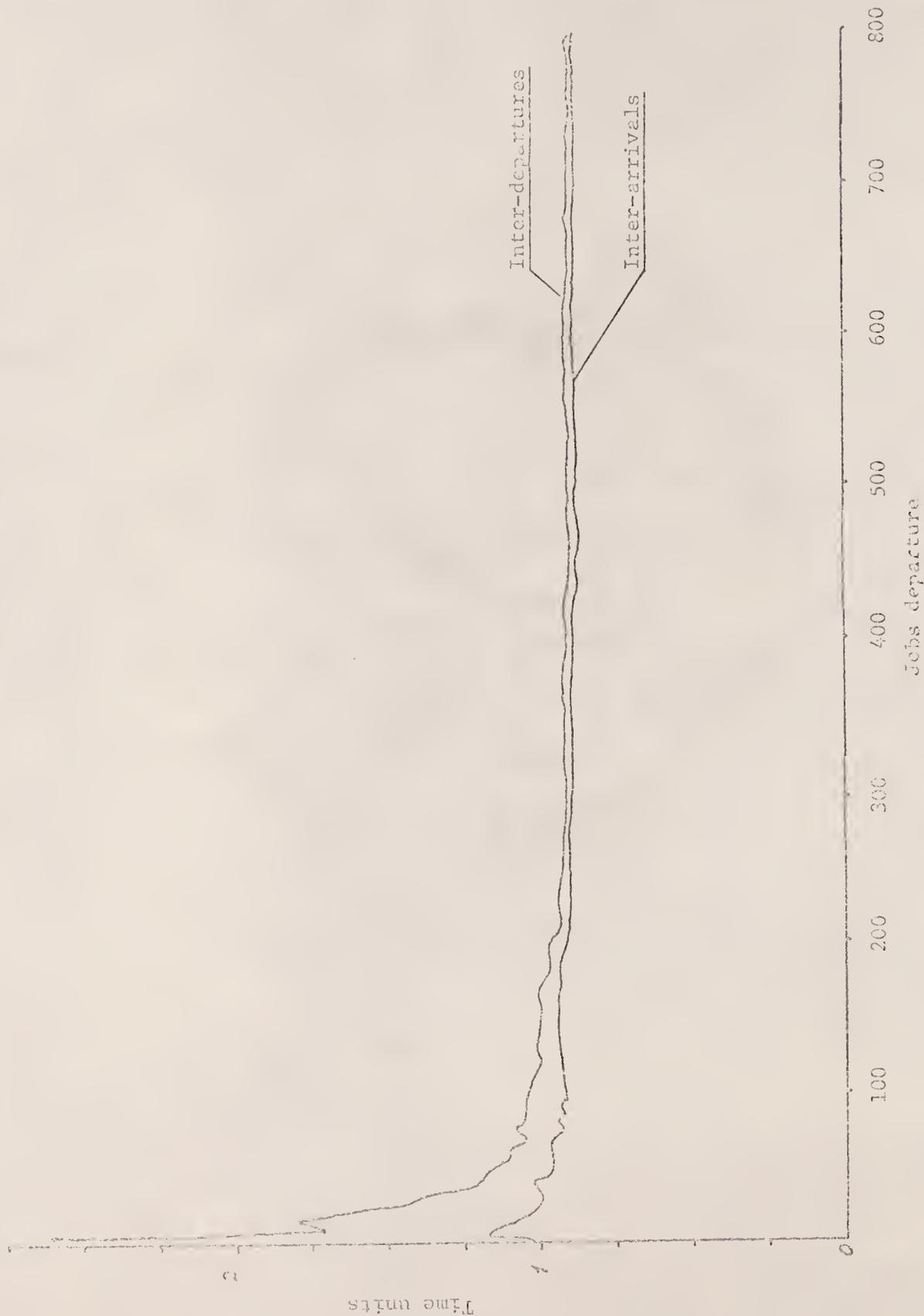


Figure B-2. Inter-arrivals and inter-departures of shortest imminent operation rule.



Figure E-3. Inter-arrivals and inter-departures of job slack time rule

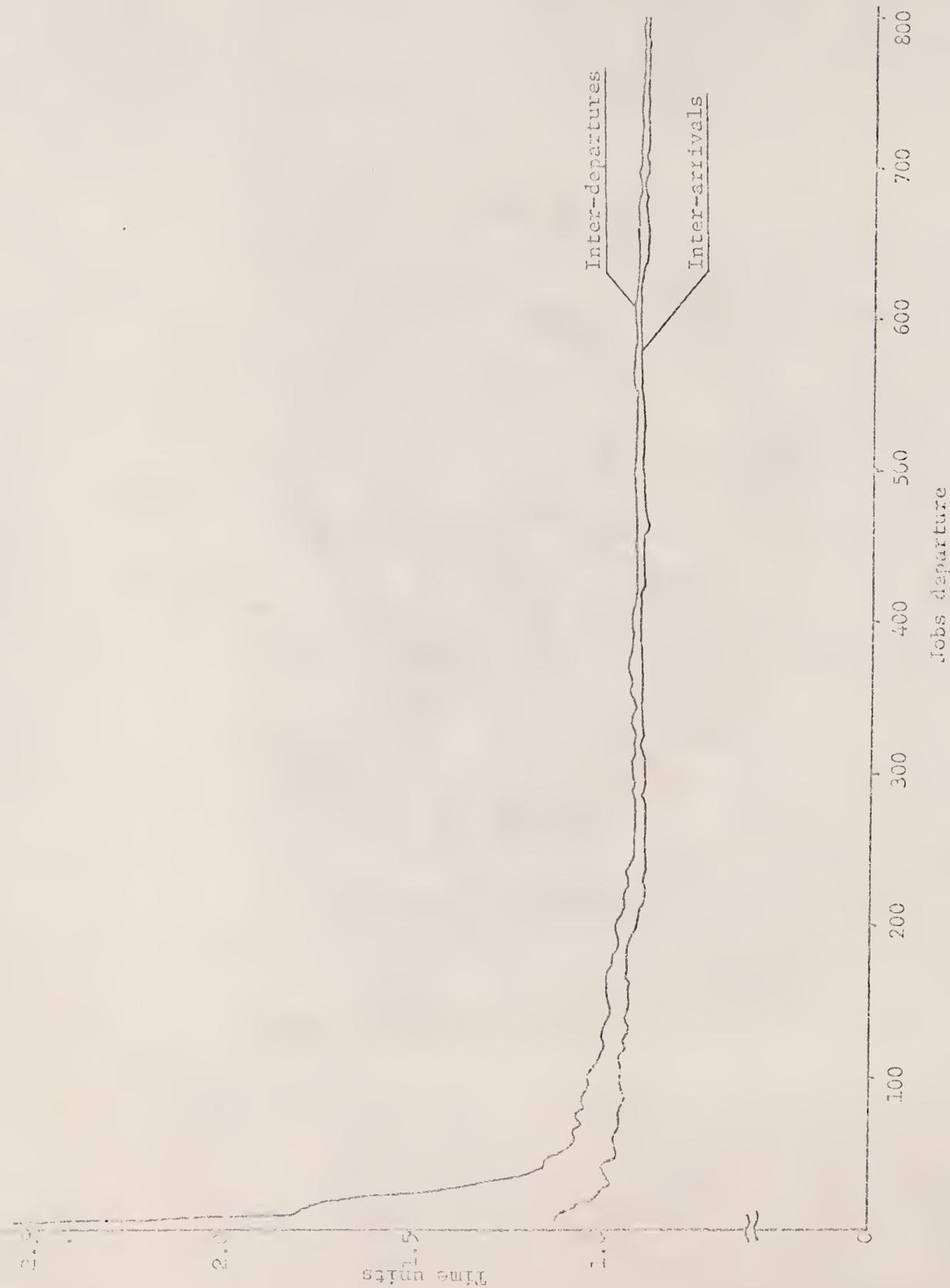


Figure B-4. Inter-arrivals and inter-departures of earliest job due-date rule

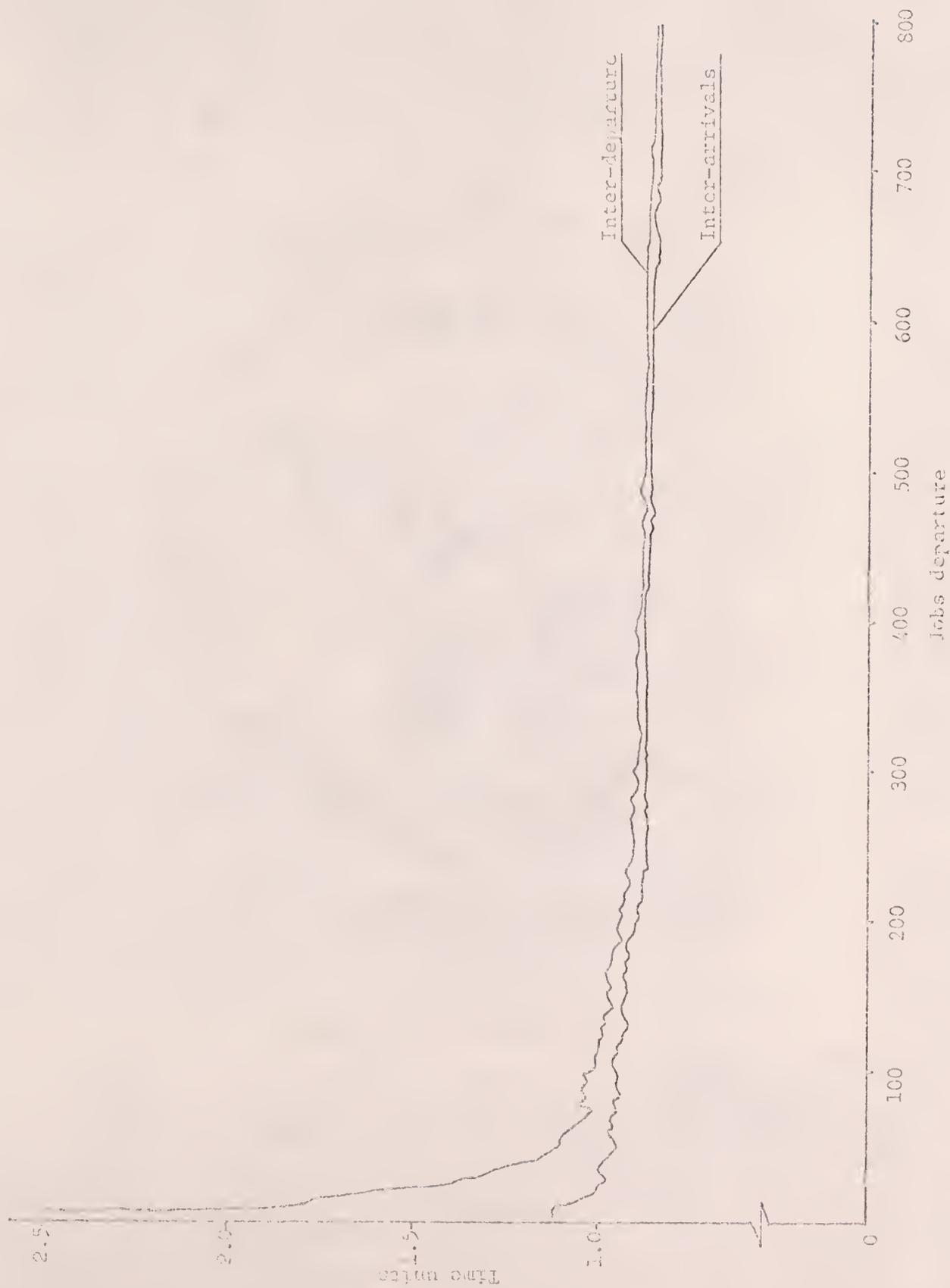


Figure B-5. Inter-arrivals and inter-departures of slack per remaining operation rule.



Figure B-6. Inter-arrivals and inter-departures of first-come first-served rule with due-dates proportional to the number of operations/job.

