THE EFFECT OF ORDER SIZE ON THE OPERATION OF A HYPOTHETICAL JOB SHOP MANUFACTURING SYSTEM

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PREFACE

This investigation was based upon the idea that the operation of a job shop manufacturing system is affected by the sizes of orders processed through it. The approach was to build a hypothetical job shop with well defined capabilities and to test its reaction to different order sizes and different mixtures of order sizes. Criteria were established to detect any differences in the reactions of the system to the various test conditions.

The literature search failed to reveal any instance where the relationships between order sizes and job shop system performance were treated explicitly. The usual approach was to account for order size by postulating distributions of machine center flow times and sampling from these distributions for each order. Order size, then, was implicitly included in the amount of time required to process an order by a center. By contrast this investigation generates machine center flow times as a function of order size.

I would like to express my deep appreciation to Professor Wilson Bentley, Chairman, Department of Industrial Engineering and Management for his patience, understanding, and assistance during an extended period of family obligations in part responsible for the delays in completing this thesis. I owe Dr. James Shamblin a large debt of gratitude for his voluntary and considerable contributions to this research effort. To the remaining members of my committee I acknowledge the debts of respect and thanks for guidance and a good education both in the classroom and out, throughout my doctoral program.

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LLOYD DUNLAP

TABLE OF CONTENTS

LIST OF TABLES

Table | Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The purpose of this dissertation is to describe the results of investigating the reactions of a hypothetical job shop manufacturing system to controlled variations in the attribute of size of orders passing through the system. The investigation concentrates attention on four measurable reactions of the system to changes in order size; idleness, order flow time, delivery time, and waiting time.

A computerized model of the system is developed and twenty-five simulations performed to generate observations under five mixes of order sizes and five conditions of setup time. Seven corollary simulations are run to test the validity of the assumption of certain equilibrium conditions in the model.

The results of this research indicate that increases in the sizes of orders processed by the job shop manufacturing system:

1. increases production in the job shop by reducing the incident of setup,

2. increases the total flow time of orders through the system in proportion to the increase in job size,

3. enlarges the means and variances of all time related distributions in the system,

4. does not materially alter the shapes of the time related distributions.

The contributions of the research are considered to be four in number. First, an estimating technique is devised to predetermine the mean time between input of jobs to the system. The technique appears to eliminate the need for service rate runs. It is probably best suited to simple systems such as the one investigated. If this is true, it has limited application.

Second, the technique of permitting one element of center flow time, queue time, to be generated as a function of the operation of the system appears to be a sound approach not noted in the literature. The technique, when refined, should permit the derivation of estimators for center flow time in systems whose records are confined to setup and processing times.

The analysis of idle time into two components reveals an opportunity to reduce idle time in the system by causing the two components to coalesce. Segmenting idle time into components of idleness caused by absence of work and idleness caused by setup makes clear the potential reduction in idle time by the expedient of a procedural change in the management of information in the job shop manufacturing system.

Finally, the investigation tends to confirm the researcher's understanding of current theory while perhaps adding a small increment of knowledge to it. What seems to be worthwhile is not that confirmation takes place, but that it is achieved by employing what is considered to be a refined technique in modeling machine center flow time in job shop systems.

The remainder of this chapter is devoted to antecedents; defining the system and reporting the results of the literature search of previous, allied investigations. Chapter II describes the computerized model constructed for the research effort. Chapter III describes the experiment in detail, formalizes the hypotheses tested, and displays the rationale for the various choices required of the researcher. Chapter IV presents the discussion and analysis of the outcomes of the experiment and the inferences drawn. Finally, Chapter V summarizes the results and conclusions, suggests future research, and discusses the reservations about the results of this research effort.

The Job Shop Manufacturing System

The job shop manufacturing system is distinguished by several usually well understood characteristics. The purpose of these next several sections is to describe these characteristics, the variety of ways they might be viewed, how they contrast with the characteristics of other manufacturing systems, the extent to which they have been treated in the past, and how they are viewed in this research effort.

Job Shop Defined

A job shop is a manufacturing system composed of differentiated work centers (23). This means that processing capability is homogeneous within centers and heterogeneous among centers. As several authors describe it, machines are grouped together in centers according to like function (27, 34). It has been observed, however, that machine centers have evolved where the function of two centers is the same, but the means of control of the machines is different, e.g., one center in a shop is composed of numerically controlled milling machines and another is composed of manually controlled milling machines.

Job shop systems are more likely to have general purpose rather than special purpose machines. It is not necessary, however, that this characteristic be inviolate. It should be expected that the smaller the system or the more diverse the demands on the system the more likely that all machines have a wide range of capabilities. Even this comment is subject to interpretation. For clarity, consider the activity of milling. Generally, this is thought of as shaping or dressing metal by passing the metal by revolving cutters of various sizes or shapes. If a machine can make only one cut or if it can make several cuts but only with one degree of freedom, it is a special purpose machine. If it is more versatile and can be set to make a variety of cuts with several degrees of freedom, it is a general purpose machine. A more exact distinction seems unnecessary.

The pure job shop system is characterized by manufacturing on demand to customer order. Its activity is not buffered or protected from fluctuations in demand as is the case with other manufacturing systems. Perhaps the best contrast of the job shop system from this point of view is with the repetitive manufacturing system. Here there exist a fairly well defined range of products and the means of forecasting future demand for these products. Machines may still be grouped by function although their relative physical location is probably influenced more by an established technological order of processing activities required for the products than is the case of the job shop. The prior knowledge of most of the products of the system and expected demand for the products provides the opportunity to manufacture to inventory rather than exclusively to customer order. This may be accomplished in one or both of two ways.

Products are assumed to be composed of component parts. These component parts may be manufactured according to some repetitive schedule and held in inventory pending customer order. When the order arrives, the parts are assembled and the product shipped. This option is common when products differ in final configuration but are basically the same. A good example is an accounting machine such as those produced by The National Cash Register Co., Dayton, Ohio. The other option is to manufacture to finished inventory. This procedure also employs a repetitive manufacturing schedule, but it differs in that products are completed and stored to meet demand.

There are, of course, a variety of ways in which these two options may be combined. Of major interest is the point that the repetitive system employs inventory to decouple demand from supply; hence, tends to provide for less fluctuation in the manufacturing activity. By contrast, the job shop system does not manufacture to inventory; hence, its activity is directly related to demand and may be highly volatile.

Another distinguishing characteristic of the job shop system is its general inability to cope systematically with the scheduling of jobs through the system (14). In the repetitive manufacturing system it is often possible and profitable to identify a production cycle in which the machine sequence, job sequence, and product run length are specified and are repeated. There is no such neat array of tasks in the job shop system. As a consequence, scheduling is almost a continuous process. When the first center in the ordered set of centers selected to process a job is free, it is the usual practice to release the job immediately to the system. If the center is not free, the job may enter the queue at that center or be diverted to an alternate processing route when technologically feasible.

There are several problems associated with random-job scheduling. As a result optimal policies for scheduling are difficult to formulate and even more difficult to defend.

In partial summary, the job shop manufacturing system is composed of differentiated work centers. The system operates only on demand and then to customer specification. It does not have any prior knowledge of when, what, or in what amount it is expected to produce, except within the scope is its advertised capability. (An industrial grinding company, for example, would not expect to be asked to extrude metal.) There are many technologically feasible routes through the system. These are both a function of the nature of the job and the existence of technically correct alternative ways of doing it. As a result, jobs interfere with one another (compete for machine time) and delays occur.

Balancing

The balancing problem deals with the equality of output of each successive operation in the sequence of a line (5). Its job shop counterpart is relative equality of output of machine centers. In both cases the desired solution to the problem means reduced interruption of work at downstream stations and elimination of excessive backlogs at any one station.

Practical solutions to the problem of maintaining balance in the job shop include the selective use of over-time, installing more capable or simply more machines, rerouting orders around centers with large backlogs, and alteration of machine loading. Machine loading, the amount of work to be accomplished by a machine, usually measured in time units, has been most often treated for the production line with continuous or repetitive manufacturing activities or a job shop with repetitive production. An early work by Salveson (31) employed linear programming to find optimal loading in what he calls a quasi-job-shop. The assembly line balancing problem has been treated by several authors (15, 17, 28, 35).

Routing

Routing determines where work is to be performed. Routing is also called technological routing, technical requirements, etc. Implicit in this description of routing is a requirement to consider the order as well as the nature of work for any given job. For example, cutting must be accomplished before polishing. Other like kinds of technical order requirements exist. The various models examined in preparation for this research did not deal with the routing problem. Rather it was assumed that routing was predetermined and fixed outside the job shop system. The other alternative, of course, is to postulate and employ alternative technologically correct routings for each job and to establish internal system rules for choosing among the alternatives.

Scheduling

Scheduling determines when work is to be accomplished. Usually scheduling is used as an inclusive term meant to describe a rather precise and complete planning function. Several jobs and several machines are considered simultaneously. Machine loading, routing, sequencing (to be discussed), materials, labor, etc. are jointly considered and jobs and machines are mixed in some best way. Usual criteria deal with the concept of efficiency; e.g., maximum use of available production time.

Scheduling as just described is not particularly appropriate to the job shop system. As observed on page 6, job shop scheduling is an almost continuous process. Additionally, it covers the whole spectrum of tasks starting with drawing materials and ending with completion of the customer order.

Sequencing

The sequencing problem, sometimes called the schedule-sequence problem, deals with the question of when to produce an order, not with respect to the clock, but with respect to other orders. The problem has been solved for continuous manufacturing systems, but not for job-shop systems (34).

Sequencing in the job shop usually has been approached by periodically adjusting the relative order of jobs waiting to be processed in the various queues in the system. Rules for making such adjustments and the criteria for choosing among them are all concerned with some function of the time a job stays in the system. Perhaps the most exhaustive research to date on sequencing rules for an idealized job shop is that reported by Conway (9). He compares and evaluates 17 basic rules plus 23 variations and combinations of these basic rules, all with different values of the control parameters. In total, he tested 92 different rules.

As a note of possible interest he did not test the rule employed in this study which is described in Chapter II. He did, however, test a modified version of SLACK (slack time rule) which is conceptually similar. The SLACK rule gives preference to the job with the least time remaining until the due date after deducting the remaining processing time. SLACK is defined as follows:

$$P_i = D_i - T - \sum_{j=k}^{M_i} P_{ij}$$

where

P_i	priority at the ith job
D_i	due date of the ith job
T	time at which a selection of machine assignment is made
P_{ij}	processing time required at the jth center for the ith job
j	index over the sequence of machine centers
k	the next center
M_i	the total number of centers for the ith job

Conway's modification of the rule involves weighting the resulting P_i by dividing it by the number of remaining centers and giving priority to the job with the smallest ratio of slack/center remaining.

Setup time (time to prepare a machine to process a job) and the sequence of jobs processed by the machine may be related. Consider two jobs A and B. If the sequence AB results in setup time S_{AB} and the sequence BA results in setup time S_{BA} and $S_{AB} < S_{BA}$, the sequence AB is preferred. This is equivalent to stating that setup time is a function of the machine, the job, and its relationship to other jobs in the stream passing through the machine. No meaningful examination of this job dependent characteristic of setup time was discovered although several authors indicate an awareness of it.

Dispatching

Dispatching is determining the time an order is released to the job shop system so that work on it may begin. It is, in effect, a decision to permit the order to compete for machine time with orders already in the system. Some authors define dispatching to include issuing instructions about the order as it proceeds through the system. However, this function is thought to be well covered under the sequencing concept.

CHAPTER II

DESCRIPTION OF THE MODEL

The model represents a job shop manufacturing system with a small number (1 to 20) of single machine centers. Each center may be made different from or identical to any other center. Each can process one and only one job at any one time. One job may not preempt another. Jobs consist of units of product which are identical both within and among jobs. The time required to process a job is a function of its magnitude in units and the center assigned to process it. The time required to prepare a center to process a job (setup time) is a function of the center. The time a job waits to be processed at any center is a function of the number and magnitude of higher priority jobs also waiting or being processed.

Machine Center Logic

Each center can process one and only one job at any one time. The time required to process a job through a center is the product of the magnitude of the job in units and the unit processing time. The unit processing time is a specified random variable.

Each job requires that the center assigned to process it be setup. This implies that the job is always different from the job immediately preceding it through the center. Setup time is a function of the center and is a specified random variable.

The time a job waits to be processed depends upon the number of higher priority jobs also waiting or being processed. Hence, queue time is a generated random variable dependent upon the utilization of the center.

The time to process a job by a center, T, is the sum of three random variables; the time the job waits, Q, the time required to prepare the center to process the job, S, and the time required to process it, P. The time required to move a job from one center to the next center is considered to be included in the waiting time at the next center. Waiting time may be zero. Setup time may be specified as zero to simulate operations for which no setup is necessary. Unit process time is always greater than zero and never less than one clock unit per unit of product. However, the sampling technique employed provides for effective unit process time of less than one clock per unit of product. For example, suppose the job is of size 100 units and that the job is to be processed by a center with a unit process time of one. The product of 100 units and one clock unit per unit equals 100 clock units. This length of time is taken as the mean of the population of process times. Suppose further that a sample of size one from this population produces a process time of 95. This results in an effective unit process time of 0.95 clock units.

Center operation probably can best be described with the aid of the schematic in Figure 1. Recall that the time required to process a job through a center is $T = Q + S + P$. Q, S and P, as listed, also provide the order of events within the center. The center is represented by the large block T. A job to be processed enters the center through block Q. It goes directly to the "on-deck" block Q_1. If Q_1 is empty and block P is idle, it moves to block S, then to block P and exits the center, T.

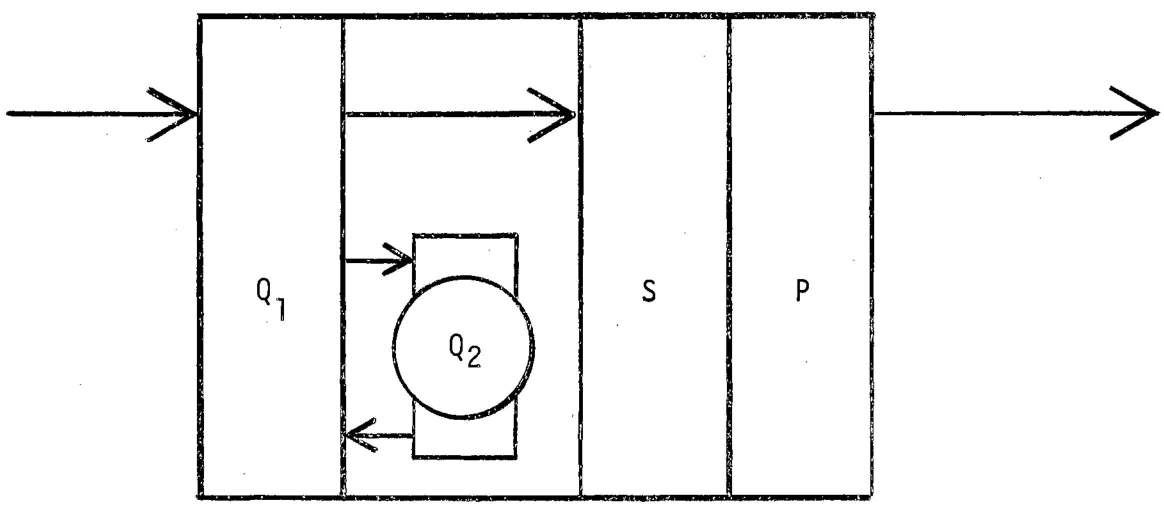

Figure 1. Machine Center Flow, Center T

If Q is empty and P is operating, the job is held in Q_1 until P is idle. If Q_1 is occupied, the priority of the incoming job is compared with that of the job occupying Q_1. The lower priority job is sent to Q_2. Blocks Q_1, S and P can hold only one job at a time; Q_2 is unrestricted.

To summarize briefly, each machine center is composed of four blocks. Two of these, Q_1 and Q_2, simulate the waiting line; block S simulates the machine setup activity; and block P simulates the processing activity. The status of block P controls the access to block S. The status of block Q_1 and the priority of the job in Q_1, if any, determine whether a job proceeds to block S or to block Q_2.

Queue Discipline

The model employs a job sequencing algorithm developed by Fabrycky and Shamblin (20). The algorithm provides a way to change the sequence of jobs waiting in the various queues in the system according to their relative urgency. This is accomplished periodically, for each order, by a standardized comparison of the due date of the order, the current date, and the expected processing time of the remaining machine centers assigned to the order.

The algorithm is based upon properties of the Central Limit Theorem. If μ_j and σ_j^2 are the mean and variance of order flow times through the jth center, the total flow time of the ith order through the shop, T_i, is approximately normally distributed with mean

$$\mu_i = \sum_{j=1}^{n} \mu_j$$

and variance

$$\sigma_i^2 = \sum_{j=1}^{n} \sigma_j^2 .$$

The more centers assigned to process jobs, the more nearly the distribution of T_i corresponds to the normal distribution.

Suppose the ith order is at machine center k, k=1, 2, ---, n. The mean flow time before completion of the order is

$$\sum_{j=k}^{n} \mu_j .$$

The flow time variance is

$$\sum_{j=k}^{n} \sigma_j^2 .$$

The expression

$$z_i = \frac{(D_i - C) - \sum_{j=k}^{n} \mu_j}{\sqrt{\sum_{j=k}^{n} \sigma_j^2}}$$

is the standardized value of the distribution of remaining flow time where D_i is the due date of the ith order and C is the current date. The values of z determine the positions of their respective orders in the machine center queues. Implicit in these z values are the probabilities of meeting the due dates. The order with the algebraically smallest z implies the smallest probability of completing the order by its due date. Hence, this order will be positioned in a queue ahead of orders whose z values are larger.

The effect of this queue discipline rule is similar to the effect of an expediter who employs current knowledge of the state of the system and jobs in progress to decide the order of near term processing activities. The rule tends to equalize the probabilities of all jobs being completed by their due dates. Implicit in the employment of this rule is the assumption that the value of completing a job on time is the same as the value of completing any other job on time.

System Service Rate

The service rate of the system is defined to be job output rate when all machine centers in the system are operating at maximum possible capacity. One hundred percent utilization of the processing capacity of the system is possible only when no setup time is required at any center.

For an unstructured system; i.e., a system in which the routes for orders are selected at random by sampling from a uniform distribution, it is possible to estimate the system service rate.

In this model, the number of machine centers in any route are equally likely. If the system contains ten centers, the probability that a route contains one center is the same as the probability that it contains 2, 3 or 10. In other words, the probability of the number of centers in a route for any order for a system with ten centers is 0.1. The expected number of centers in a route from this system is

$$E[n] = \frac{\sum_{n=1}^{10} n}{10} = 5.5$$

It is not true that routes through the system are equally likely. The method of choosing the number of centers in each route precludes this. There are ten ways to have routes containing one center and 10^{10} ways to have routes containing ten centers. Since returns are permitted, in general, there are $\sum_{n=1}^{10} 10^n$ (more than 1.1 billion) routes through the system. If it were true that the routes were equally likely, the expected number of centers in any route would be in excess of 9.9.

Consider the system with zero setup times. A production day is defined as 1000 clock units. The real time equivalent is approximately 28.8 seconds per clock unit. In a system of ten machine centers there are a maximum of 10,000 production clock units available per day. Suppose the system processes jobs of size 100 units and that the unit processing time is one clock unit at all centers. It is easy to see that product of the expected number of centers and the expected processing time per job per center will result in the expected time per job through the system since these are independent events. Hence, for this case the expected flow time through the system is

$$5.5\ (100) = 550 \text{ clock units/job.}$$

Since there are 10,000 clock units available, the expected service rate must be 10000/550, or about 18 jobs per day. In this simple case, then, for jobs of size m with unit process time of t, processed by a system of size n, the expected service rate, μ, can be estimated as follows

$$\hat{\mu} = \frac{1000n}{\frac{mt}{n} \sum_{j=1}^{n} j}$$

or

$$\hat{\mu} = \frac{1000n}{mtE[n]}$$

where E[n] is the expected number of centers per order.

When setup time is greater than zero and equal at all n centers, μ can be estimated as follows;

$$\hat{\mu} = \frac{1000n}{(mt + s)\ E[n]}.$$

Using the previous values and setting s = 10 clock units per order per center,

$$\hat{\mu} = \frac{1000n}{[100(1) + 10]5.5} = 16.5 \text{ orders/day.}$$

A third case arises when orders are of different, but known sizes. Suppose two sizes of orders are processed by the system and that the percentage of time each order occurs is known. If half the orders are of size m_1 and half are of size m_2, the service rate calculation is

$$\hat{\mu} = \frac{1000n}{\left[\frac{(m_1 t + m_2 t)}{2} + s\right] E[n]}$$

Again, using the previous values and setting $m_1 = 100$ and $m_2 = 10$

$$\hat{\mu} = \frac{1000(10)}{\left[\frac{100(1) + 10(1)}{2} + 10\right] 5.5}$$

$$= 27.9 \text{ orders/day.}$$

In general, then

$$\hat{\mu} = \frac{1000n}{(E[mt] + s)\, E[n]}.$$

Finally, when setup time is allowed to vary among centers, the computation becomes

$$\hat{\mu} = \frac{1000n}{(E[mt] + E[s])\, E[n]}.$$

Establishment of Job Due Dates

Due dates are a function of job size, technical processing requirements, system performance, and management's interest in on-time deliveries.