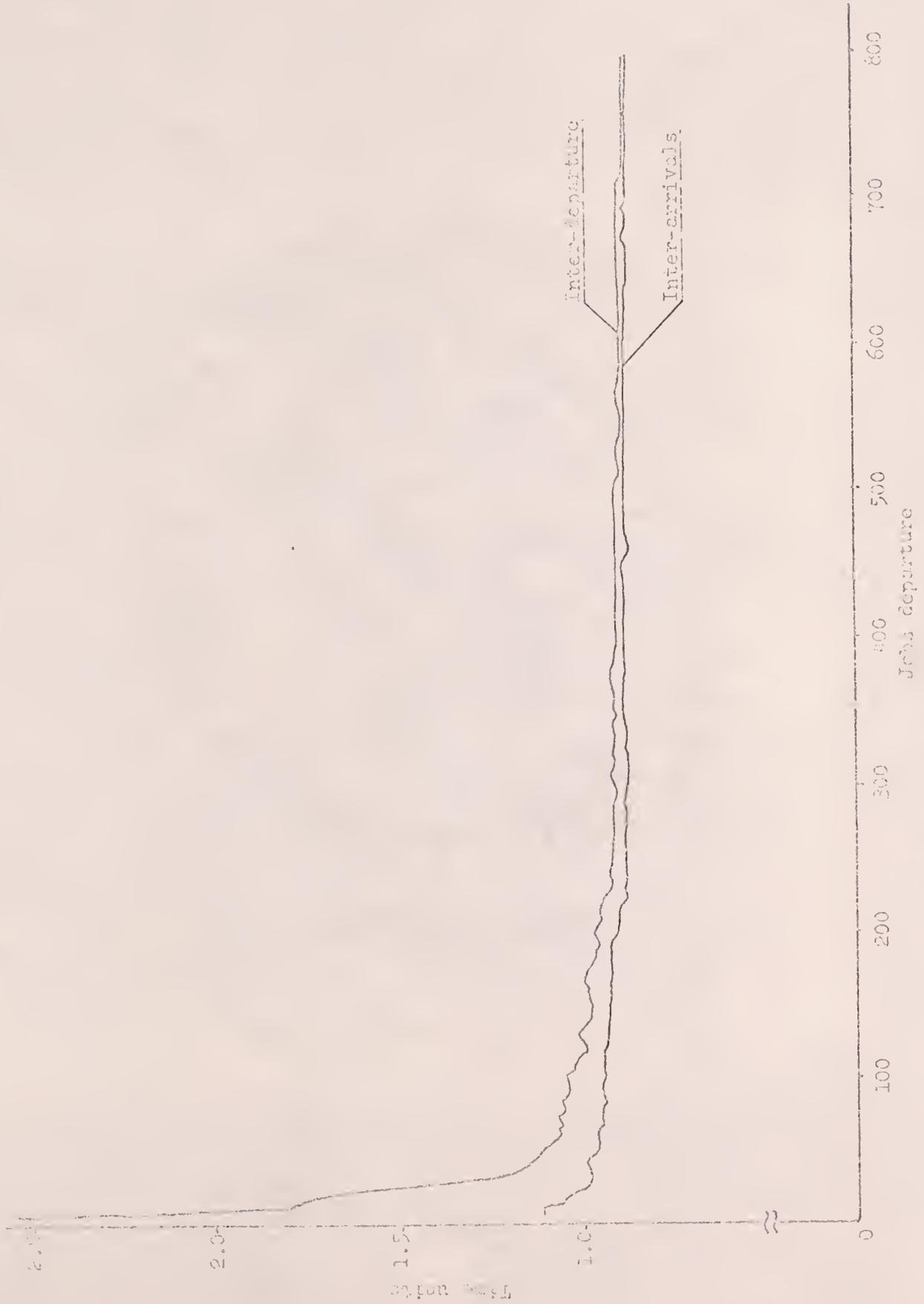


Figure B-7. Inter-arrivals and inter-departures of shortest imminent operation rule with due-dates proportional to the number of operations/job.

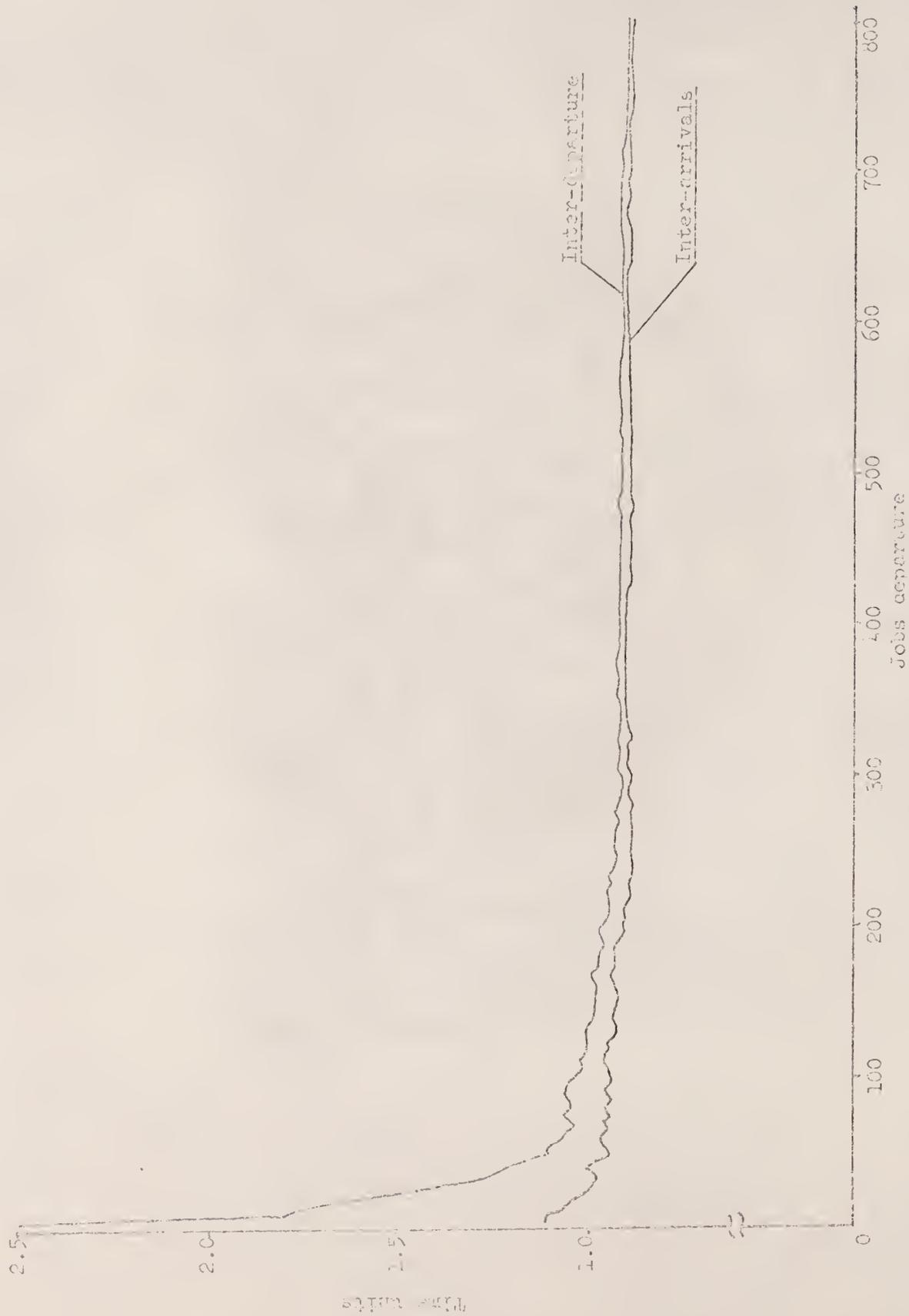


Figure B-8. Inter-arrivals and inter-departures of job slack time rule with que-dates proportional to the number of operations/job.

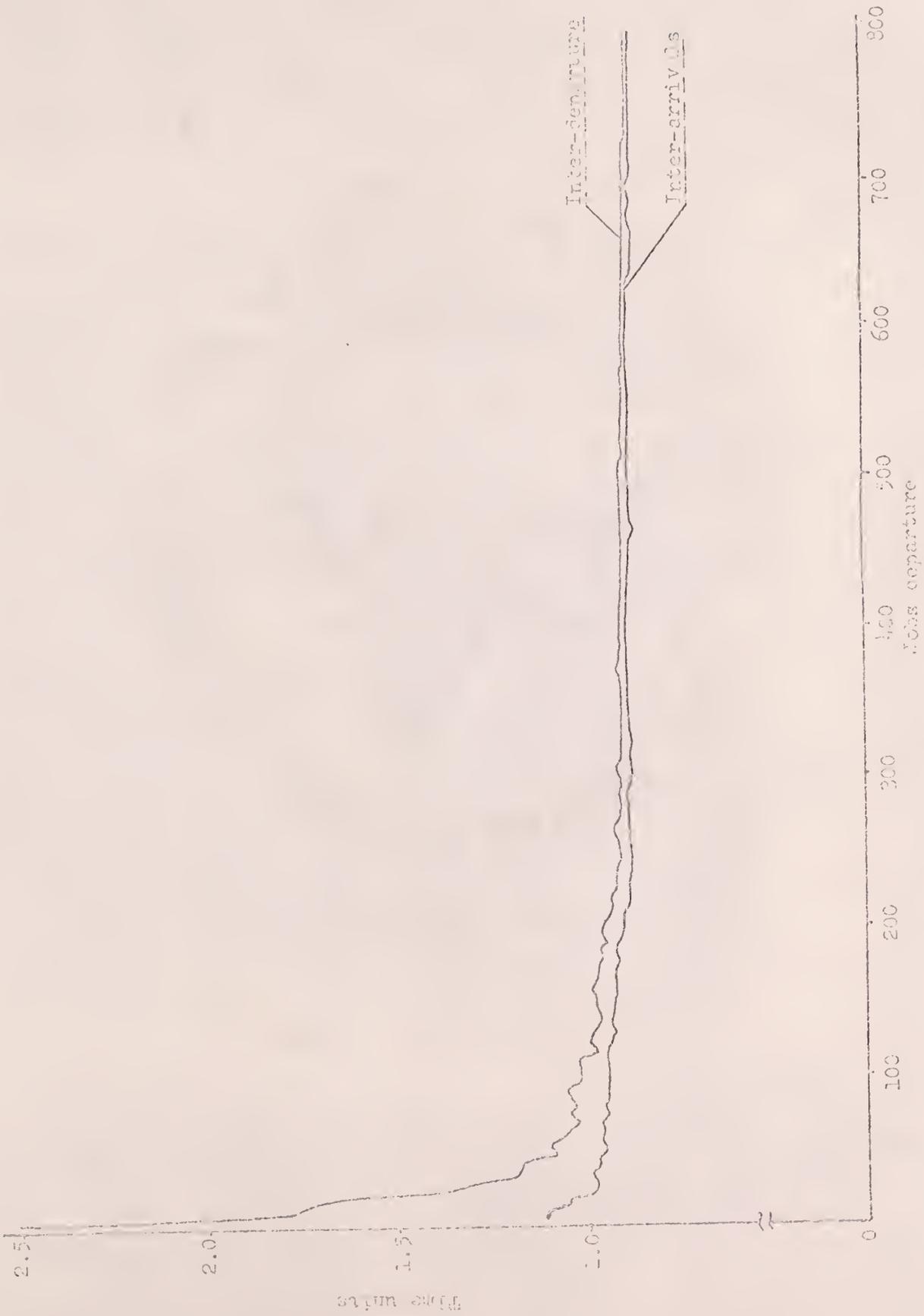


Figure 4-9. Inter-arrivals and inter-departures of earliest job due date rule with due-dates proportional to the number of operations/job.

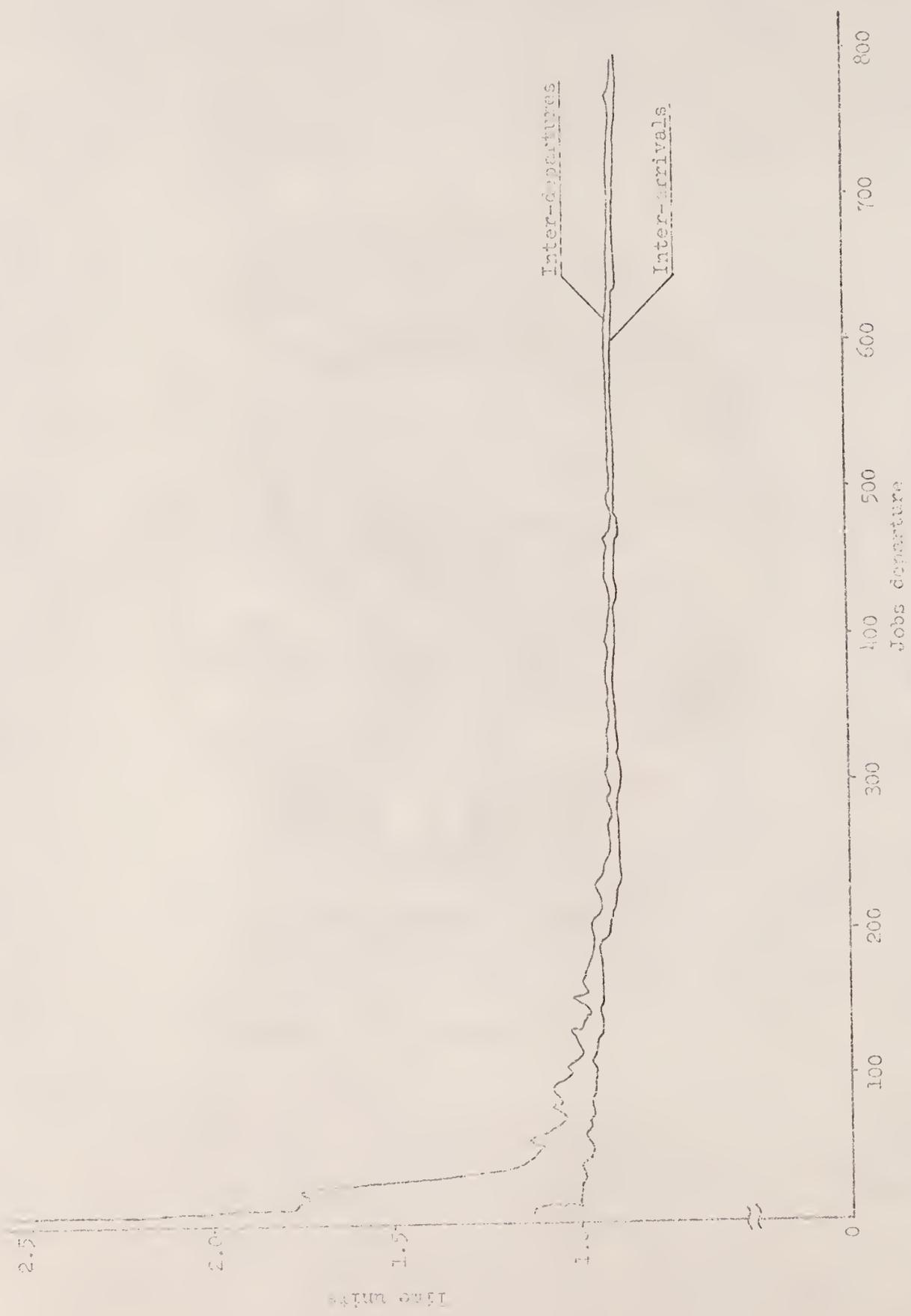


Figure 6-13. Inter-arrivals and inter-departures of slack per remaining operation rule with due dates proportion to the number of operations/job.