Job size, the number of units of product in an order, partially determines the system flow time distribution from which future system performance is estimated. Technical processing requirements, the number and sequence of centers needed to process the job, are accounted for by assuming that all permutations of machine centers are feasible. Management's interest in on-time deliveries is reflected explicitly by considering the variation in system performance.

Due dates are established in accordance with

$$D_i = R_i + \sum_{j=1}^{n} \mu'_j + z_i \sqrt{\sum_{j=1}^{n} \sigma'^2_j}$$

where R_i is the release date of the ith order. In the model, jobs are released as soon as they arrive. The passage of time to contract for the order, prepare specifications, coordinate delivery of materials, etc., is assumed to have occurred previously. If the total flow time of the ith order is approximately normally distributed with mean

$$\mu'_i = \sum_{j=1}^{n} \mu'_j$$

and variance

$$\sigma'^2_i = \sum_{j=1}^{n} \sigma'^2_j$$

then

$$D_i = R_i + \mu'_i + z_i \sigma'_i$$

where the prime designates parameters of populations of times by order size. Now z_i may be chosen so that management is satisfied with the probability of on-time delivery (29).

The model permits five choices of z_i and the means of selecting them according to any distribution. This capability is useful to the extent that it provides a means of simulating underestimating and overestimating system performance, promising due dates which cannot be met, or other deviations from policy.

Job Sizes

Five job sizes are possible. One of these, NTYPE(3) energizes a TRACE block. Consequently, it is possible to record the complete history of all NTYPE(3) jobs as they proceed through the job shop. This feature is useful as a diagnostic tool in the early stages of manipulating and testing the model. An example of the TRACE report is contained in Appendix A.

The main reason for providing for various job size inputs is to test the effect of different job sizes on the operation of the job shop manufacturing system; the purpose of this research.

Job size mixes may be chosen in any proportion desired. Job sizes may be any integer value greater than or equal to one and less than 2^{15}.

Demand on the System

Demand on the job shop manufacturing system may be created by drawing from a distribution of demand with job sizes subsequently assigned by sampling from a distribution of job sizes.

The mean arrival rate must be less than or equal to the system service rate to prevent the building of infinite queues. Since it is possible to estimate the service rate of the system with reasonable accuracy, service rate runs don't appear to be absolutely necessary.

Periodic Status Reports

Periodic status report capability has been built into the model to provide for examination of the state of the system at intermediate points during a simulation. A status report is available as often as once at the end of each day or it may be suppressed entirely during a simulation. An example of the status report is presented in Appendix B.

The primary value of this feature of the model is in providing a way to observe the rate at which the model achieves steady state, the functioning of the random number generators, the growth of some of the various statistics recorded at the end of a simulation, and a way of comparing reactions according to other than terminal run conditions. During diagnostic runs, it provides an additional means of pinpointing error sources.

Statistics

In addition to the information available from the model through the TRACE report and the STATUS reports, the model generates a variety of statistical tables. Some of these are provided automatically by the General Purpose Systems Simulator II. Others are unique to this model.

The output consists of 53 tables:

Tables	Tabulated by Frequency Class
1 - 10	Center Flow Time
21 - 30	Center Idle Time
41 - 50	Center Queue Time
61 - 65	System Flow Time by Size Type
66 - 70	D-A Time by Size Type
71 - 75	System Flow Time by z Type
76 - 80	D-A Time by z Type
81	System Flow Time
82	System D-A Time
83	System Inter-exit Time

Examples of these tables are contained in Appendix C.

Each table contains the distribution of the observed frequency of occurrence of values of a system variable or function of a system variable. These are recorded by frequency class. There is no limit on the number, incremental size, or range of frequency classes except that resulting from computer space allocation. In addition to the frequency distribution, (which may be in the form of weighted entries) each table provides the total number of entries in the table, the mean, and the standard deviation.

Variables and Rules

The description of the model thus far indicates that it is possible to control two variables. These are the values of the initial z and the sizes of orders. Choosing a positive value of the initial z corresponds to a management decision to contract for due dates which will enhance the probabilities of completing orders on time. Choosing the sizes of orders to be processed by the system implies both the capability and the reason for combining or splitting orders to improve system performance. For this research, the only decision variable is taken to be the choice of the order or job sizes. The choice of initial z with minor perturbations is employed as an unchanging rule by which orders are released to the system.

To recapitulate, the variable under the control of the decision maker is the size of the order in homogeneous units of product. All other variables either are assigned magnitudes based upon what may be regarded as preestablished rules for repetitive decision situations, or they are considered to be variables describing the nature of the environment and the system and outside the control of the decision maker.

Events occur in chronological order. Orders arrive according to some distribution of demand. They are assigned the number of centers to process the order; then they are assigned to specific centers, both actions by sampling from the uniform distribution. Each order is given a due date and it is released to the system. During its processing it competes for machine time at each center according to the value of its urgency number, z. When it has been processed by all assigned centers, it departs the system and appropriate statistics are recorded. This process is repeated for all orders until the simulation is terminated. Termination may be accomplished in one of two ways; time, or orders processed. In the experiment reported in this paper, termination is accomplished by controlling run lengths (time).

CHAPTER III

THE EXPERIMENT

The method of experimentation with the model is to make changes in selected variables and then to analyze the effects of these changes upon the behavior of the job shop manufacturing system. In order to study the results in some systematic way, it is necessary to decide upon the proper method or strategy for analysis. Such considerations are the subject of this chapter.

The Delimited System

Chapter II describes a computerized model with the capability of simulating any number of job shop manufacturing systems with similar characteristics. It is now necessary to define one or more with which to experiment. This is accomplished by making a number of choices. These include the number of centers to be in the system, the operating characteristic of each center, and the period of the queue discipline rule. The important effect of the second of the three choices is the decision to employ a number of identical or different machine centers in the system. It appears to be the most critical of the choices and will be discussed at some length. The other two choices can be dispatched quickly and will be treated first.

Ten machine centers are to be employed in the system. The selection of this number of centers is not entirely arbitrary. There are four practical, if not important, reasons for selecting ten. First, it is a convenient factor, thus facilitating computational effort. Second, the queue discipline rule was first tested in a system of ten centers. Curiosity dictates the same size system to see if comparable results obtain. Third, diagnostic runs with the model proved the computer to be extremely slow, thus placing a high cost in computations per center in the system. Finally, ten centers appear to be a sufficient number to create the kind of interference and competition for machine center processing time thought to be present in real systems.

The period for the queue discipline rule; i.e., the period of time permitted to elapse before the urgency numbers are recomputed for each of the orders in the system, is taken as one day. The urgency numbers are computed and the orders realigned in the ten queues in the system at the end of the work day and before the beginning of the next work day. It would be possible, of course, to choose other intervals of time between updating the positions of orders in the queues, but there seems to be no compelling reason to do so.

The question of the operating characteristics of the individual machine centers in the system appears to be of substantially more importance than the other choices just discussed. First, should the centers be identical or different and why? Second, should machine center processing time per unit of product and setup time per order be taken as constants or random variables? And third, if they are taken as random variables, what function or functions should be employed to assign value to each sample point?

Building a model of a hypothetical system doesn't appear to sever the researcher from all connection with reality. At a minimum, the hypothetical system ought to be a reasonable representation of a possible real system. While no claim of general applicability of the results of this research will be made, the possibility of such application should not be foregone for lack of reasonableness. In this same vein, the delimiting choices are thought to result in a suitable system for study. This kind of belief cannot, of course, be completely validated. What can and will be done is to display the choices and the rationale for them for separate examination.

In addition to the stated need for reasonableness is a need for simplicity, at least to the extent that the opposite, complexity, may tend to camouflage sought after answers. Simplicity is not necessarily achieved at the expense of reasonableness or validity. All models are simplifications to some degree and this one is not an exception. Neither complexity nor simplicity are necessary conditions for validity. The acid test of the validity of a model is its ability to predict so the degree of complexity of the model is only important to this end, if at all. It appears, then, that simplicity is not antithetical to validity but preferred for the different reason of visibility. In other words, simplicity is desirable to increase the probability of seeing answers; reasonableness is desirable to increase the probability of the applicability of those answers. These two points of view are intended as general arguments in support of the remaining choices.

The system is taken as a set of ten identical machine centers analogous to a network of identical single-server queues. This system, and the arguments for it, are much like that employed in the previously cited work of Conway (9). One notable difference is the inability to postulate distributions of service times until after the fact of simulation since service times (center flow times) are generated as the sum of three random variables only two of which are specified. The primary benefit accruing through the use of identical centers, at least with respect to the attribute of time, is a symmetrical or balanced system. This balanced condition eliminates the need to introduce ways to combat inbalance leading to excessively large individual queues or excessive idle time at downstream centers. Additionally, starting with a balanced system portends no loss of generality since inbalance would have to be corrected in any event.

The remaining choices are discussed jointly. As will be recalled, these deal with the matter of variability in the operations at each center - the nature of the distributions of setup and processing time. It was decided that both should be treated as random variables rather than as constants, if for no other reason than to be consistent in acknowledging the stochastic nature of real systems. This choice is not judged critical since the sum of a constant and a random variable remains a random variable. Hence, one statistic of interest, center flow time ($T = Q + S + P$) will be a random variable regardless of which choice is made. Finally, setup time, S, is specified as a uniformly distributed random variable

$$f(S) = \frac{1}{b-a} \quad a < S < b$$

$$= 0 \quad \text{otherwise}$$

with parameters $a = .9S$, $b = 1.1S$ and $E[S] = (0, 50, 100, 250, 500)$. Process time, P, is specified as a uniformly distributed random variable with the same treatment of the parameters a and b and with $E[P] = 100$ or $E[P] = 500$ corresponding to the size of the order being processed.