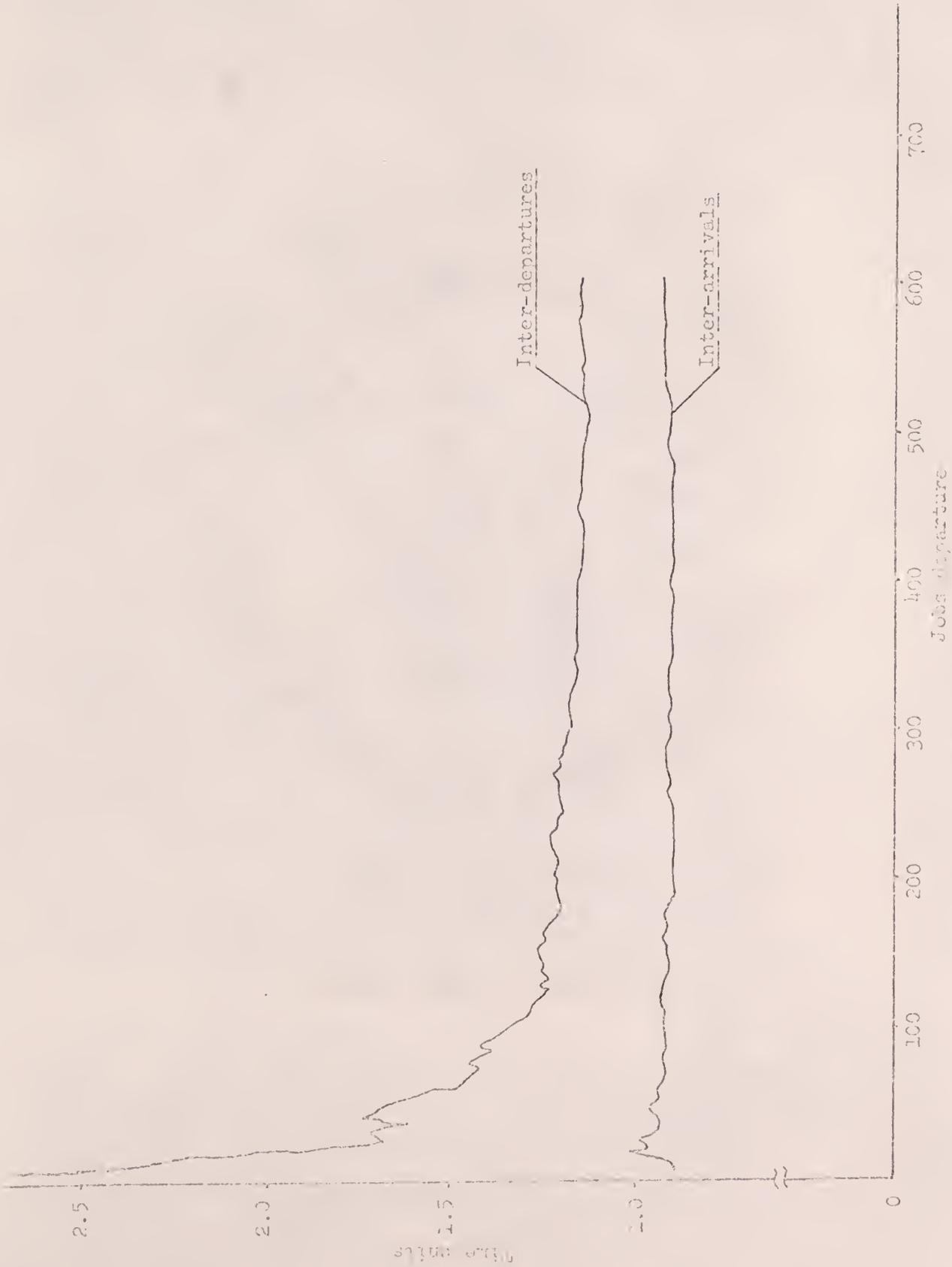


Figure B-11. Inter-arrivals and inter-departures of shortest imminent operation rule with processing time distribution of Example 4.

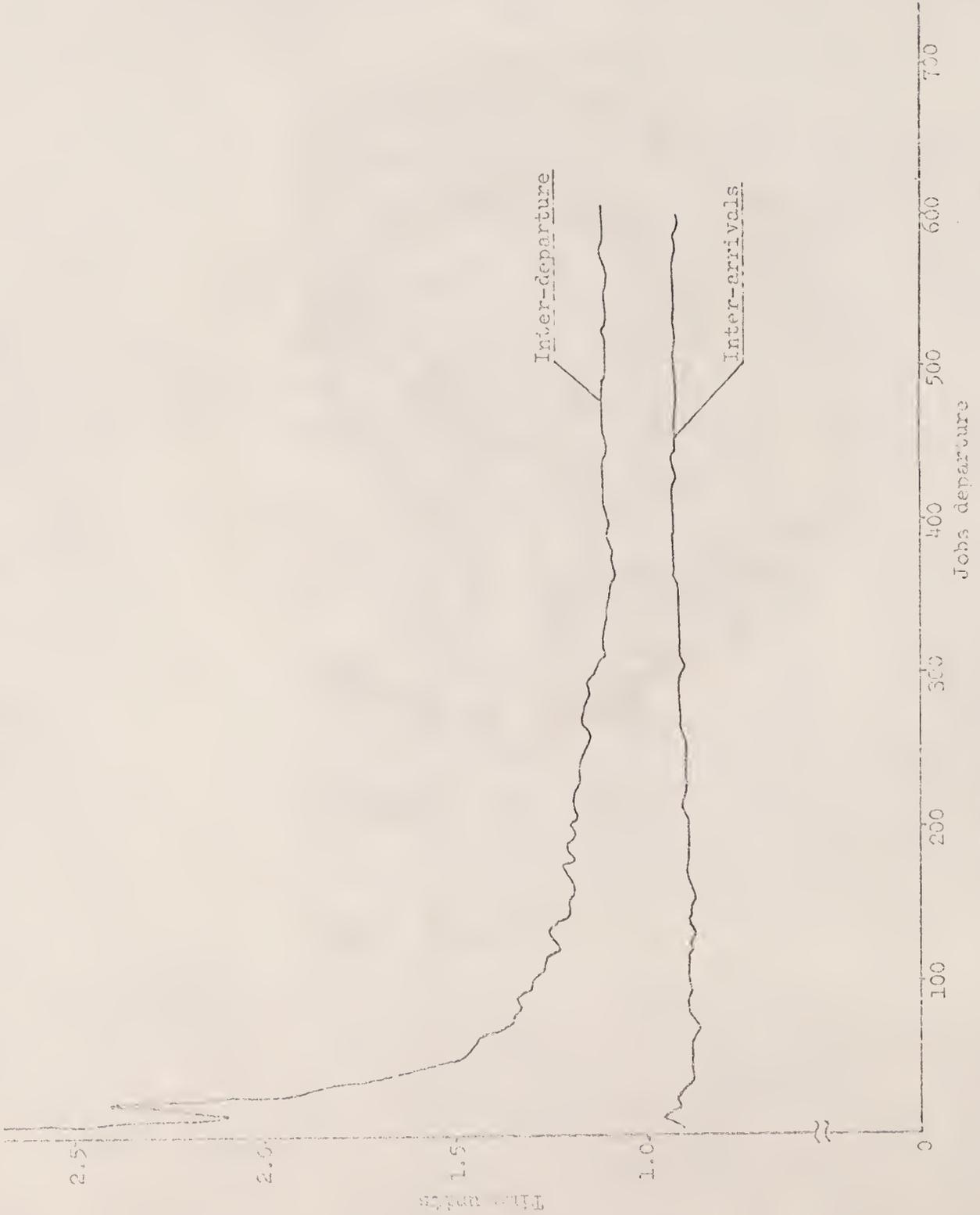


Figure B-12. Inter-arrivals and inter-departures of shortest imminent operation rule with processing time distribution of Erlang 8.

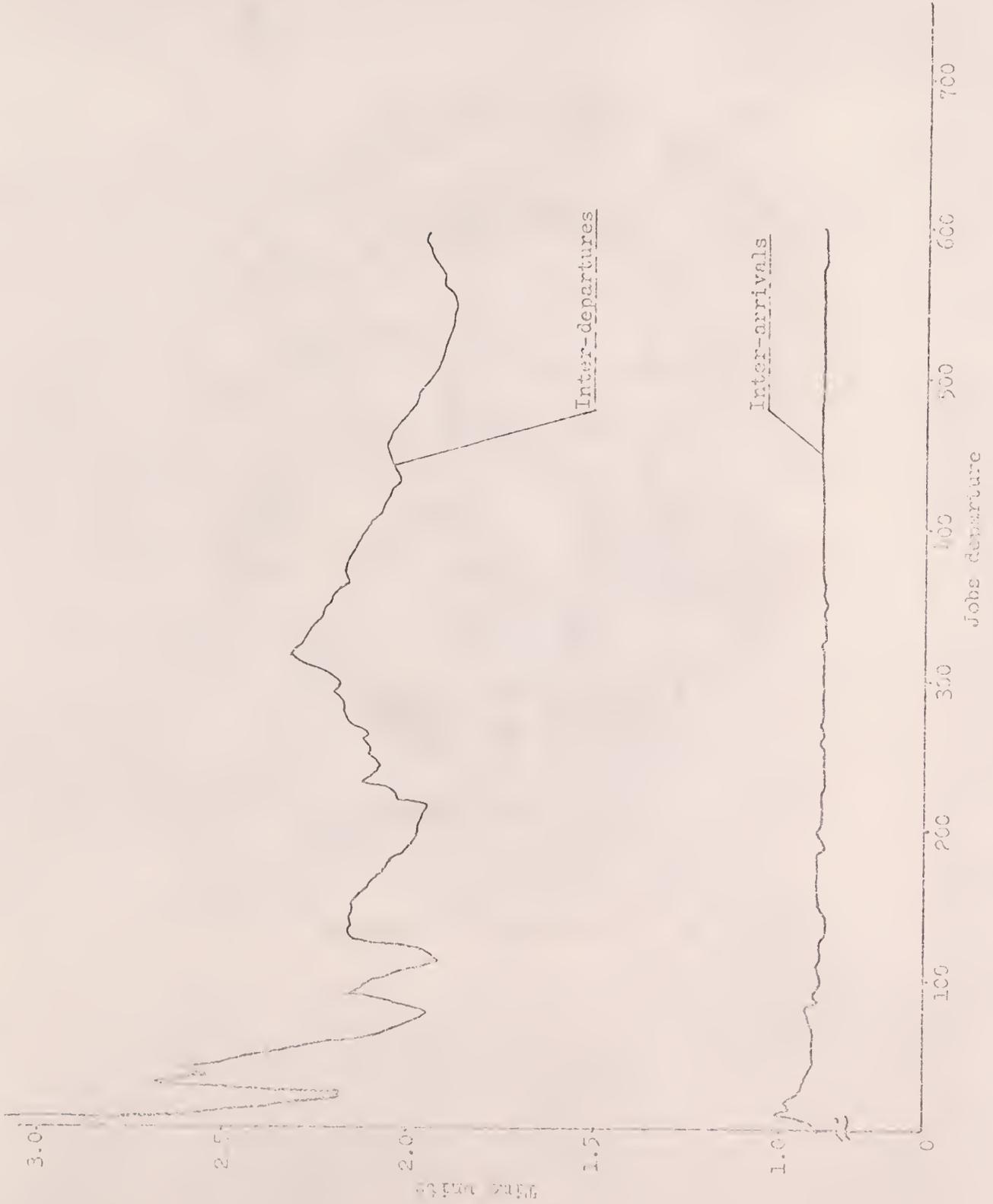


Figure B-12. Inter-arrivals and inter-departures of slack per remaining operations rule with processing time distribution of Figure 8.

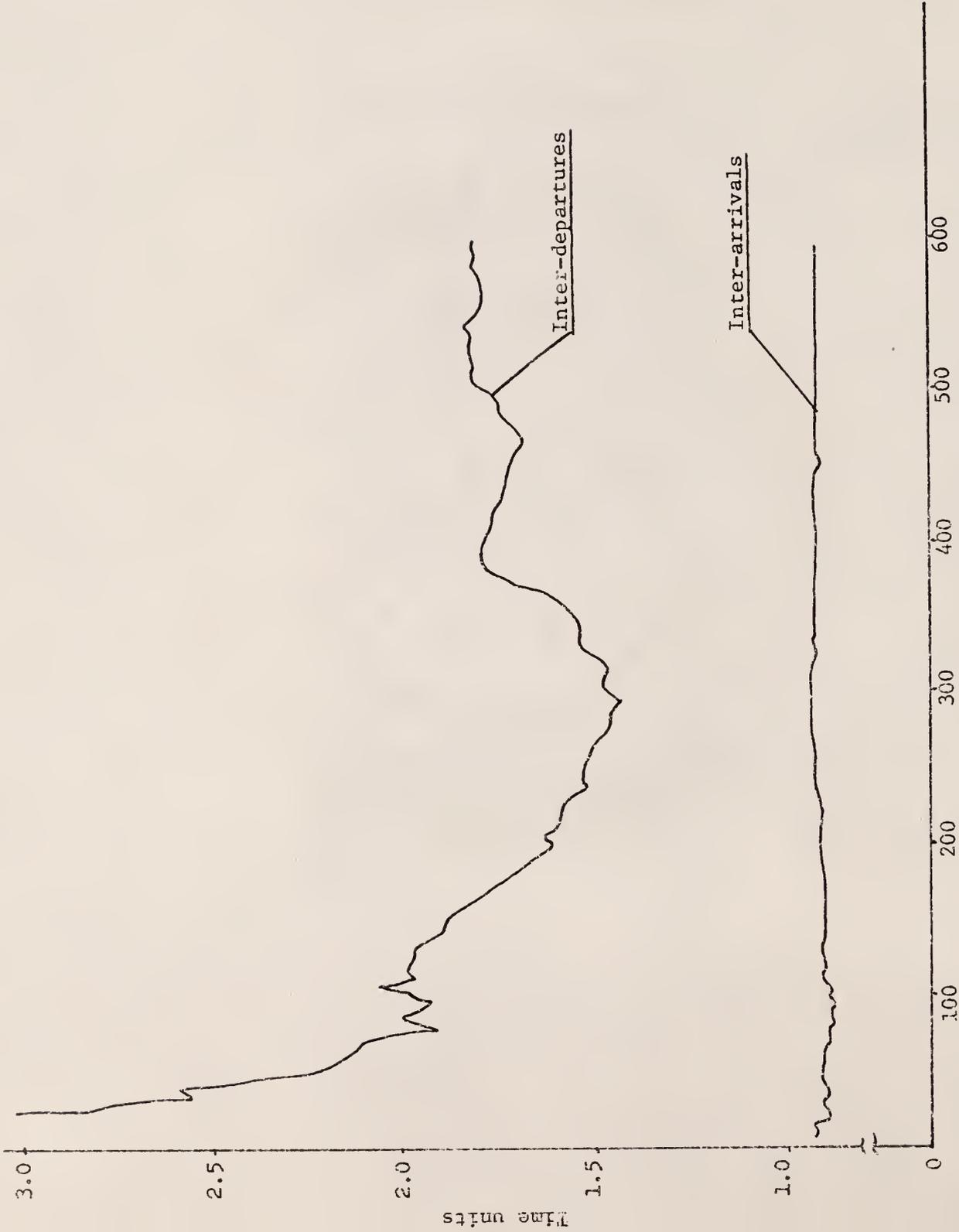


Figure B-14. Inter-arrivals and inter-departures of slack per remaining operations rule with processing time distribution of Erlang 8.

GASP SUMMARY REPORT

GENERATED DATA

CODE	OBS.	MEAN	STD. DEV.	MIN.	MAX.
------	------	------	-----------	------	------

STATISTICS FOR JOB LATENESS

1	1300	-35.48	24.08	-106.24	-4.17
2	100	-35.04	22.97	-82.80	-4.17
3	100	-34.60	24.48	-106.24	-5.11
4	100	-34.10	23.77	-78.85	-4.57
5	100	-36.39	25.22	-86.09	-4.79
6	100	-37.60	25.81	-93.70	-5.75
7	100	-35.70	24.24	-85.07	-5.69
8	100	-37.58	25.76	-85.91	-5.49
9	100	-32.52	21.84	-73.96	-5.37
10	100	-33.73	23.76	-80.57	-5.63
11	100	-38.22	22.39	-82.76	-5.40
12	100	-37.16	26.21	-98.64	-5.19
13	100	-34.09	23.21	-89.10	-4.88
14	100	-34.53	23.60	-87.03	-5.67
15		NO VALUES	RECORDED		

STATISTICS FOR SHOP FLOW TIME

16	1300	7.54	5.49	0.79	27.41
17	100	7.15	5.14	0.79	19.88
18	100	7.16	5.38	0.83	21.08
19	100	7.63	5.43	1.06	23.36
20	100	7.66	5.61	0.79	27.28
21	100	8.56	6.14	0.79	23.12
22	100	7.85	5.84	0.79	22.29
23	100	7.48	5.23	0.96	19.93
24	100	7.48	5.90	0.79	27.41
25	100	6.35	4.68	0.87	22.99
26	100	8.84	5.58	0.79	25.92
27	100	8.29	5.79	0.79	20.21
28	100	6.94	5.36	0.80	25.10
29	100	6.61	4.81	0.79	19.18
30		NO VALUES	RECORDED		
31		NO VALUES	RECORDED		

GASP SUMMARY REPORT

GENERATED DATA

CODE	OBS.	MEAN	STD. DEV.	MIN.	MAX.
------	------	------	-----------	------	------

STATISTICS FOR INTER-DEPARTURE

32	1300	0.89	0.81	0.0	5.51
33	100	1.04	0.93	0.0	4.06
34	100	0.88	0.77	0.01	3.46
35	100	0.81	0.70	0.0	4.19
36	100	0.91	0.84	0.0	4.39
37	100	0.84	0.73	0.0	2.82
38	100	0.86	0.91	0.0	5.51
39	100	0.87	0.78	0.0	3.81
40	100	0.79	0.69	0.02	3.44
41		NO VALUES RECORDED			

STATISTICS FOR INTER-ARRIVAL

42	1306	0.89	0.42	0.50	1.50
43	110	0.95	0.43	0.50	1.50
44	103	0.85	0.41	0.50	1.50
45	96	0.85	0.40	0.50	1.50
46	101	0.90	0.42	0.50	1.50
47	99	0.86	0.39	0.50	1.50
48	102	0.85	0.42	0.50	1.50
49	101	0.86	0.44	0.50	1.50
50	97	0.81	0.38	0.50	1.50

CODE	MEAN	STD. DEV.	TLOB	MAX.	TOTAL TIME
1	0.92	0.27	1155.45	1.00	1155.450
2	0.94	0.23	1156.99	1.00	1156.990
3	0.96	0.20	1154.67	1.00	1154.670
4	0.95	0.22	1157.00	1.00	1157.000
5	0.93	0.26	1156.14	1.00	1156.140
6	0.95	0.21	1156.34	1.00	1156.340
7	0.94	0.24	1146.56	1.00	1146.560
8	0.92	0.28	1153.66	1.00	1153.660
9	0.92	0.27	1156.85	1.00	1156.850
10	9.47	2.51	1157.20	18.00	1157.200

GROSS MACHINE UTILIZATION = 93.61

QUEUE PRINTOUT, QUEUE NO. 1

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 5.296
MAXIMUM 10

QUEUE CONTENTS

1157.32	2.00	1155.53	3.00	2.00	1.40	1305.00	2.00	1.40	1171.73	1170.33	1170.33	0.0
1157.39	2.00	1147.46	6.00	11.00	0.40	1297.00	10.00	0.80	1214.61	1213.81	606.90	1.00
1157.49	1.00	1157.49	4.00	12.00	0.40	1307.00	1.00	7.62	1226.09	1218.47	101.53	7.00
1157.73	2.00	1150.38	1.00	7.00	1.40	1300.00	5.00	3.23	1209.31	1206.08	402.02	5.00
1157.84	2.00	1156.98	2.00	7.00	0.86	1306.00	1.00	6.22	1212.97	1206.75	172.38	1.00

QUEUE PRINTOUT, QUEUE NO. 2

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 0.330
MAXIMUM 5

QUEUE CONTENTS

1156.42	1.00	1151.38	1.00	12.00	0.40	1302.00	8.00	5.31	1240.22	1234.91	246.97	8.00
---------	------	---------	------	-------	------	---------	------	------	---------	---------	--------	------

QUEUE PRINTOUT, QUEUE NO. 3

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 0.334
MAXIMUM 4

QUEUE CONTENTS

THE QUEUE IS EMPTY

QUEUE PRINTOUT, QUEUE NO. 4

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 0.338
MAXIMUM 6

QUEUE CONTENTS

1156.40	1.00	1152.88	3.00	8.00	1.08	1303.00	5.00	3.53	1204.90	1201.37	300.33	2.00
---------	------	---------	------	------	------	---------	------	------	---------	---------	--------	------

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 0.339
MAXIMUM 5

QUEUE CONTENTS

THE QUEUE IS EMPTY

QUEUE PRINTOUT, QUEUE NO. 6

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 0.433
MAXIMUM 5

QUEUE CONTENTS

THE QUEUE IS EMPTY

QUEUE PRINTOUT, QUEUE NO. 7

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 0.367
MAXIMUM 5

QUEUE CONTENTS

THE QUEUE IS EMPTY

QUEUE PRINTOUT, QUEUE NO. 8

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 0.407
MAXIMUM 5

QUEUE CONTENTS

THE QUEUE IS EMPTY

QUEUE PRINTOUT, QUEUE NO. 9

AVERAGE NO. OF ITEMS IN THE QUEUE WAS
MAXIMUM 6

0.314

QUEUE CONTENTS

THE QUEUE IS EMPTY

QUEUE PRINTOUT, QUEUE NO. 10

AVERAGE NO. OF ITEMS IN THE QUEUE WAS
MAXIMUM 5

0.320

QUEUE CONTENTS

THE QUEUE IS EMPTY

QUEUE PRINTOUT, QUEUE NO. 11

AVERAGE NO. OF ITEMS IN THE QUEUE WAS
MAXIMUM 12

4.499

QUEUE CONTENTS

1147.47	1.00	1147.47	1.00	11.00	0.40	1297.00
1156.99	1.00	1156.99	1.00	7.00	0.82	1306.00
1156.99	1.00	1156.99	1.00	7.00	1.40	1306.00
1157.49	1.00	1157.49	1.00	12.00	0.56	1307.00
1157.49	1.00	1157.49	1.00	12.00	1.25	1307.00

QUEUE PRINTOUT, QUEUE NO. 12

AVERAGE NO. OF ITEMS IN THE QUEUE WAS
MAXIMUM 13

4.273

QUEUE CONTENTS

1151.39	1.00	1151.39	2.00	12.00	1.04	1302.00
1152.89	1.00	1152.89	2.00	8.00	0.40	1303.00
1157.49	1.00	1157.49	2.00	12.00	0.45	1307.00

QUEUE PRINTOUT, QUEUE NO. 13

AVERAGE NO. OF ITEMS IN THE QUEUE WAS
MAXIMUM 14

4.384

11.00	0.40	1214.62	1214.22	1214.22	0.0
2.00	5.35	1212.98	1207.63	201.27	7.00
5.00	2.20	1212.98	1210.78	403.59	8.00
9.00	2.61	1226.09	1223.47	305.86	5.00
12.00	1.25	1226.09	1224.83	1224.83	0.0

10.00	3.51	1240.23	1236.72	412.23	7.00
6.00	2.44	1204.91	1202.46	400.82	8.00
8.00	3.07	1226.09	1223.02	244.60	1.00

QUEUE CONTENTS

1157.49	1.00	1157.49	3.00	12.00	0.51	1307.00
1157.49	1.00	1157.49	3.00	12.00	1.33	1307.00
1157.49	1.00	1157.49	3.00	12.00	0.40	1307.00

QUEUE PRINTOUT, QUEUE NO. 14

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 4.195
 MAXIMUM 13

QUEUE CONTENTS

1152.89	1.00	1152.89	4.00	8.00	1.40	1303.00
---------	------	---------	------	------	------	---------

QUEUE PRINTOUT, QUEUE NO. 15

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 4.303
 MAXIMUM 13

QUEUE CONTENTS

1150.39	1.00	1150.39	5.00	7.00	0.43	1300.00
1151.39	1.00	1151.39	5.00	12.00	1.06	1302.00
1156.99	1.00	1156.99	5.00	7.00	0.93	1306.00
1157.49	1.00	1157.49	5.00	12.00	0.40	1307.00

QUEUE PRINTOUT, QUEUE NO. 16

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 4.450
 MAXIMUM 12

QUEUE CONTENTS

1156.99	1.00	1156.99	6.00	7.00	0.40	1306.00
1157.49	1.00	1157.49	6.00	12.00	1.01	1307.00

QUEUE PRINTOUT, QUEUE NO. 17

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 4.172
 MAXIMUM 13

QUEUE CONTENTS

1151.39	1.00	1151.39	7.00	12.00	1.40	1302.00
1156.99	1.00	1156.99	7.00	7.00	1.40	1306.00
1157.49	1.00	1157.49	7.00	12.00	0.40	1307.00

QUEUE PRINTOUT, QUEUE NO. 18

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 4.253

3.00	6.82	1226.09	1219.27	121.92	6.00
6.00	4.89	1226.09	1221.20	174.45	9.00
11.00	1.65	1226.09	1224.43	612.21	1.00

8.00	1.40	1204.91	1203.51	1203.51	0.0
------	------	---------	---------	---------	-----

6.00	1.83	1209.32	1207.49	603.74	8.00
12.00	1.06	1240.23	1239.16	1239.16	0.0
4.00	3.13	1212.98	1209.85	302.46	1.00
10.00	2.05	1226.09	1224.03	408.01	3.00

7.00	0.40	1212.98	1212.58	1212.58	0.0
4.00	6.30	1226.09	1219.78	135.53	9.00

11.00	2.46	1240.23	1237.76	618.88	5.00
3.00	4.53	1212.98	1208.45	241.69	5.00
2.00	7.22	1226.09	1218.87	110.80	3.00

QUEUE CONTENTS

1150.39	1.00	1150.39	8.00	7.00	1.40	1300.00	7.00	1.40	1209.32	1207.92	1207.92	0.0
1151.39	1.00	1151.39	8.00	12.00	1.40	1302.00	9.00	4.91	1240.23	1235.32	308.83	2.00
1152.89	1.00	1152.89	8.00	8.00	0.64	1303.00	7.00	2.04	1204.91	1202.86	601.43	4.00
1156.99	1.00	1156.99	8.00	7.00	0.40	1306.00	6.00	0.80	1212.98	1212.18	606.09	6.00

QUEUE PRINTOUT, QUEUE NO. 19

AVERAGE NO. OF ITEMS IN THE QUEUE WAS 4.376
MAXIMUM 14

QUEUE CONTENTS

1157.49	1.00	1157.49	9.00	12.00	0.40	1307.00	5.00	5.29	1226.09	1220.80	152.60	3.00
1157.49	1.00	1157.49	9.00	12.00	0.48	1307.00	7.00	3.56	1226.09	1222.53	203.75	2.00

** RESULTS OF THE SIMULATION RUN **

PRIORITY RULE CODE	1
TOTAL NO. OF JOBS ARRIVED	1307
TOTAL NO. OF JOBS COMPLETED	1300
TOTAL NO. OF JOBS LATE	0
TOTAL UNCOMPLETED JOBS IN SHOP	7.