Since center flow time has been identified as a statistic of interest, and since the choice of distributions from which to draw setup and process time may appear questionable, the results will be displayed and argued here. Figure 2 is the continuous analogue of a typical discrete distribution of center flow time, T, from one of the 32

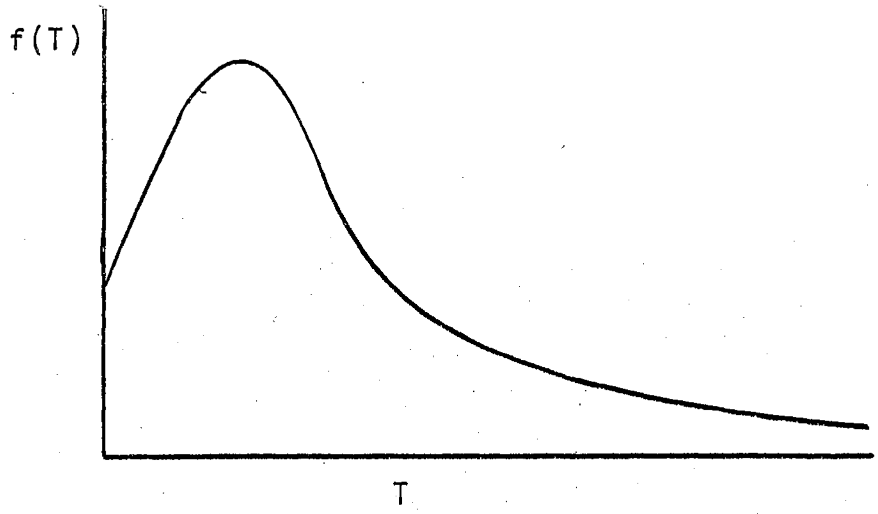

Figure 2. Typical Distribution of Center Flow Time (T)

experimental runs which serve as the information base for this research. Note that the center flow time distributions generated in these simulations have a form very similar to those discovered in research with a currently operating job shop manufacturing system. This information is an unpublished observation, according to the author, of the research reported on the development of the probability based sequencing algorithm (20).

Demand on the System

Jobs are released to the system one at a time in order and when generated. Interarrival times are obtained by sampling from an exponential distribution with the mean set to yield a nominal system utilization of 90 percent (hence a utilization of 90 percent at each center) under each of the 25 conditions chosen for the experiment. These interarrival times are displayed in Table I. They were pre-

TABLE I

MEANS OF EXPONENTIAL INTERARRIVAL TIMES
TO PRODUCE 90 PERCENT UTILIZATION

Mean Setup Time	Job Size Mix				
	(1)100 (0)500	(.75)100 (.25)500	(.5)100 (.5)500	(.25)100 (.75)500	(0)100 (1)500
0	60	120	180	240	300
50	90	150	210	270	330
100	120	180	240	300	360
250	210	270	330	390	450
500	360	420	480	540	600

determined using the estimating techniques described in Chapter II. The worth of this technique may be assessed by examining the achieved utilizations reported in Table II.

TABLE II

SYSTEM UTILIZATION IN PERCENT

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	91.7	90.8	86.1	88.0	93.0
50	92.1	91.7	92.3	90.6	92.5
100	90.2	90.4	93.7	88.9	92.4
250	85.2	92.4	92.4	90.6	94.4
500	88.3	89.1	92.4	93.9	94.4

The mean of the entries in this table is 91.1 percent. The extremes are 85.2 and 94.4 resulting in a range of 9.2 percent. Another measure of the worth of the estimating procedure is displayed in Table III. The information in this table is the expected and achieved production in orders per day.

TABLE III

PRODUCTION IN ORDERS, PER DAY
EXPECTED AND (ACTUAL)

Mean Setup Time	Job Size Mix (1)100 (0)500	(.75)100 (.25)500	(.5)100 (.5)500	(.25)100 (.75)500	(0)100 (1)500
0	16.66 (16.65)	8.33 (8.33)	5.55 (5.42)	4.17 (3.98)	3.33 (3.40)
50	11.11 (11.09)	6.67 (6.53)	4.76 (4.82)	3.70 (3.62)	3.03 (3.01)
100	8.33 (8.23)	5.55 (5.60)	4.17 (4.22)	3.33 (3.22)	2.77 (2.82)
250	4.76 (4.38)	3.70 (3.72)	3.03 (3.37)	2.56 (2.58)	2.22 (2.33)
500	2.77 (2.68)	2.38 (2.38)	2.08 (2.05)	1.85 (1.97)	1.67 (1.75)

To bring the system from idle to full operation as quickly as possible, 50 jobs are generated so as to enter the system simultaneously at the beginning of each run. Each run is permitted to continue 20 days before the process of collecting statistics begins.

Establishment of Due Dates

Since one measure of system performance, E = D-A, depends upon the due date established for each order processed through the system, it is important that due dates be set bias free with respect to order size. This is accomplished using the procedure described in Chapter II employing split statistics. It was decided to set the initial z at zero to improve visibility of results. No generality is lost since the effect of choosing z is to alter the probability that a job will be early or late. Concern with this aspect of the measure seems appropriate only when there are costs associated with deviations from on time deliveries. Since this research is a study of the physical job shop system, rather than the economics of the system, taking z = 0, which is equivalent to stating that the probability is 0.5 that a job will be completed on time, seems as good as any other choice.

The Experimental Runs

Each of the 25 primary experimental runs consisted of operating the system for 145 days. As previously noted, the first 20 days are employed to approach equilibrium performance. In addition to these primary runs, seven others were made, five for 520 days each, one for 900 days, and one for 1,800 days. The reasons for these seven runs will be discussed in Chapter IV.

The objective in every run is to measure or estimate equilibrium performance to increase comparability among runs. Most of the discussion so far in this chapter on the preliminaries of the design of the experiment has been to describe the choices made to achieve both visibility and comparability of results. The same conditions and procedures are used for every run. The demand generator employs the same seed thus providing the same sequence of random numbers to control the arrival time and size of jobs entering the system. The remainder of this chapter is devoted to describing and explaining the conditions and intentions of the experiment.

Job Size Selection

The experiment consists of testing five mixes of two job sizes under five different conditions of setup time. As indicated, this produces 25 separate observations on each of the statistics of interest. Job sizes of 100 units and 500 units of homogeneous product are employed. They are combined in the following ways:

Mix			
1	(1)100 + (0)500	=	100
2	(.75)100 + (.25)500	=	200
3	(.50)100 + (.50)500	=	300
4	(.25)100 + (.75)500	=	400
5	(0)100 + (1)500	=	500

The sum of these products are interpreted as follows: Mix 1 consists only of jobs of size 100; Mix 2 is 75 percent jobs of size 100 and 25 percent jobs of size 500, etc. And, of course, the right hand side of the array contains the expected job size per mix.

The motivations for choosing jobs of sizes 100 and 500 are two in number. As is discussed in Chapter V, the computer-program combination is very costly in scarce computer time. Diagnostic runs were initially accomplished with jobs of size 10 and size 100. The jobs of size 10 produced so many transactions as to make computer time requirements beyond that likely to be available. More important, jobs of size 10 produced such neat, "textbook" distributions of center flow time, total flow time, etc., as to be suspect. Further trials indicated the jobs of size 100 and jobs of another substantially larger size, 500, would minimize both objections. Finally, two sizes, rather than the 3, 4, or 5 of which the model is capable, were selected for the sake of simplicity. Of course, at least two sizes are required to produce mixes of sizes.

Completing the Design

It is possible to design this experiment in a variety of ways. If one starts with the five job mixes just described, several options are possible. It seems appropriate to discuss some of these along with the design chosen to complete the job discussion of the conditions of the experiment and to introduce the discussion of the intentions.

One obvious and simple way to complete the design is to choose one common value of mean setup time at each center. This produces a results vector of five elements. A natural extension is to replicate each run several times with different sequences of demand caused by changing the random number generator seed. Two or more levels of system utilization imposed along with these other conditions would appear to offer substantially correct design amenable to the statistical analysis of one system. However, this strategy and others similar to it are rejected in favor of one which provides the opportunity to acquire information about system reaction to changes in an important characteristic of job shops, setup time.

It was decided to test each job mix under each of five different but common mean setup times at each of the ten centers in the system. For example, jobs of size 100 are tested under mean setup times of 0, 50, 100, 250, and 500. In run 1, say, all center setup times are set to zero and all jobs are of size 100; in run 2, all setup times are 50, and all jobs are size 100, etc. The end results are arrays with 25 entries, 5 mixes by 5 setup times.

The advantages of this design are several. Even though this is a study of the physical aspects of the problem of job size, the ultimate interest will be in the economics associated with the results. Whether traditional inventory models apply to this work is of no special interest, but it is to be expected that the costs associated with inventory (in process) and setup time still will be appropriate. It has been shown by Little (26) that there are basically four measures of performance in the job shop; in-process inventory, utilization of centers, total flow time, and lateness. All of these are interrelated and associated with the cost of operating the system. However, they provide only incomplete information when setup time and its associated costs are not included.

Does altering setup time in the selected fashion result in experimenting with one system or several? The question probably can be argued convincingly both ways. Earlier in this chapter, it is observed that several choices are required to delimit the experimental system. It is also noted in Chapter II that setup time is considered a function of the machine center and not the job or the sequence of jobs passing through it. Consequently, it is concluded that the experiment involves several systems, five to be exact, identical except with respect to setup time. This is taken to mean that there is no available rationale to permit statistical analysis of the joint results of one system. It means also that the design is in essence artificial (not possible with one real system) and is chosen only because of the overriding interest in seeing the results of operation under the different conditions of setup time. Finally, on the matter of setup time, the magnitudes chosen correspond to multiples of processing time. It is of interest to note results when setup time is less than, approximately equal to, and greater than processing time per order.

Hypotheses

There are generally two kinds of results to be expected from experimentation of the kind being described; formulation of hypotheses and tests of hypotheses. Each of these is examined in turn.

Probably the most beneficial use of the model of the hypothetical system is in the formulation or discovery of apparently relevant questions during the course of the experimentation. Of course, some propositions occur to the researcher during the preliminary, problem definition phase of the research. Certainly this is true of the general question prompting the effort. Others arise during the diagnostic work with the model. More appear upon examination of the results of the experiment. It is clearly appropriate to test and to draw conclusions about those propositions arising in the problem definition phase. Here the propositions are stated in the absence of recognized order among the facts which may be at hand or the applicability of related theory with which the researcher may be familiar. In other words, questions translated into testable propositions at this point serve to direct the search for answers. It is considered important then, to set down propositions before the acts of testing or verification. Alternatively, it would be possible to "take credit" for propositions uncovered during the diagnostic and experimentation phases of the research; to accept as verified those relationships revealed in the course of the experimental runs. This approach is rejected as improper since further experimentation should be conducted with these "revelations" carefully restated as testable propositions. All finite research efforts must terminate somewhere. Since this effort is not an exception, apparently relevant questions unearthed during the experiment will be discussed, restated as working hypotheses, some perhaps with tentative implications, and offered as propositions of possible worth for further research.

Propositions about the behavior of the job shop manufacturing system under the conditions specified for the experiment may be gleaned from the prior knowledge of the objects, attributes and relationships in the system established during the problem definition phase. Other sources of propositions are the disciplines and activities of industrial engineering, operations research, systems analysis, etc.; the prior work with job shop systems. Other plausible propositions have roots in recognizable bodies of theory such as queueing theory, network analysis, and inventory theory. It is not possible within the scope of the current effort to analyze the reactions of the system to all changes and reasonable propositions it is possible to contrive. It is necessary to be selective in what is chosen for study. As a consequence of this view, the discourse in Chapters IV and V pertaining to the analysis of the results and the conclusions to be drawn will be restricted to the following questions:

1. What is the effect or order size on the idle time in the system?

2. What is the effect of order size on the total flow time of orders through the system?

3. What is the effect of order size on the measure, E = D-A?

4. What is the effect of order size on the various queues in the system?

It remains to stipulate that the conventional null hypothesis is taken for each of these questions. Where appropriate, statistical hypotheses are stated and tested.