APPENDIX C

COMPUTER PROGRAM FLOW CHARTS AND LISTINGS

This appendix includes the flow charts of the computer program (internal subroutines). The computer program listings with the definitions of external subroutines and NON-GASP variables are also included.

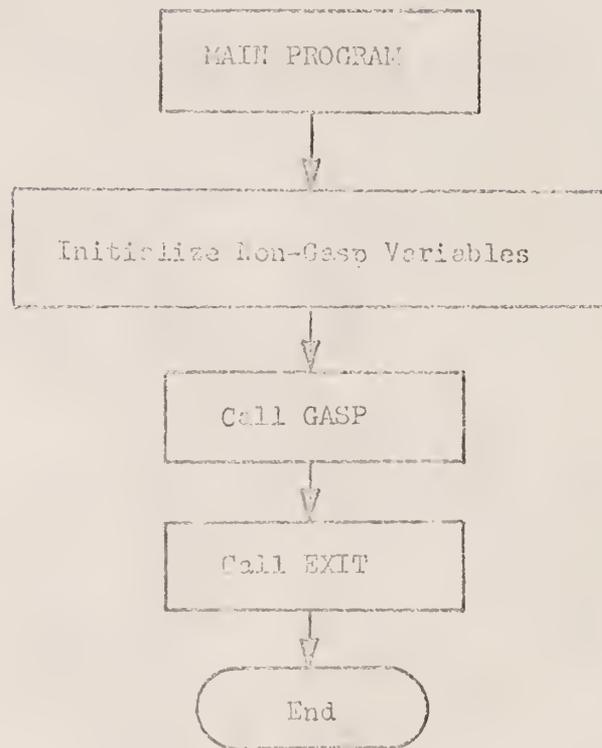
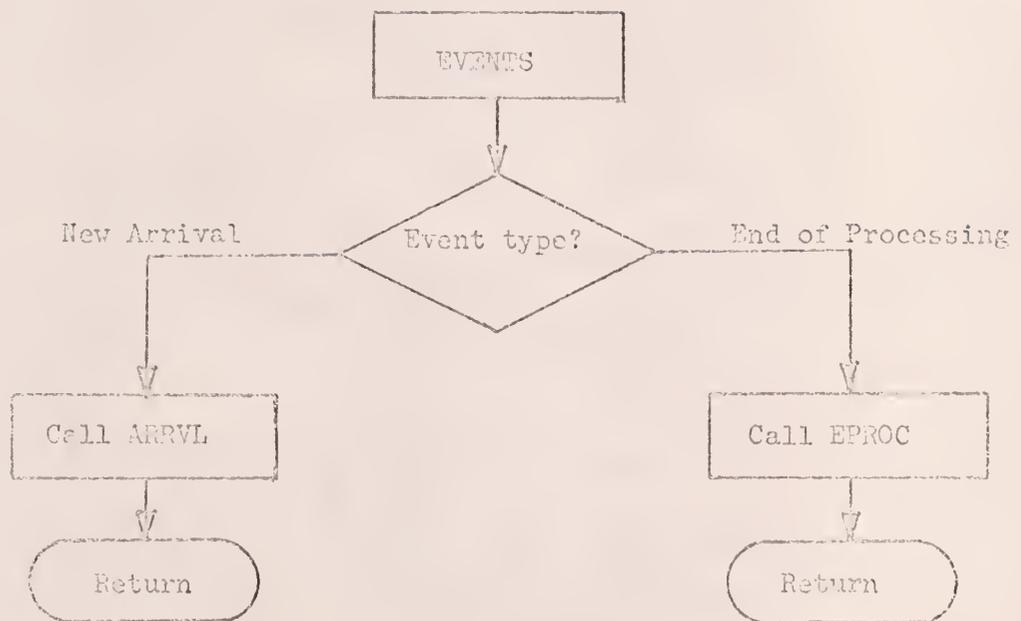


Figure C-1. Main Program

Figure C-2. Subroutine `EVENTS`

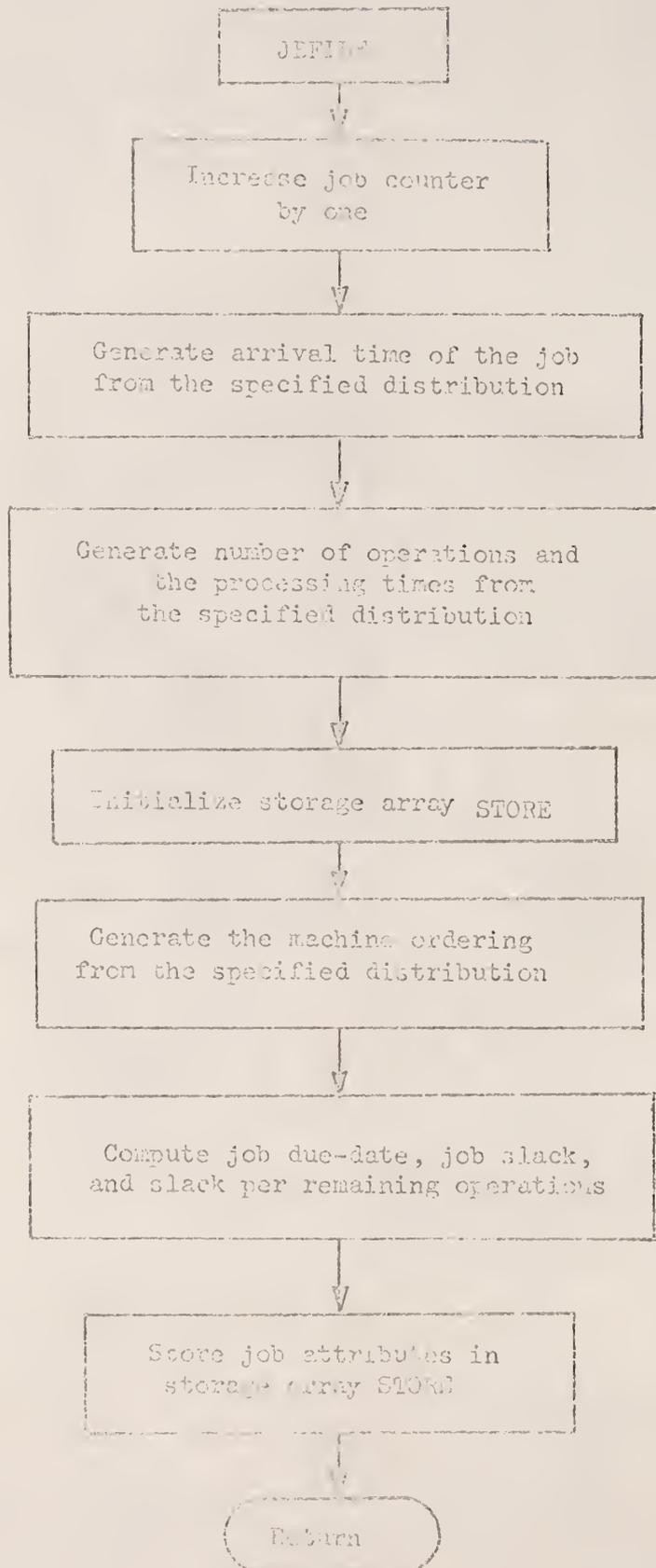
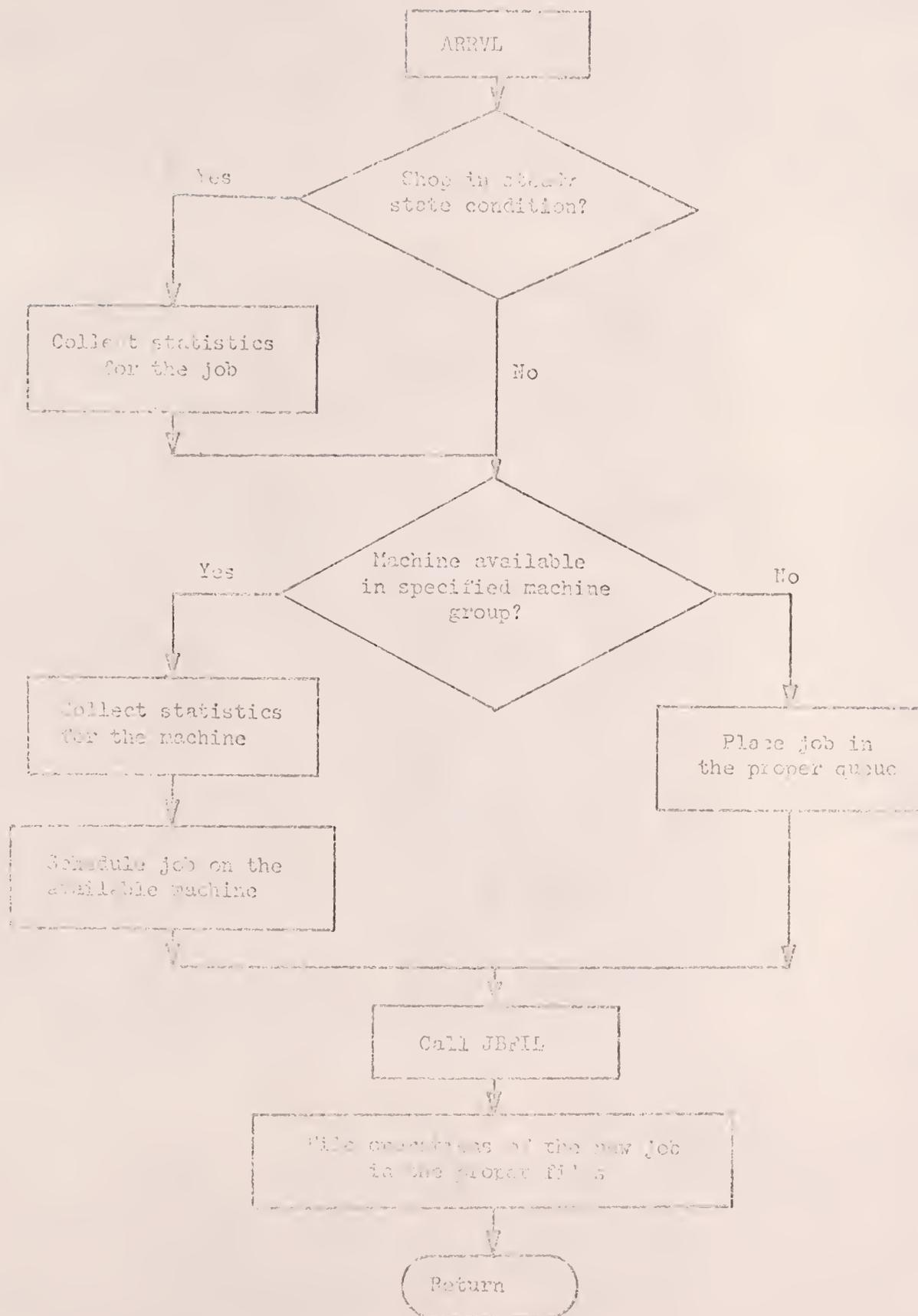


Figure C-3. Subroutine JEFIND



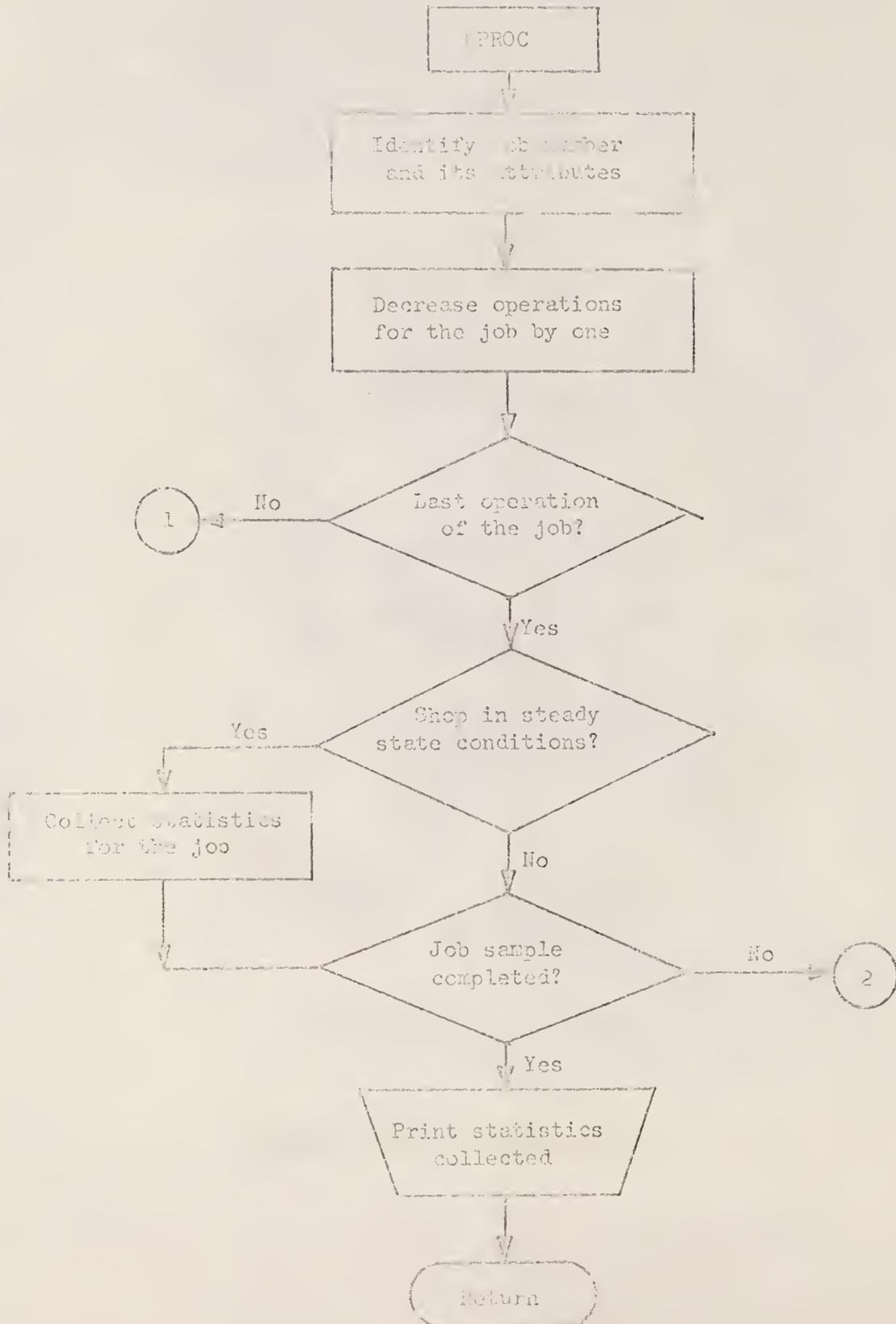


Figure C-5. Subroutine PROC

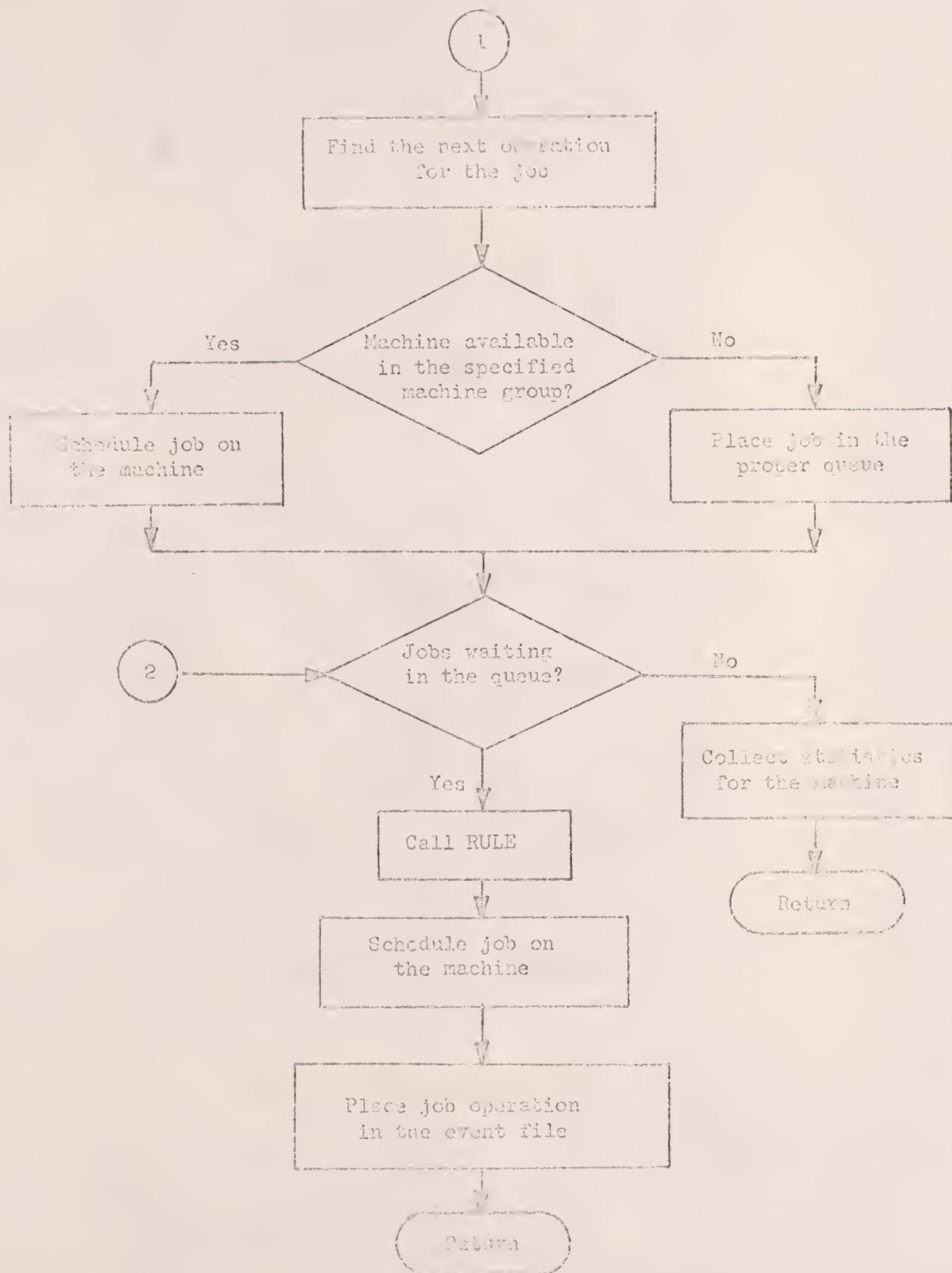


Figure G-5, Subroutine PROC (cont'd.)

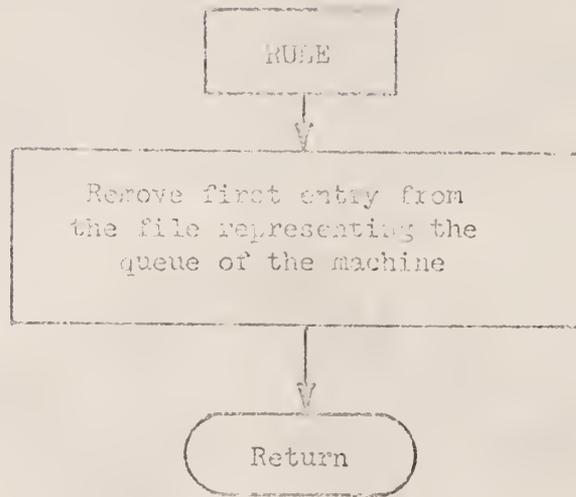


Figure C-6. Subroutine RULE

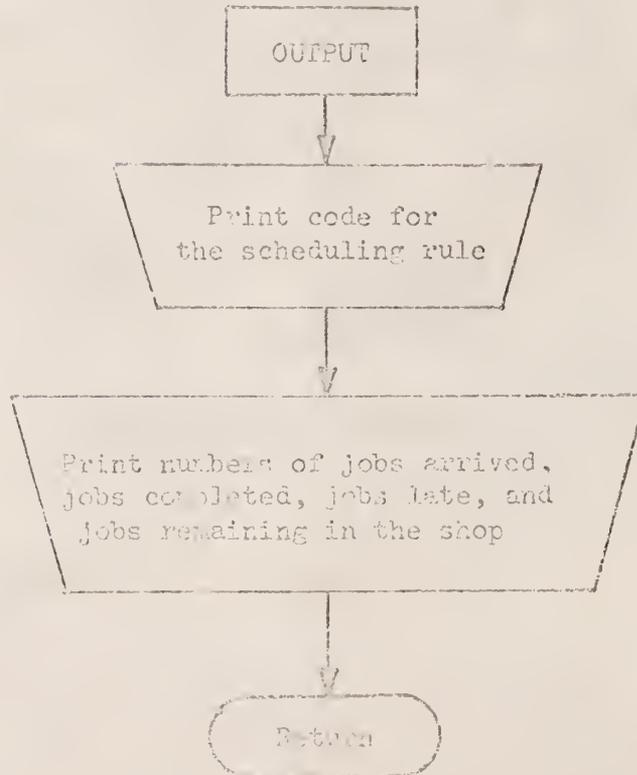


Figure C-7. Subroutine OUTPUT

C COMPUTER PROGRAM FOR TESTING SCHEDULING RULES IN AN
C INDEPENDENT NETWORK OF WORK CENTERS IN A JOB SHOP.
C THIS SIMULATION PROGRAM CONSISTS OF TWO GROUPS OF
C ROUTINES, THE EXTERNAL PROGRAM AND GASP ASSEMBLY PROGRAM.
C
C
C EXTERNAL PROGRAM SUBROUTINES
C
C MAIN : THIS ROUTINE INITIALIZES THE CONTROLLED
C VARIABLES AND CALLS SUBROUTINE GASP.
C
C
C EVENTS : THIS SUBROUTINE IS CALLED BY GASP AND FORMS A
C LINK BETWEEN EXTERNAL SUBROUTINES AND GASP
C DECK . A COMPUTED GO TO STATEMENT CALLS IN
C PROPER EVENT SUBROUTINE DEPENDING UPON THE
C NATURE OF EVENT .
C
C
C ARRVL : THIS SUBROUTINE IS CALLED BY EVENTS WHENEVER
C A NEW JOB ARRIVES IN THE SHOP . A CUSTOMER
C WAITS IN PROPER LINE OR IS SCHEDULED ON THE
C MACHINE DEPENDING UPON WHETHER THE MACHINE IS
C BUSY OR IDLE. THIS SUBROUTINE ALSO CALLS JBFIL
C WHICH GENERATES A FUTURE JOB WHICH IS TO ARRIVE
C LATTER IN THE SHOP.
C
C
C EPROC : THIS SUBROUTINE IS CALLED BY SUBROUTINE EVENTS
C WHENEVER AN END OF SERVICE EVENT TAKES PLACE .
C IT PROVIDES INFORMATION AS REGARDS TO THE
C MACHINE WHICH IS TO PROCESS NEXT THE JOB AS PER
C THE TECHNOLOGICAL ROUTING SPECIFIED . IT ALSO
C CALLS SUBROUTINE RULE WHICH, DEPENDING UPON
C THE PRIORITY RULE, SELECTS A JOB FROM A NUMBER
C OF JOBS WAITING IN A LINE OF THE MACHINE UNDER
C CONSIDERATION.
C
C
C RULE : THIS SUBROUTINE IS CALLED BY EPROC WHENEVER A
C A JOB IS TO BE SELECTED FROM A WAITING LINE OF
C A MACHINE AS PER THE PRIORITY RULE SPECIFIED .
C
C
C JBFIL : THIS SUBROUTINE IS CALLED WHEN A NEW JOB
C ARRIVES IN THE SHOP . IT GENERATES RANDOMLY
C FROM THE DESIRED DISTRIBUTIONS, VARIOOUS
C ATTRIBUTES OF THE JOB WHICH ARE STORED IN AN
C ARRAY STORE.
C
C
C
C ATTRIBUTES OF A GENERATED JOB:
C
C ATTRIB(1) SCHEDULED TIME OF NEXT EVENT

```

C      ATTRIB(2)      EVENT CODE
C                          1 = ARRIVAL
C                          2 = END OF PROCESSING
C
C      ATTRIB(3)      ARRIVAL TIME OF JOB IN SHOP
C      ATTRIB(4)      MACHINE GROUP NUMBER
C      ATTRIB(5)      NUMBER OF OPERATIONS ON JOB
C      ATTRIB(6)      PROCESSING TIME OF OPERATION
C      ATTRIB(7)      JOB NUMBER
C      ATTRIB(8)      OPERATION NUMBER
C      ATTRIB(9)      WORK REMAINING OF JOB ON ROUTING
C      ATTRIB(10)     DUE DATE OF JOB
C      ATTRIB(11)     NEXT MACHINE TO OPERATE ON JOB

```

CONTROL CARDS VARIABLES READ IN SUBROUTINE DATAIN:

CONTROL CARD NO. 1

```

C      NAME          NAME OF THE PROGRAMMER
C      NPROJ         PROJECT NUMBER
C      MON           MONTH
C      MDAY          DAY
C      NYR           YEAR
C      NRUNS        NUMBER OF SIMULATION RUNS

```

CONTROL CARD NO. 2

```

C      NPRAMS       NUMBER OF SETS OF PARAMETERS TO BE READ IN
C                  ( NPRAMS < 20 )
C      NHISTO       NUMBER OF HISTOGRAMS TO BE OBTAINED IN
C                  SIMULATION . ( NHISTO < 5 )
C      NCOLCT       NUMBER OF SETS OF STATISTICS TO BE COLLECTED
C                  IN SUBROUTINE COLECT . ( NCOLCT < 10 )
C      NSTAT        NUMBER OF SETS OF STATISTICS TO BE COLLECTED
C                  IN SUBROUTINE TMSTAT . ( NSTAT < 10 )
C      ID           NUMBER OF COLUMNS IN ARRAY NSET
C      IM           NUMBER OF ATTRIBUTES ROW IN NSET
C      NOQ          NUMBER OF FILES TO BE MAINTAINED
C      MXC          LARGEST NUMBER OF CELLS USED IN HISTOGRAM
C                  ( MXC < 22 )
C      SCALE        A PARAMETER USED TO MULTIPLY FLOATING POINT
C                  ATTRIBUTES PRIOR TO CHANGING THEM TO FIXED
C                  POINT FOR STORAGE IN NSET