In this experiment, the null hypotheses are of the form:

$$H_0: \quad \Sigma\phi_j = 0$$
$$H_1: \quad \Sigma\phi_j \neq 0.$$

The interpretation is as follows: The null hypotheses, H_0, imply that there are no differences in the measured attributes of idleness, time in the system, lateness, and waiting lines, caused by job size. The alternate hypotheses, H_1, imply that job size does indeed cause some significant differences. It is hoped, of course, that some null hypotheses will be accepted and some rejected.

Statistical Models

Some of the experimental data are investigated by employing a fixed effects analysis of variance model, ANOVA. In the fixed model a difference in mean response at a certain level of significance is detected by an F ratio of the mean square of the columns (in this study) to the residual mean square. Note that all ANOVA are fixed-effects, 2-way, one observation per cell.

The model for this situation is a statement of linear treatment effects as follows:

$$x_{ij} = \mu + \gamma_i + \phi_j + \varepsilon_{ij} \quad : \quad \begin{matrix} i=1,\ 2,\ ----,\ r \\ j=1,\ 2,\ ----,\ c \end{matrix}$$

where μ is the general mean, and ε_{ij} are the experimental errors which are assumed to be normally distributed, each with mean zero and variance σ^2.

In the fixed effects model with one observation per cell:

γ_i is the effect of adding the ith row treatment

$$\sum_{i=1}^{r} \gamma_i = 0$$

ϕ_j is the effect of adding the jth fixed column treatment

$$\sum_{j=1}^{c} \phi_j = 0.$$

A second model is employed to generate the coefficient of correlation r where

$$r = \pm \sqrt{1 - \frac{\Sigma(y - y')^2}{\Sigma(y - \bar{y})^2}} .$$

In words, we compare the sum of the squares of the vertical deviations from the least-squares line with the sum of the squares of the deviations of the y's from their mean.

The proper hypothesis in this situation is

$$H_0: \quad \rho = 0$$
$$H_1: \quad \rho \neq 0.$$

The test for significance may be summarized as follows:

if the $|r| > |r_{\alpha/2}|$, reject H_0.

Choice of Significance Level

The five percent level of significance is chosen for the statistical analyses because it is commonly used and extensively tabulated for Snedecor's F.

CHAPTER IV

ANALYSIS

The goal of this chapter is a lucid and detailed description and analysis of the results of the experiment. The questions posed for this investigation will be treated in the order listed in Chapter III, namely: idleness, flow time, lateness, and waiting time. Certain sections are devoted to observations not properly a part of the analysis of the four primary questions.

Idleness in the System

If any center in the system is not engaged in physically altering a unit of product, it is said to be idle. Idleness, then, is the condition of not doing work. The attributes of idleness chosen for examination are the parameters and shapes of the distributions of idle time occurring at each center in the system.

In the language of Chapter II, and referring to Figure 1, page 14, if block P is not occupied, the center, T, is idle. If block S is occupied, P's idleness is caused by the occasion of setup. It makes no difference if block Q is empty or full. If Q, S, and P are all empty, however, idleness is not caused by setup but by absence of work at the center.

It will be recalled from Chapter III that the arrival rate of jobs was determined to achieve a 90 percent utilization of each center in the job shop system. This is equivalent to stating that idleness caused by the absence of work at any center is 10 percent. Of course, 90 percent utilization was not achieved in every case, hence, neither was 10 percent idleness, because of the absence of work. What was achieved is displayed in Table IV.

TABLE IV

MEAN IDLENESS IN PERCENT CAUSED BY ABSENCE OF WORK

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	8.3	9.2	13.9	12.0	7.0
50	7.9	8.3	7.7	9.4	7.5
100	9.8	9.6	6.3	11.1	7.6
250	14.8	7.6	7.6	9.4	5.6
500	11.7	10.9	7.6	6.1	5.6

Since the mean idleness caused by the absence of work is fixed by the choice of the utilization rate, it is not of special interest in this study.

Idleness caused by setup at a machine center is exactly equal to the time required for each setup multiplied by the number of setups. In symbols

$$I_{s(j)} = nE[S_j].$$

In different words, the total idle time, I_s, because of setup at center j is equal to the product of the number of times setup occurred, n, and the expected value of setup at center j. Table V contains the mean idle time caused by setup in each test. Easily seen is the well understood fact that setup time causes loss of production in direct proportion to the product of its occurrence and magnitude.

TABLE V

MEAN IDLENESS IN PERCENT CAUSED BY SETUP TIME

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	91.7	90.8	86.1	88.0	93.0
50	30.7	18.2	13.4	10.0	8.4
100	45.2	49.5	23.6	22.8	15.5
250	60.8	51.3	41.5	35.3	31.5
500	73.6	65.4	57.6	52.6	47.2

Additionally, setup time defines a lower bound on idle time such that no incident of idle time can be less than the smallest possible setup time. For example: It will be recalled that S is drawn from the uniform distribution with range E[S] ± (0.1)S. Suppose E[S] = 100. The minimum value S can assume is 90, and 90, then, is also, the minimum possible magnitude of idle time. This effect of setup time on idle time is an unsought consequence of the research and does not appear to bear directly upon the questions addressed.

As implied earlier in this section, for a given common setup time and fixed system utilization rate, there is no effect of order size on the mean idle time caused by the absence of work at centers in the system. On the other hand, mean idle time resulting from setup decreases as order size increases. Since this is true under the condition of common setup time, it must follow that the true effect of increasing the mean order size is to reduce the number of setups. This is not an unexpected result. Table VI compares five ratios of the mean number of setups at each center to the units of product processed by the system.

TABLE VI

RATIO OF MEAN NUMBER OF SETUPS PER CENTER
TO SYSTEM PRODUCTION IN JOBS

	Mean Job Size				
Setup	100	200	300	400	500
500	.0047	.0024	.0015	.0011	.0009

That these ratios decrease as order size increases substantiates the previous conclusion. Ratios, rather than absolute values, were employed because of unequal production.

Order size has an effect on the dispersion in the idle time distribution and the larger portion of this effect is on idle time generated because of the absence of work. This must be the case since idle time caused by setup also has an upper bound. If E[S] = 100, then the maximum idle time caused by setup is 110 units for each job passing through a center. Hence, it follows that 90 < I < 110 from this and the previous example on the lower bound of I. Continuing with the case where E[S] = 100, the mean range of idle time tends to increase with the increase in job size. The standard deviation increases also, but the range appears to be more descriptive of the nature of the dispersion as will be discussed. Below are the ranges of idle times for each mean job size when E[S] = 100.

Job Size	Range (days)
100	1.21
200	1.41
300	1.31
400	2.41
500	1.91

The distributions of idle times at all centers in all runs with S > 0 perhaps are described best by taking advantage of the way in which the statistics are recorded. An example of this is contained in the 20 series table in Appendix C. Statistics are recorded in increments of 100 clock units (tenths of days). The number of times idleness occurs such that its magnitude lies between, say, 101 and 200, is recorded in class interval 200. The result is a histogram, Figure 3. The magnitude of idle time by class is recorded on the abscissa and frequency of the magnitude on the ordinate. Viewed in this artificial way, the distributions of idle time are essentially 2-valued. Figure 3 displays the distribution of idle time for center 3, with

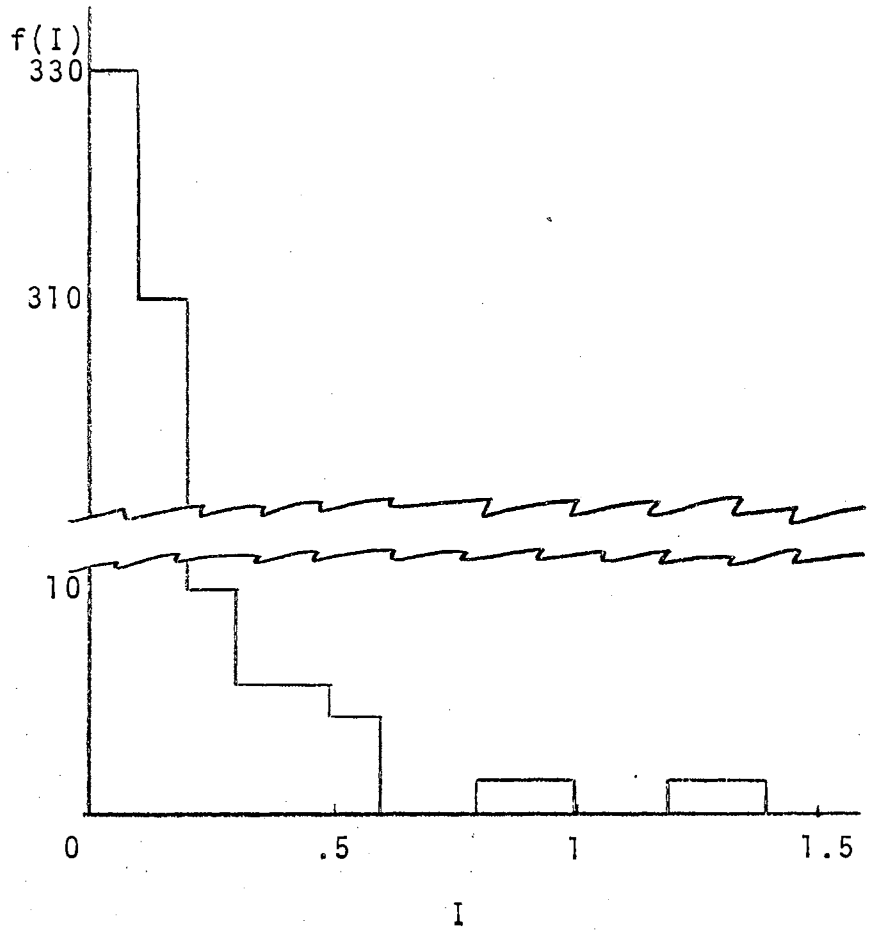

Figure 3. Distribution of Observed Idle Time, Center 3, Run 100-100

E[S] = 100, E[P] = 100. Actually, in this case, 95.37 percent of idle time lies between 90 and 200 clock units (between .09 and .2 days). As job size increases, this percentage increases until for jobs of size 500 it is 97.88. The net effect of increasing the mean job size passing through the system seems to be to increase the concentration of idle time near the mean of the population and, at the same time, to create small numbers of increasingly longer periods of idleness. This explains the preference for the range as a measure of dispersion.