```

CONTROL CARD NO. 3

```

C      MSTOP        CODE FOR METHOD OF ENDING SIMULATION
C                  MSTOP = 0, SIMULATION TERMINATES WHEN END
C                  OF SIMULATION EVENT OCCURS
C                  MSTOP > 0, SIMULATION TERMINATES WHEN
C                  PREDETERMINED TIME IS REACHED
C      JCLEAR       JCLEAR = 0 , SIMULATION IS STARTED FROM

```

C BEGINNING (TNOW = TSTART) . AND WITHOUT
 C CHANGING COMDITIONS OF RUN
 C JCLEAR = 1 , SYSTEM IS INITIALIZED AGAIN
 C PRIOR TO REPEATING A SIMULATION RUN
 C NORPT NORPT = 1 , SUBROUTINES SUMARY & OUTPUT
 C ARE BYPASSED
 C NORPT = 0 , SUMARY & OUTPUT ARE USED
 C NEP NEP = 1 , NEW PARAMETERS IN SUBROUTINE
 C DATAIN ARE READ IN
 C NEP = 1 , ONLY NSET, TNOW & STATISTICAL
 C ARRAYS ARE INITIALIZED
 C TSTART STARTING TIME OF SIMULATION
 C TSTOP TIME TO END SIMULATION
 C NSEED NUMBER OF SEED VALUES TO BE READ IN
 C
 C CONTROL CARD NO. 4
 C IX(I) VALUE OF INITIAL SEED NUMBER USING SEED
 C NO. I FOR GENERATING JOB ATTRIBUTES
 C
 C CONTROL CARD NO. 5
 C INN(I) IF INN(I) = 1, THE ENTRIES IN FILE I ARE
 C ORDERED BY KRANK(I) FROM LOWEST VALUE TO
 C HIGHEST VALUE(FIFO). IF INN(I)=2 8 THE
 C ENTRIES ARE ORDERED BY KRANK(I) FROM
 C HIGHEST VALUE TO LOWEST VALUE(LIFO)9
 C
 C CONTROL CARD NO. 6
 C KRANK(I) JOB ATTRIBUTE ROW ON WHICH FILE I IS RANKED
 C
 C CONTROL CARD NO. 7
 C JSMP JOBS PER SIMULATION RUN
 C MGRP NO. OF MACHINE GROUPS IN SHOP
 C NRUL PRIORITY RULE CODE NUMBER
 C 1 SHORTEST IMMINENT OPERATION
 C 2 FIRST COME FIRST SERVED
 C 3 EARLIEST JOB DUE DATE
 C 4 JOB SLACK TIME
 C 5 SLACK PER REMAINING OPERATIONS
 C
 C KODE CODE FOR METHOD OF COMPUTING DUE DATES
 C 2 MULTIPLIER EQUAL TO NUMBER OF
 C OPERATIONS PER JOB
 C
 C NJOB JOB ARRIVAL COUNTER
 C
 C CONTROL CARD NO. 8
 C MACH(I) NUMBER OF MACHINES IN MACHINE GROUP I
 C
 C CONTROL CARD NO. 9
 C NCELLS(I) NUMBER OF CELLS IN HISTOGRAM I

C
C CONTROL CARDS NO. 10,11,12,13

C EACH OF THE FOLLOWING CARD CONSISTS OF FOUR
C PARAMETERS, J=1,2,3,4

- C - ARRIVAL DISTRIBUTION PARAMETERS (I=1)
C - INTERARRIVAL DISTRIBUTION PARAMETERS (I=2)
C - NUMBER OF OPERATIONS DISTRIBUTION PARAMETERS (I=3)
C - MACHINE ROUTING DISTRIBUTION PARAMETERS (I=4)
C - PROCESSING TIME DISTRIBUTION PARAMETERS (I=5)

C CONTROL CARD NO. 11

C KDSTAR CODE FOR ARRIVAL DISTRIBUTION
C KDSTIA CODE FOR INTERARRIVAL DISTRIBUTION
C KDSTOP CODE FOR DISTR. FOR NUMBER OF OPERATIO S
C KDSTRT CODE FOR MACHINE ROUTING
C KDSTPR CODE FOR PROCESSING TIME DISTRIBUTION

- C 1 ERLANG
C 2 POISSON
C 3 GEOMETRIC
C 4 UNIFORM
C 5 NORMAL

C CONTROL CARDS NO. 14

C THE POSITION OF THE CONTROL CARD(WITHIN CONTROL
C CARDS NO. 10,11,12,13) TO BE READ FOR SPECIFYING:

C ICDARR ARRIVAL DISTRIBUTION
C ICDIAR INTERARRIVAL DISTRIBUTION
C ICDOPR NUMBER OF OPERATION DISTRIBUTION
C ICDRTG MACHINE ROUTING DISTRIBUTION
C ICDPRC PROCESSING TIME DISTRIBUTION

C EXTERNAL PROGRAM VARIABLES :

C LTNES JOB LATENESS
C TBD TIME BETWEEN DEPARTURES
C JA JOB ARRIVAL COUNTER
C JD JOB DEPARTURE COUNTER
C MG NUMBER OF MACHINE GROUPS IN THE SHOP
C IOPN NUMBER OF OPERATIONS
C JLAT& NUMBE- OF JOBS LATE
C NOPRM(J) NUMBER OF OPERATIONS REMAINING FOR JOB J
C MACH(I) NUMBER OF MACHINES IN MACHINE GROUP I
C MAVL(I) NUMBER OF MACHINES AVAILABLE IN MACHINE
C GROUP I
C MCG(J) MACHINE NUMBER FOR JOB J
C XIAT INTER-ARRIVAL TIME
C TLA TIME OF LAST ARRIVAL OF A JOB

SUBROUTINE JBFILE(NSET)

C
C
C
C
C
C
C
C

ERLANG	1
POISSON	2
GEOMETRIC	3
UNIFORM	4
NORMAL	5

```

COMMON ID,IM,INIT,JEVENT,JMONIT,MFA,MSTOP,MX,MXC,
1NORPT,NOT,NPRAMS,NRUN,NRUNS,NSTAT,NSEED,MAXX,NEP,
2NCOLCT,NHISTO,NOQ
COMMON INN(19),JCELLS(5,22),KRANK(19),MAXNQ(19),
1MFE(19),MLC(19),MLE(19),NCELLS(5),NQ(19),IX(8)
COMMON OUT,SCALE,TNOW,TSTART,TSTOP
COMMON ATTRIB(13),ENQ(19),PARAMS(20,4),QTIME(19),
1SSUMA(30,5),SUMA(50,5)
COMMON MGQ,LTNES,NJOB,JA,JD,JOB,KODE,KTR,MG,
1JWRM,JSMP,ISUMR,IOPN,LONE,JLATE
COMMON NOPRM(1500),MACH(19),MAVL(19),MCG(20)
COMMON WRM,XIAT,TLA,DDT,XISHP,XMBUZ,TLD,TBD
COMMON SPTM(1500),STORE(15,15),TSHOP(1500),
1WORKQ(15),PTM(25)
COMMON MGRP,NPRL,NRUL,ICDARR,ICDIAR,ICDOPR,
1ICDRTG,ICDPRC,KDSTAR,KDSTIA,KDSTOP,KDSTRT,KDSTPR
COMMON XLTNS

```

C

```

DIMENSION NSET(15,1)
ATTRIB(1) = 0.
NJOB = NJOB+1
JA = NJOB
IF(KDSTAR.EQ.0) GO TO 5
GO TO (1,2,3),KDSTAR
1 PRINT 4000
4000 FORMAT(1H1,' WRONG DIST. SELECTED '/')
CALL EXIT
2 ARVTM = NPOISN(1,ICDARR)
GO TO 14
3 ARVTM = GEMTR(1,ICDARR)
14 ATTRIB(1) = ARVTM
GO TO 16
5 IF(KDSTIA.EQ.0) GO TO 6
GO TO 7
6 PRINT 406
406 FORMAT(1H1,' NO DIST. SELECTED FOR ARRIVALS '/')
CALL EXIT
7 GO TO (8,1,1,1,9),KDSTIA
8 BARVTM = ERLANG(1,ICDIAR)
GO TO 10
9 BARVTM = RNORML(1,ICDIAR)

```

```

10 GO TO 12
12 ATTRIB(1) = BT+BARVTM
   BT = ATTRIB(1)
16 ATTRIB(2) = 1.
   ATTRIB(3) = ATTRIB(1)
   ATTRIB(7) = JA

```

C
C
C

GENERATING NUMBER OF OPERATIOIS PER JOB

```

   GO TO (1,1,18,17,1),KDSTOP
17 A = PARAMS(ICDOPR,1)
   B = PARAMS(ICDOPR,2)
   IOPN = A+(B-A)*DRAND(1)
   GO TO 19
18 IOPN = GEMTR(1,ICDOPR)
19 ATTRIB(5) = IOPN

```

C
C
C

GENERATING PROCESSING TIME OF EACH OPERATION

```

   SPTM(JA) = 0.
   GO TO (21,1,1,1,22),KDSTPR
21 DO 20 I=1,IOPN
   PTM(I) = ERLANG(1,ICDPRC)
   SPTM(JA) = SPTM(JA)+PTM(I)
   DO 20 J=1,11
   STORE(I,J) = 0.
20 CONTINUE
   GO TO 24
22 DO 23 I= 1,IOPN
   PTM(I) = RNORML(1,ICDPRC)
   SPTM(JA) = SPTM(JA)+PTM(I)
   DO 23 J=1,11
   STORE(I,J) = 0.
23 CONTINUE

```

C
C
C

GENERATING MACHINE ROUTING

```

24 WRM = SPTM(JA)
   IP = 10
   DO 60 I=1,IOPN
35 MCG(I) = 1+(MGRP)*DRAND(1)
   IF(MCG(I).EQ.IP) GO TO 35
   ATTRIB(4) = MCG(I)
   IP = MCG(I)
   ATTRIB(8) = I
   ATTRIB(6) = PTM(I)
   IF(I.EQ.1) GO TO 40
   WRM = WRM-PTM(I-1)
   ATTRIB(9) = WRM
   GO TO (36,37),KODE

```

```
36 ATTRIB(10) = ATTRIB(1)+9.*SPTM(JA)
   GO TO 50
37 ATTRIB(10) = ATTRIB(1)+IOPN*SPTM(JA)
   GO TO 50
40 ATTRIB(9) = WRM
   GO TO (38,39),KODE
38 ATTRIB(10) = ATTRIB(1)+9.*SPTM(JA)
   GO TO 50
39 ATTRIB(10) = ATTRIB(1)+IOPN*SPTM(JA)
50 ATTRIB(11) = ATTRIB(10)-ATTRIB(9)
   ATTRIB(12) = ATTRIB(11)/(IOPN-I+1)
   DO 60 J=1,12
60 STORE(I,J) = ATTRIB(J)
   STORE(IOPN,13) = 0.
   LL = IOPN-1
   DO 70 I=1,LL
70 STORE(I,13) = MCG(I+1)
   RETURN
   END
```

SUBROUTINE EVENTS(I,NSET)

C

```
COMMON ID,IM,INIT,JEVENT,JMONIT,MFA,MSTOP,MX,MXC,
1NORPT,NOT,NPRAMS,NRUN,NRUNS,NSTAT,NSEED,MXX,NEP,
2NCOLCT,NHISTO,NOQ
```

```
COMMON INN(19),JCELLS(5,22),KRANK(19),MAXNQ(19),
1MFE(19),MLC(19),MLE(19),NCELLS(5),NQ(19),IX(8)
```

```
COMMON OUT,SCALE,TNOW,TSTART,TSTOP
```

```
COMMON ATTRIB(13),ENQ(19),PARAMS(20,4),QTIME(19),
1SSUMA(30,5),SUMA(50,5)
```

```
COMMON MGQ,LTNES,NJOB,JA,JD,JOB,KODE,KTR,MG,
1JWRM,JSMP,ISUMR,IOPN,LONE, JLATE
```

```
COMMON NOPRM(1500),MACH(19),MAVL(19),MCG(20)
```

```
COMMON WRM,XIAT,TLA,DDT,XISHP,XMBUZ,TLD,TBD
```

```
COMMON SPTM(1500),STORE(15,15),TSHOP(1500),
1WORKQ(15),PTM(25)
```

```
COMMON MGRP,NPRL,NRUL,ICDARR,ICDIAR,ICDOPR,
1ICDRTG,ICDPRC,KDSTAR,KDSTIA,KDSTOP,KDSTRT,KDSTPR
```

```
COMMON XLTNS
```

C

```
DIMENSION NSET(15,1)
```

```
GO TO (1,2),I
```

```
1 CALL ARRVL(NSET)
```

```
RETURN
```

```
2 CALL EPROC(NSET)
```

```
RETURN
```

```
END
```

SUBROUTINE ARRVL(NSET)

C

```

COMMON ID,IM,INIT,JEVENT,JMONIT,MFA,MSTOP,MX,MXC,
1NORPT,NOT,NPRAMS,NRUN,NRUNS,NSTAT,NSEED,MXX,NEP,
2NCOLCT,NHISTO,NOQ
COMMON INN(19),JCELLS(5,22),KRANK(19),MAXNQ(19),
1MFE(19),MLC(19),MLE(19),NCELLS(5),NQ(19),IX(8)
COMMON OUT,SCALE,TNOW,TSTART,TSTOP
COMMON ATTRIB(13),ENQ(19),PARAMS(20,4),QTIME(19),
1SSUMA(30,5),SUMA(50,5)
COMMON MGQ,LTNES,NJOB,JA,JD,JOB,KODE,KTR,MG,
1JWRM,JSMP,ISUMR,IOPN,LONE, JLATE
COMMON NOPRM(1500),MACH(19),MAVL(19),MCG(20)
COMMON WRM,XIAT,TLA,DDT,XISHP,XMBUZ,TLD,TBD
COMMON SPTM(1500),STORE(15,15),TSHOP(1500),
1WORKQ(15),PTM(25)
COMMON MGRP,NPRL,NRUL,ICDARR,ICDIAR,ICDOPR,
1ICDRTG,ICDPRC,KDSTAR,KDSTIA,KDSTOP,KDSTRT,KDSTPR
COMMON XLTNS