It is concluded that job size:

1. does not affect the mean idle time in the system caused by absence of work at centers in the system,

2. does affect mean idle time caused by setup requirements at the centers in the systems by altering the number of setups required,

3. does affect the dispersion of idle time distributions at centers in the system by creating a small number of increasingly long periods of idleness as job size increases.

Consequently, the null hypothesis, that job size does not affect idle time, is not accepted.

Speculation on Idle Time

The examination of the effect of order size on the idle time in a job shop manufacturing system prompts some observations about idle time not appropriately a part of the previous discussion. If it is assumed that reducing idle time is a preferred course of action, then it is important to suggest ways in which this might be accomplished. The point of departure for the discussion of one possible way is the system employed in this study.

A moments reflection will substantiate that, in a system with $S > 0$, the frequency of occurrence of idle time at each center is equal to the number of orders passing through a center. Further, idle time caused by absence of work invariably precedes idleness caused by setup. The implications of these conditions are fairly obvious. First, there appears to be an opportunity to reduce idle time caused by setup. Second, the way to accomplish this is to arrange for setup to occur concurrently with the absence of work. For ease of discussion, idle time per job, I, is the sum of idle time caused by absence of work, A, and idle time caused by setup, S. Then $I = A + S$ not only describes the amount of idle time associated with a given order but also the proper chronological order of A and S.

As previously discussed $S > 0$. However, $A \geq 0$. As a matter of fact, $A = 0$ is the rule rather than the exception. Of course, $A = 0$ is equivalent to stating that the order about to be setup is already in the queue where the work is to be performed. In this study, $A > 0$ occurred about 15% of the time. Further, $A < S$ occurred more frequently by far than $A \geq S$. Hence, the concurrence of A and S is not expected to be complete and the reduction in I is expected to be small, especially in systems with high utilization.

The development of this proposition would be incomplete without offering some ideas about the kinds of control information required to achieve partial concurrence of A and S in the job shop manufacturing system. If it is assumed that the empty center will begin work (setup) on the first job to arrive, then it remains only to determine which job among the other centers in the system (or dispatching) will arrive next and the specifications of the required operation.

For clarification, consider a job shop system of three centers. Center 3 in this system is idle; Centers 1 and 2 are occupied. If neither job in Center 1 or 2 is scheduled for 3, there is no action to be taken in Center 3. If one of the two jobs is scheduled for Center 3, then it is an easy matter to begin to prepare Center 3 for that job. If both jobs at Centers 1 and 2 are scheduled for Center 3 it is necessary to determine which will be completed first. When this is determined, setup at Center 3 may begin. If it begins before the job is through at the preceding center, part or all of the idleness because of setup time may be saved. Suppose it is determined that the job at Center 2 will be completed before the job at Center 1. If Center 3 is setup and ready to begin processing the job from Center 2 before it leaves Center 2, then all of the idleness due to setup is saved. If the setup is half complete before the job from Center 2 arrives, then half of the idleness due to setup is saved. Permitting a downstream center to prepare for jobs that have yet to arrive reduces total idleness at the center by the amount of setup that can be completed before the arrival of the jobs. It is this idea, then, which has been labeled "the partial concurrence of A and S".

The concept of partial concurrence of A and S is not new. The advantages of parallel, simultaneous, or overlapping operations seem to be well understood in other forms of activity. An unlikely analogy comes from the game of contract bridge where the declarer often has to contrive a way to combine two losing tricks into one by playing the losing cards on the same trick.

The literature search preceding this dissertation did not reveal any treatment of the proposition of reducing idle time in the job shop manufacturing system by the means of partial concurrence. It appears, therefore, to be a worthwhile subject for further investigation.

Order Flow Time

The next proposition to be considered is that job size has no effect upon the time it takes orders to traverse the system. As with idle time the attributes of flow time are the parameters and shapes of the distributions of flow times generated at the centers in the system and the distribution of flow time through the entire system, or total flow time.

The subject of total flow time is considered first. Here there are three propositions about expected flow time:

1. mean job size does not affect expected total flow time,
2. mean job size does not affect the expected total flow time of jobs of size 100,
3. mean job size does not affect the expected total flow time of jobs of size 500.

Each of these propositions is tested by ANOVA as described in Chapter III.

As may be seen from examining Table VII, the test of the first proposition seems almost trivial. Still it is of some interest to see a statistical conformation of the

TABLE VII

AVERAGE TOTAL FLOW TIME IN DAYS/ORDER

Mean Setup Time	Mean Job Size 100	200	300	400	500
0	3.150	10.221	7.630	10.239	18.209
50	4.763	10.280	15.124	15.407	16.870
100	5.468	12.853	17.613	12.202	18.301
250	7.047	15.917	17.854	17.359	23.123
500	14.749	17.710	22.020	26.524	27.248

anticipated outcomes and to compare the effects of job size and setup time on total flow time. Table VIII contains the results of the ANOVA calculations to test the proposition that mean job size does not affect expected total flow time.

TABLE VIII

ANOVA, TOTAL FLOW TIME

Source	Degrees of Freedom	Sum of Squares	Mean Square	Test
Total	24	983.442		
Job	4	403.817	100.953	22.489*
Setup	4	507.798	126.949	28.280*
Residual	16	71.827	4.489	

$F_{0.05,\ 4,\ 16} = 3.01$ *Reject H_0

The raw data for these calculations is taken from Table VII above. Of course, the null hypothesis is rejected and it is concluded that job size does alter expected total flow time. This is considered a natural result. As jobs increase in size, they require more work, hence, more time at each center and in the system.

The next two propositions require the use of responses in Table IX. This table shows total flow time by job size rather than by expected job size. Additionally, all responses are not employed in the analyses. The first row is deleted. Its purpose, that of serving as a means of observing certain aspects of model performance, is fulfilled.

TABLE IX

AVERAGE TOTAL FLOW TIME PER ORDER BY SIZE

Mean Setup Time	Mean Job Size 100		200		300		400		500	
	100	500	100	500	100	500	100	500	100	500
0	3.2	0	9.3	12.9	6.3	9.0	7.9	11.0	0	18.2
50	4.8	0	9.4	12.7	13.8	16.5	13.4	16.0	0	16.9
100	5.5	0	12.0	15.9	15.5	19.6	9.5	13.2	0	18.3
250	7.0	0	14.9	19.0	15.6	20.1	19.0	16.9	0	23.1
500	14.7	0	17.8	17.4	21.9	22.1	27.2	26.3	0	27.2

The responses under the conditions of zero setup time are not considered comparable to the other row responses. Additionally, column 5 is deleted for the test of the second proposition and column 1 is deleted from the test of the third proposition. Tables X and XI display the results of the ANOVA calculations for both of these tests. The null hypothesis is rejected in both cases and it is concluded that expected job size does alter the total flow time of the two individual job sizes.

TABLE X

ANOVA, TOTAL FLOW TIME, SIZE 100

Source	Degrees of Freedom	Sum of Squares	Mean Square	Test
Total	15	533.0		
Job	3	258.7	86.2	10.3*
Setup	3	199.0	66.3	7.9
Residual	9	75.3	8.4	

$F_{0.05, 3, 9} = 3.86$ *Reject H_0

It is interesting to note from Table XI that setup does not significantly alter flow time for jobs of size 500. The explanation is believed to lie in the fact that for the larger job, setup time is relatively smaller; e.g., there is no case tested where job size is smaller than setup.

TABLE XI

ANOVA, TOTAL FLOW TIME, SIZE 500

Source	Degrees of Freedom	Sum of Squares	Mean Square	Test
Total	15	257		
Job	3	142.5	47.5	7.3*
Setup	3	55.6	18.5	2.8
Residual	9	58.9	6.5	

$F_{0.05, 3, 9} = 3.86$ *Reject H_0

All three statistical analyses of mean total flow time produce a small residual mean square. Residual mean square is composed of interaction between setup and job size as well as error mean square. Consequently, the small magnitudes suggest the absence of interaction. Conformation of this would require replication of the experiments and use of an expanded linear model to identify mean response because of interaction.

The dispersion in the total flow distributions increases with both job size and setup time as may be seen in Table XII. Here are recorded the magnitudes of one standard deviation in days from each of the 25 total flow time distributions. Another approach to examining the dispersion

TABLE XII

MAGNITUDE IN DAYS OF ONE STANDARD DEVIATION IN TOTAL FLOW TIME

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	1.8	6.0	5.2	3.0	9.1
50	2.7	5.7	7.8	8.4	8.9
100	3.0	7.1	9.7	7.5	9.6
250	4.3	8.7	9.5	9.4	11.4
500	8.7	9.9	11.8	14.1	13.7

under the various experimental conditions is to compare the variance or standard deviation along one common path through the system. This is done in Table XIII by computing the standard deviation along the path through the system which contains each center only once. This path can occur in 10! or 3,628,800 ways, roughly 0.3 percent of all possible paths.

TABLE XIII

STANDARD DEVIATION IN DAYS OF A TEN CENTER PATH

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	2.238	8.083	5.233	4.460	10.817
50	3.187	6.985	9.412	9.059	9.591
100	3.520	8.007	10.271	7.434	10.906
250	4.290	8.590	10.706	9.706	11.200
500	8.748	9.372	10.530	11.132	11.684

Finally, the shape of both the center flow time and total flow time distributions appear only slightly changed by changing job size. As observed in Chapter III, the center flow time distributions are Poisson-like. This characteristic remained essentially unchanged during all runs. The total flow time distributions are best described by the uniform distribution, although there is a slight tailing-off at the upper magnitudes of flow time. The same uniform character holds for the total flow time distributions recorded for individual job sizes. These statistics were maintained when mixes of jobs were fed through the system. (Mixes are columns 200, 300, and 400 in all tables using this type identification.)

The analysis of flow time leads to the conclusion that job size does alter the means and standard deviations of the flow time distributions, but leaves the shape of the distributions essentially undistrubred.

Late Delivery of Orders

The third proposition to test is that job size does not affect the value of the measure, E = D-A, where D is the due date of the order and A is the completion date. Positive values of E indicate that an order is early, negative values of E indicate that it is late. It will be recalled that initial z = 0 in this experiment so that the E[E] = 0. This means, of course, the responses recorded in Tables XIV, XV, and XVI should be near zero or of like magnitudes among column entries to conclude that job size does not alter E.

TABLE XIV

D-A IN DAYS, POSITIVE ENTRIES ARE DAYS EARLY

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	.176	-3.203	.736	.251	-4.309
50	.171	-1.985	-2.977	-2.954	-2.802
100	-0.152	-1.541	-5.361	- .189	-3.976
250	.226	-2.967	-4.056	-3.106	-6.581
500	-1.169	-2.656	-6.156	-8.892	-9.464

The means, standard deviations, and shapes of the distributions of delivery times are the attributes of interest in this analysis.

Table XIV is the array of mean E recorded at the end (145 days) of the experimental runs. That both increases in job size and setup alter E, tend to increase late deliveries, is fairly obvious.

Table XV, shows mean E at a point of equal production in all cases (approximately 40,000 units of product). Again the difference in the mean response of E is pronounced.

TABLE XV

D-A IN DAYS, EQUAL PRODUCTION IN UNITS, POSITIVE ENTRIES ARE DAYS EARLY

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	- .378	-1.031	- 2.385	- 3.368	-10.973
50	- .112	-1.949	- 4.796	- 5.543	-11.452
100	- .057	-3.598	- 5.128	- 6.615	-12.014
250	.438	-4.801	- 7.785	-10.255	-14.109
500	.321	-4.619	-11.318	-17.503	-19.937

Table XVI, displays the same information as the previous table except at a point of equal production in jobs completed (approximately 220). There is again no change in the marked affect of job size on late deliveries. Note the value of the periodic status report as an analytical tool. Without it there would have been no way to compare the values of E except with terminal statistics; i.e., at the end of 145 days.

TABLE XVI

D-A IN DAYS, EQUAL ORDER PRODUCTION, POSITIVE ENTRIES ARE DAYS EARLY

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	- .224	-1.031	- .446	- .991	-5.744
50	- .332	-1.819	-3.281	-4.460	-4.922
100	- .664	-3.598	-4.356	-2.499	-5.396
250	.408	-4.145	-5.456	-4.885	-7.960
500	-2.668	-4.408	-6.723	-9.355	-9.464

A typical distribution of E is shown in Figure 4. Increase in job size does not alter the shape of this distribution except to increase the length of the tails in both directions but mainly in the direction of late deliveries. In Chapter III interest was expressed in achieving comparable results to those reported by Fabrycky and Shamblin (20) in their test of the probability based sequencing algorithm. Their work shows the distribution of E skewed towards early delivery. The results of this experiment show the distribution E skewed toward late delivery. No other differences are apparent.

The results clearly indicate the rejection of H_0. Increase in job size contributes significantly to lateness. However, this conclusion is offered with considerable

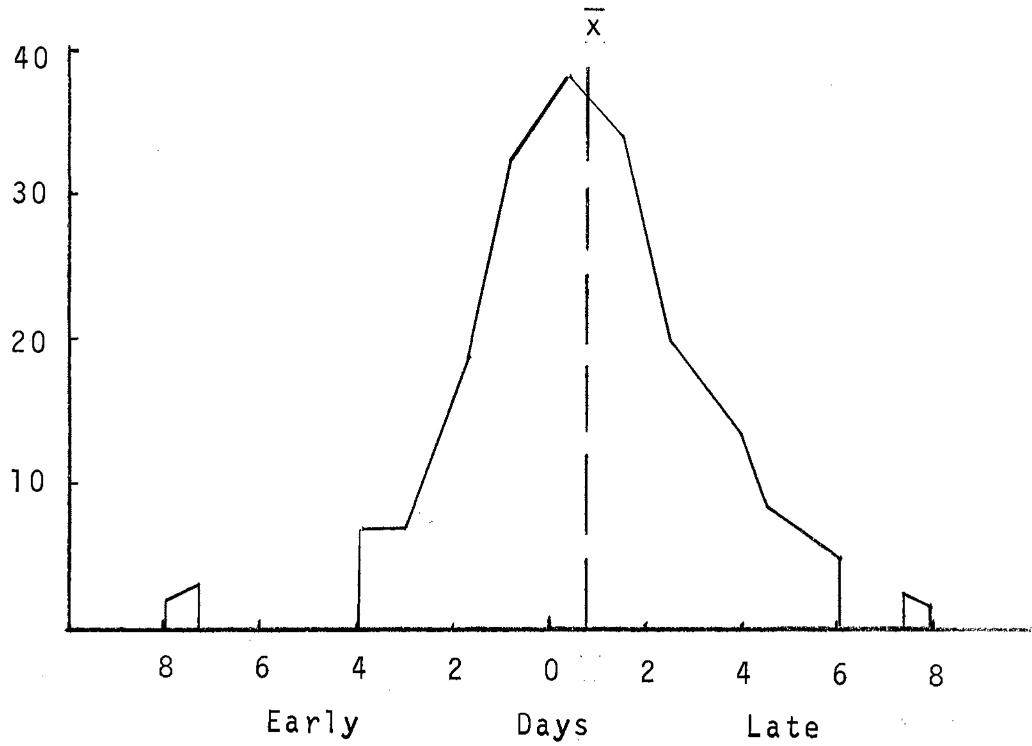

Figure 4. Typical Distribution of E = D-A

reservation as will be discussed below.

Reservations on Lateness

E is a relative measure. Its magnitude depends upon the predetermined due date, D. D is a changing standard against which to measure since its value is partly a function of the mean performance of the system. In other words, a feedback loop is employed to adjust the computation of D to correspond to the current state of the job shop manufacturing system. This is accomplished, of course, taking into account the differences in expected setup and processing times for the two different job sizes, thus removing bias because of job size and setup.

One of the necessary conditions for comparability of results in situations like this is the condition of equilibrium.

So far as the systems and jobs flowing through them are concerned, the general state of the process, there is every reason to believe that equilibrium conditions exist. The conditions observed are best described to be like statistical control, a stable mean with random fluctuations about the mean as in Figure 5. However, the same cannot be said, in all cases, about the generation of E.

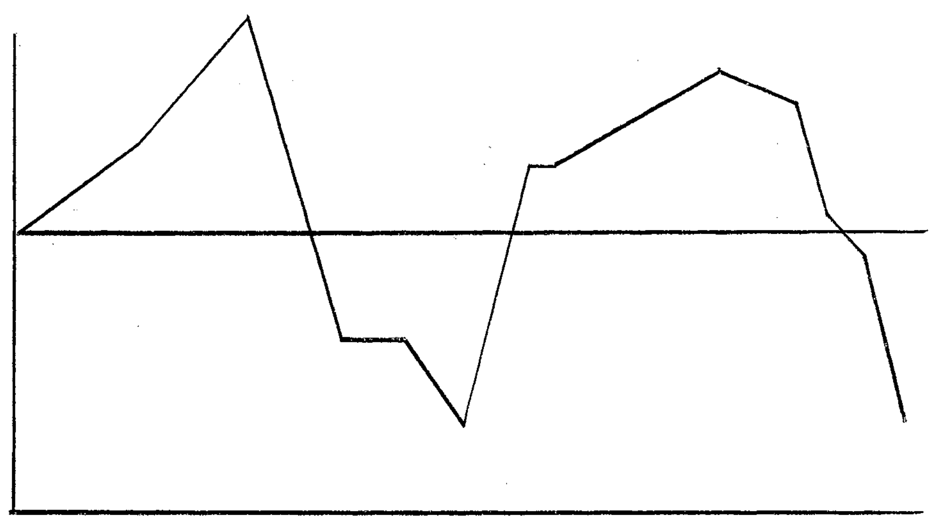

Figure 5. Statistical Control

Seven additional simulations were performed repeating the runs with E[S] = 500. Mean job sizes through 400 were run once at 520 days each. Job size 500 was run three times at 500, 900, and 1,800 days. None of these runs produced any results indicating that E[E] had stabilized. Consequently, the results of the previous section are, at a minimum, suspect.

Even partial failure is not without its reward, however. It turns out that E[E] did stabilize in at least one run of smaller job size and less setup time. This particular run produced 2000 completed jobs. The final run of 1,800 days (7.2 years) produced 3000 completed jobs and had yet to achieve stability. This comparison suggests that increasing job size or setup time or both have a marked impact on the rate of stabilization of E[E]. It might prove valuable to test the proposition that as the ratio of job size to system capacity increases, due date based sequencing algorithms tend to lose their efficiency. From the practical point of view, it is difficult to visualize a job shop like system in operation for more than seven years without a significant change in some of its characteristics.

Waiting Time

The final proposition is that job size does not alter the times a job waits in the various queues in the system. In addition to the parameters and shapes of the distribution of waiting time at the centers in the job shop manufacturing system, it is of interest to discuss the jobs which do not have to wait.

Table XVII shows the mean waiting time per job per center for each of the 25 tests. Statistical analysis of

TABLE XVII

MEAN WAITING TIME PER JOB PER CENTER
IN DAYS

Mean Setup Time	Mean Job Size 100	200	300	400	500
0	.462	1.695	.959	1.451	2.726
50	.473	1.625	2.425	2.172	2.365
100	.790	1.925	2.487	1.680	2.629
250	.878	2.313	2.549	2.355	2.846
500	1.737	2.289	2.654	3.069	3.193

these responses, Table XVIII, requires that the null hypothesis be rejected. Variance in the waiting time distributions (not displayed) increased in the same manner as the mean waiting time. The effect of increase in job sizes

TABLE XVIII

ANOVA, MEAN WAITING TIME PER JOB
PER CENTER**

Source	Degrees of Freedom	Sum of Squares	Mean Square	Test
Total	24	149,270		
Job	4	36,533	9,133.25	8.3*
Setup	4	95,158	23,789.50	21.7
Residual	16	17,579	1,098.70	

$F_{0.05;\, 4,\, 16} = 3.01$

*Reject H_0

**Coded Data

on the shape of the distribution of waiting time is slight. The tail of the distribution is lengthened and rate of change of slope is slightly reduced.

Table XIX shows the percentage of jobs which, on the average, did not have to wait. The correlation between these figures and corresponding system utilization shown in Table II is obvious. As system utilization decreases, the

TABLE XIX

MEAN PERCENT OF JOBS PER CENTER
WITH ZERO WAITING TIME

Mean Setup Time	Mean Job Size				
	100	200	300	400	500
0	7.1	9.8	14.1	13.4	7.5
50	7.2	8.5	7.2	9.5	8.3
100	10.5	10.2	8.6	11.9	9.1
250	15.6	9.2	7.7	11.1	7.0
500	13.2	12.3	8.0	8.0	7.0

mean percentage of jobs receiving service without waiting increases. The computations are not shown, but the correlation between these two types of response is high, r = -.84. This relationship leads to interest in another, namely the mean percentage of jobs not waiting and the corresponding production time. The coefficient of correlation of these data is calculated below.

$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{n(\Sigma x^2) - (\Sigma x)^2}\ \sqrt{n(\Sigma y^2) - (\Sigma y)^2}}$$

$$r = \frac{198{,}620 - 208{,}190}{(396.2)(26.24)}$$

$$= -0.52.$$

Employing the standard critical value of r, assuming the x's as constants and the y's as normally distributed with common variance σ^2, we may reject H_0: $\rho = 0$ and accept H_1: $\rho \neq 0$ based upon $r = -0.52 < r_{.025} = -0.444$, for a sample size of 20. Note that row 1 was deleted from this calculation since under perfect conditions, $r = -1.0$ for the responses under conditions of zero setup.