```

C

```

DIMENSION NSET(15,1)
CALL TMSTAT(XISHP,TNOW,10,NSET)
XISHP = XISHP+1.
XIAT = TNOW-TLA
CALL HISTOG(XIAT,0.,0.4,1)
CALL COLECT(XIAT,42,NSET)
TLA = TNOW
LSF = 1
DO 20 I=101,1501,100
LSF = LSF+1
IF(JD.LT.I) GO TO 21
20 CONTINUE
21 IF(JD.GT.800) GO TO 23
22 JSF = LSF+41
CALL COLECT(XIAT,JSF,NSET)
23 CALL HISTOG(TNOW,0.,0.4,2)
IOPN = ATTRIB(5)
NOPRM(JA) = IOPN
MG = ATTRIB(4)
IF (MAVL(MG))12,30,25
12 CALL ERROR(NSET)

```

C

C

C

SCHEDULE NEXT JOB ON IDLE MACHINE

```

25 XMBUZ = MACH(MG)-MAVL(MG)
CALL TMSTAT(XMBUZ,TNOW,MG,NSET)
MAVL(MG) = MAVL(MG)-1
ATTRIB(1) = TNOW+ATTRIB(6)
ATTRIB(2) = 2.
CALL FILEM(1,NSET)

```

```
GO TO 65
C
C     IF NO MACHINE IS AVAILABLE THEN JOB MUST WAIT
C
30 ATTRIB(1) = TNOW
   ATTRIB(2) = 1.
   MGQ = MG+1
   CALL FILEM(MGQ,NSET)
C
C     RELEASE NEXT JOB IN THE SHOP
C
65 CALL JBFILE(NSET)
   DO 70 K=1,13
70 ATTRIB(K) = STORE(1,K)
   ATTRIB(3) = ATTRIB(1)
   IOPN = ATTRIB(5)
   CALL FILEM(1,NSET)
   DO 80 I=2,IOPN
   DO 90 J=1,13
90 ATTRIB(J) = STORE(I,J)
   ATTRIB(3) = ATTRIB(1)
   MG = ATTRIB(4)
   LONE = MG+10
   CALL FILEM(LONE,NSET)
80 CONTINUE
   RETURN
   END
```

SUBROUTINE RULE(NSET)

C
COMMON ID,IM,INIT,JEVENT,JMONIT,MFA,MSTOP,MX,MXC,
1NORPT,NOT,NPRAMS,NRUN,NRUNS,NSTAT,NSEED,MXX,NEP,
2NCOLCT,NHISTO,NOQ
COMMON INN(19),JCELLS(5,22),KRANK(19),MAXNQ(19),
1MFE(19),MLC(19),MLE(19),NCELLS(5),NQ(19),IX(8)
COMMON OUT,SCALE,TNOW,TSTART,TSTOP
COMMON ATTRIB(13),ENQ(19),PARAMS(20,4),QTIME(19),
1SSUMA(30,5),SUMA(50,5)
COMMON MGQ,LTNES,NJOB,JA,JD,JOB,KODE,KTR,MG,
1JWRM,JSMP,ISUMR,IOPN,LONE, JLATE
COMMON NOPRM(1500),MACH(19),MAVL(19),MCG(20)
COMMON WRM,XIAT,TLA,DDT,XISHP,XMBUZ,TLD,TBD
COMMON SPTM(1500),STORE(15,15),TSHOP(1500),
1WORKQ(15),PTM(25)
COMMON MGRP,NPRL,NRUL,ICDARR,ICDIAR,ICDOPR,
1ICDRTG,ICDPRC,KDSTAR,KDSTIA,KDSTOP,KDSTRT,KDSTPR
COMMON XLTNS
C
DIMENSION NSET(15,1)
C
MFEQ = MFE(MGQ)
1 CALL REMOVE(MFEQ,MGQ,NSET)
RETURN
END

```

SUBROUTINE EPROC(NSET)
C
COMMON ID,IM,INIT,JEVENT,JMONIT,MFA,MSTOP,MX,MXC,
1NORPT,NOT,NPRAMS,NRUN,NRUNS,NSTAT,NSEED,MXX,NEP,
2NCOLCT,NHISTO,NOQ
COMMON INN(19),JCELLS(5,22),KRANK(19),MAXNQ(19),
1MFE(19),MLC(19),MLE(19),NCELLS(5),NQ(19),IX(8)
COMMON OUT,SCALE,TNOW,TSTART,TSTOP
COMMON ATTRIB(13),ENQ(19),PARAMS(20,4),QTIME(19),
1SSUMA(30,5),SUMA(50,5)
COMMON MGQ,LTNES,NJOB,JA,JD,JOB,KODE,KTR,MG,
1JWRM,JSMP,ISUMR,IOPN,LONE, JLATE
COMMON NOPRM(1500),MACH(19),MAVL(19),MCG(20)
COMMON WRM,XIAT,TLA,DDT,XISHP,XMBUZ,TLD,TBD
COMMON SPTM(1500),STORE(15,15),TSHOP(1500),
1WORKQ(15),PTM(25)
COMMON MGRP,NPRL,NRUL,ICDARR,ICDIAR,ICDOPR,
1ICDRTG,ICDPRC,KDSTAR,KDSTIA,KDSTOP,KDSTRT,KDSTPR
COMMON XLTNS
C
DIMENSION NSET(15,1)
7000 FORMAT(1H ,4I5)
LONE = ATTRIB(13)+10.
DDT = ATTRIB(10)
MG = ATTRIB(4)
MGQ = MG+1
JOB = ATTRIB(7)
NOPRM(JOB) = NOPRM(JOB)-1
C
C      IF ALL OPERATIONS HAVE BEEN COMPLETED ON A JOB
C
IF (NOPRM(JOB)) 10,10,50
10 IF (ATTRIB(3)-TSTART)20,20,5
5 IF (ATTRIB(3)-TSTOP)2,2,20
C
C      COLLECT STATISTICS ON COMPLETED JOB
C
2 M = ATTRIB(5)
XLTNS = ATTRIB(1)-DDT
IF(XLTNS.GT.0) GO TO 12
GO TO 14
12 JLATE = JLATE+1
14 CALL COLECT(XLTNS,1,NSET)
CALL HISTOG(XLTNS,-200.,20.,4)
15 TSHOP(JOB) = ATTRIB(1)-ATTRIB(3)
CALL COLECT(TSHOP(JOB),16,NSET)
CALL HISTOG(TSHOP(JOB),5.,10.,5)
CALL TMSTAT(XISHP,TNOW,10,NSET)
XISHP = XISHP-1.
JD = JD+1

```

```

TBD = TNOW-TLD
CALL COLECT(TBD,32,NSET)
TLD = TNOW
IF(JD.GT.800) GO TO 6
8  XIAVG = SUMA(42,1)/SUMA(42,3)
   XBDVG = SUMA(32,1)/SUMA(32,3)
   XTSVG = SUMA(16,1)/SUMA(16,3)
   XLTVG = SUMA(1,1)/SUMA(1,3)
1000 FORMAT(1H ,2I6,F8.1,4F10.2)
    PRINT 1000,JA,JD,TNOW,XIAVG,XBDVG,XTSVG,XLTVG
6  CALL HISTOG(TBD,0.,0.4,3)
   NSF = 1
   DO 22 I=101,1501,100
   NSF = NSF+1
   IF(JD.LT.I) GO TO 23
22 CONTINUE
23 MSF = NSF+15
   CALL COLECT(XLTNS,NSF,NSET)
   CALL COLECT(TSHOP(JOB),MSF,NSET)
   IF(JD.GT.800) GO TO 17
21 KSF = NSF+31
   CALL COLECT(TBD,KSF,NSET)
   GO TO 17
16 JD = JD+1
   XISHP = XISHP-1.
   TBD = TNOW-TLD
   TLD = TNOW
17 IF(JA.EQ.1499) GO TO 3
   IF (JD-JSMP) 20,3,3

```

C
C
C

JOB SAMPLE HAS BEEN COMPLETED AT THIS POINT

```

3  NEP = 1
   MSTOP =-1
   NORPT =0
   RETURN

```

C
C
C

UPDATING STATUS OF MACHINE GROUP

```

20 IF (NQ(MGQ)) 30,30,40
30 XMBUZ = MACH(MG)-MAVL(MG)
   CALL TMSTAT(XMBUZ,TNOW,MG,NSET)
18 MAVL(MG) = MAVL(MG)+1
   RETURN

```

C
C
C

SELECT NEXT OPERATION OF JOB

```

50 XJOB = JOB
   CALL FIND(XJOB,7,LONE,5,KCOL,NSET)
   CALL REMOVE(KCOL,LONE,NSET)

```

```
MCH = ATTRIB(4)
MCF = MCH+1
IF(MAVL(MCH)) 45,45,60
45 ATTRIB(1) = TNOW
ATTRIB(2) = 1.
CALL FILEM(MCF,NSET)
70 IF(NQ(MGQ)) 55,55,40
55 XMBUZ = MACH(MG)-MAVL(MG)
CALL TMSTAT(XMBUZ,TNOW,MG,NSET)
19 MAVL(MG) = MAVL(MG)+1
RETURN
60 MAVL(MCH) = MAVL(MCH)-1
ATTRIB(1) = TNOW+ATTRIB(6)
ATTRIB(2) = 2.
CALL FILEM(1,NSET)
GO TO 70
40 CALL RULE(NSET)
ATTRIB(1) = TNOW+ATTRIB(6)
ATTRIB(2) = 2.
WORKQ(MG) = WORKQ(MG)-ATTRIB(6)
CALL FILEM(1,NSET)
RETURN
END
```

SUBROUTINE OUTPUT(NSET)

C

```

COMMON ID,IM,INIT,JEVENT,JMONIT,MFA,MSTOP,MX,MXC,
1NORPT,NOT,NPRAMS,NRUN,NRUNS,NSTAT,NSEED,MXX,NEP,
2NCOLCT,NHISTO,NOQ
COMMON INN(19),JCELLS(5,22),KRANK(19),MAXNQ(19),
1MFE(19),MLC(19),MLE(19),NCELLS(5),NQ(19),IX(8)
COMMON OUT,SCALE,TNOW,TSTART,TSTOP
COMMON ATTRIB(13),ENQ(19),PARAMS(20,4),QTIME(19),
1SSUMA(30,5),SUMA(50,5)
COMMON MGQ,LTNES,NJOB,JA,JD,JOB,KODE,KTR,MG,
1JWRM,JSMP,ISUMR,IOPN,LONE,JLATE
COMMON NOPRM(1500),MACH(19),MAVL(19),MCG(20)
COMMON WRM,XIAT,TLA,DDT,XISHP,XMBUZ,TLD,TBD
COMMON SPTM(1500),STORE(15,15),TSHOP(1500),
1WORKQ(15),PTM(25)
COMMON MGRP,NPRL,NRUL,ICDARR,ICDIAR,ICDOPR,
1ICDRTG,ICDPRC,KDSTAR,KDSTIA,KDSTOP,KDSTRT,KDSTPR
COMMON XLTNS

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C

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DIMENSION NSET(15,1)
100 FORMAT(1H1,20X,' ** RESULTS OF SIMULATION RUN ** ' //)
200 FORMAT(1H ,20X,' PRIORITY RULE CODE ',7X,I10/)
300 FORMAT(1H ,20X,' TOTAL NO. OF JOBS ARRIVED',I10/)
400 FORMAT(1H ,20X,' TOTAL NO. OF JOBS COMPLETED ',I7/)
500 FORMAT(1H ,20X,' TOTAL NO. OF JOBS LATE ',3X,I10/)
600 FORMAT(1H1)
700 FORMAT(1H ,20X,' TOTAL UNCOMPLETED JOBS IN SHOP',F5.0/)
PRINT 100
PRINT 200,NRUL
PRINT 300,JA
PRINT 400,JD
PRINT 500,JLATE
PRINT 700,XISHP
PRINT 600
RETURN
END

```

JOB SHOP SIMULATION

by

SANTOSH DIPCHAND VASWANI

B. E. (Mech. and Elect.), Shivaji University, 1965

AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1969

The purpose of the research is to (1) present a consistent and more comprehensive review of the most important job shop simulation experiments conducted since 1960; (2) develop a method of assigning job due-dates, and testing it; (3) evaluate the efficiency of GASP-II in handling simulation experiments; and (4) study the effect of different processing time distribution on the performance of the rules.

Considerable experimental investigation is conducted. The most significant results are: (1) the shortest imminent operation rule is superior to others in reducing job lateness and shop flow time; (2) the procedure in which the due-date allowance is proportional to the number of operations and work content of the jobs has proved to be beneficial in the case of the non-due-date rules such as first-come first-served and shortest imminent operation time rules; (3) the performance of the shortest imminent operation time and slack per remaining number of operations rules are affected badly with the use of the processing time distributions of Erlang with parameter K equalling 4 and 8. However, the performances under Erlang 8 are better than those obtained under Erlang 4; and (4) the GASP-II works equally good for large size of shop problems. The simulation computer execution time of runs; ranging from 600 to 1300 departed jobs, varies from 18 to 23 minutes depending on the rules tested.