CHAPTER V

SUMMARY AND CONCLUSIONS

This chapter is composed of five sections. The first is a brief summary of the research effort. The second contains the conclusions reached. The third offers proposals for further study. The fourth acknowledges possible sources of errors and the fifth treats some practical considerations involving the computer and program employed in this study.

Summary

This investigation treated the general question of the effect of order size on the operation of a job shop manufacturing system. Chapter II described the computerized model built for the research. Chapter III was the exercise of designing the experiment to produce reasonable, visible and comparable results. The need to make careful choices was emphasized. Hopefully, any errors in this work are the result of making wrong choices rather than overlooking situations where choices should have been made. Chapter IV deals with the analysis of the four propositions under investigation.

Conclusions

The relationships between job size and job shop operation as derived in this dissertation indicate that increases in job sizes:

1. increases production in the job shop by reducing the incident of setup,

2. increases the total flow time of orders through the system in proportion to the increase in job size,

3. enlarges the means and variances of all time related distributions in the system,

4. do not materially alter the shapes of the time related distributions.

The major worth of this research effort appears to be in four areas. First, the question addressed has not, in the knowledge of the researcher, been treated before. That it has now been asked and partially answered should be a step forward. Second, the work serves to confirm existing theory, not by repeating previous experiments, but by the employment of a refined technique of splitting center flow time into component parts of process, setup and queue time. This categorization and others are articulated in the literature but there is no evidence that they have been employed in models of systems. Third, the estimating technique developed to set mean arrival times, while simple enough, appears to be new and useful ableit limited in application. Finally, the concept of reducing system idle time by causing essentially two kinds of idle time to coalesce seems important.

Future Research

Probably the most interesting proposition for future study is the possibility of devising a repetitive decision rule to reduce idle time through achieving partial concurrence of idle time caused by absence of work and idle time caused by setup time.

A second question to be addressed is the feasibility of due date based sequencing algorithms in low production situations as discussed in Chapter IV.

Due dates themselves deserve additional attention. There is little evidence in the literature to indicate research on this subject. There appears to be a need to objectively examine several alternative ways of assigning due dates to determine their relative merits. It is suggested that any examination of due dates should be accomplished by taking into account the economics associated with deviations from on time deliveries.

It would be worthwhile to reproduce this study with minor adjustment to explore more mixes of jobs and more basic job sizes. The purpose would be to discriminate more finely the differences which occur and to introduce replication to test for interaction.

Possible Error Sources

As discussed in Chapter IV, the probability of an error in the results of the analysis of lateness remains because of the apparent inability to achieve steady state conditions for E[E] in the low production situations.

Another possible source of error is the assumption of normality of the distribution of total flow time of jobs through the system. As noted in Chapter IV, total flow time distributions were more nearly uniform.

Statistics recorded by class interval tend to conceal the true shape of the distribution of variables. While care was exercised, it is possible that error is present.

The Computer and The Program

This subject is saved until last because it bears more on the possible future work of others than on this research.

Considerable care was employed in constructing the computer program so that it might be used by others. Examination of Appendix D will show that the program is carefully annotated as to the function of all routines.

It is now necessary to recommend that it not be used. The programming language, GPSS II with FORTRAN, when combined with the UNIVAC 1107, on which this work was accomplished, is painfully slow. The diagnostic and experimental runs for this study consumed more than 50 hours computer running time. Fortunately, GPSS II is now available with FORTRAN. There is also a routine to convert this study's program to GPSS III. If converted and rerun on, say, the IBM 7090, the running time should be less than 10 hours - a substantial savings. There are also basic errors in the version of GPSS II employed. The version is called EXEC II. The two errors causing the most difficulty are the inconsistent use of the relative and absolute clocks and the failure to provide the means to produce both weighted and unweighted statistics. Both capabilities are described in the programming manual but are absent in the EXEC II version of GPSS II.

The problem of the relative and absolute clocks resulted in considerable difficulty in delaying the collection of statistics until equilibrium conditions were achieved. As a result, it was necessary to bypass this feature of GPSS II and develop a FORTRAN subroutine to recycle the summary statistics.

The second program error was never corrected. Histograms are either weighted or unweighted, but not both for any given variable. In this study, it would have been an advantage to be able to compare weighted to unweighted entries in class intervals because of the mixes of jobs. The existence of the mixes made it difficult to relate the numbers of jobs to the numbers of units of product within corresponding intervals.

SELECTED BIBLIOGRAPHY

(1) Abruzzi, Adam, "The Production Process: Operating Characteristics", Management Science, Vol. 11, No. 6, April 1965.

(2) Baker, C. T. and B. P. Dzielinski, "Simulation of a Simplified Job Shop", International Business Machines Corporation, Research Report RC-96, May 15, 1959, pp. 1-3.

(3) Blake, Kenneth R. and William S. Stapakis, "Some Theoretical Results on the Job Shop Scheduling Problem", M-1533-1, United Aircraft Corporation, July 1959, p. 19.

(4) Brooks, George H. and Charles R. White, "An Algorithm for Finding Optimal or Near Optimal Solutions to the Production Scheduling Problem", The Journal of Industrial Engineering, Jan-Feb 1965, Vol, XVI, No. 1, pp. 34-40.

(5) Buffa, E. S., "Models for Production and Operations Management", John Wiley and Sons, New York, 1963, p. 55.

(6) Canning, Francis L., "Estimating Load Requirements in a Job Shop", Journal of Industrial Engineering, Vol. X, No. 6, Nov-Dec 1959.

(7) Colley, John L., Jr., "Simulation as a Production Aid", The Journal of Industrial Engineering, Vol. X, No. 4, July-Aug 1959.

(8) Conway, R. W., "Preliminary Report on an Experimental Comparison of Priority Dispatching Rules", Cornell Production Control Research Committee, April 13, 1962.

(9) Conway, R. W., "An Experimental Investigation of Priority Assignment in a Job Shop", The RAND Corporation, RM-3789-PR, February 1964.

(10) Conway, Richard W., Bruce M. Johnson, and William L. Maxwell, "An Experimental Investigation of Priority Dispatching", The Journal of Industrial Engineering, Vol. XI, No. 3, May-June 1960.

(11) Conway, Richard W., "Priority Dispatching and Job Lateness in a Job Shop", The Journal of Industrial Engineering, Vol. XVI, No. 4, July-Aug 1965.

(12) Dzielinski, B. P., "An Analysis of the Simulation Tests of a Simplified Job Shop Process", International Business Machines Corporation, File No. 61-13.

(13) Dzielinski, B. P., C. T. Baker, and A. S. Manne, "Simulation Tests of Lot Size Programming", IBM Research Report RC-489, June 1961, p. 9.

(14) Eilon, Samuel, "Elements of Production Planning and Control", The MacMillan Company, New York, 1962, p. 350.

(15) Eisemann, Kurt, "The Generalized Stepping Stone Method for the Machine Loading Model", Management Science, Vol. II, No. 1, September 1964, p. 154.

(16) Elmaghraby, Salah E. and Roger T. Cole, "On the Control of Production in Small Job Shops", The Journal of Industrial Engineering, Vol. XIV, No. 4, July-Aug 1963.

(17) Elmaghraby, Salah E. and Allen S. Ginsberg, "A Dynamic Model for the Optimal Loading of Linear Multi-Operation Shops", Management Technology, Vol. 4, No. 1, June 1964.

(18) Evans, Richard V., "The Structure of Production and Processing Systems", Western Management Science Institute, University of California, Los Angeles, California 90024.

(19) Evans, Richard V., "Some Aspects of the Optimal Production Policy for Producing Two Products Under a Resource Limitation", Management Sciences Research Project, Research Report No. 84.

(20) Fabrycky, W. J. and J. E. Shamblin, "A Probability Based Sequencing Algorithm", The Journal of Industrial Engineering, Vol. XVII, No. 6, June 1966, pp. 308-312.

(21) Jackson, James R., "Research in Production Sequencing", Management Sciences Research Project, Research Report No. 57, October 1958.

(22) Jackson, James R., "Job Shop-Like Queueing Systems", Management Science, Vol. 10, No. 1, Oct. 1963, p. 131.

(23) Jackson, James R., Rosser T. Nelson, and Andrew A. Grindlay, "Research On Job Shop-Like Models: A Progress Report". Management Sciences Research Project No. 76, July 18, 1962, p. 1.

(24) Karush, W. and L. A. Moody, "Determination of Feasible Shipping Schedules for a Job Shop". Presentation, ORSA, Philadelphia, Penn., May 9-10, 1957.

(25) Kunreuther, Howard, "Scheduling Short-Run Changes in Production to Minimize Long-Run Expected Costs", Management Science, Vol. 12, No. 7, March 1966.

(26) Little, J. D. C., "A Proof for the Queueing Formula $L = \gamma W$," Operations Research, Vol. 9, No. 3, May-June 1961, pp. 383-388.

(27) Magee, J. F., "Production Planning and Inventory Control", McGraw Hill, New York, 1958, p. 198.

(28) Mansoor, E. M., "Assembly Line Balancing - An Improvement of the Ranked Positional Weight Technique", The Journal of Industrial Engineering, Vol. XV, No. 2, March-April 1964.

(29) Reinitz, R. C., "On the Job Shop Scheduling Problem", Chapter 5 of Industrial Scheduling, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1963.

(30) Rowe, Alan J., "Toward a Theory of Scheduling", The Journal of Industrial Engineering, Vol. XI, No. 2, March-April 1960, p. 125.

(31) Salveson, M. E., "A Problem in Optimal Machine Loading", Management Science, Vol. 2, No. 3, April 1956.

(32) Sisson, Roger L., "Methods of Sequencing in Job Shops - A Review", Operations Research, 1959, Jan-Feb.

(33) Smith, Wayland, P. and Jasvantrai, C. Shah, "Design and Development of a Manufacturing Systems Simulator", The Journal of Industrial Engineering, Vol. XV, No. 4, July-Aug 1964.

(34) Timms, H. L., "The Production Function in Business", Richard D. Irwin, Homewood, Illinois, 1966, p. 521.

(35) Tonge, Fred M., "Assembly Line Balancing Using Probabilistic Combinations of Heuristics", Management Science, Vol. 11, No. 7, May 1965.

(36) Wadsworth, Harrison M. and Sang Hoon Chang, "The Reject Allowance Problem: An Analysis and Application to

Job Lot Production", The Journal of Industrial Engineering, Vol. XV, No. 3, May-June 1964.

APPENDIX A

TRACE REPORT

The trace report is generated by introducing NTYPE(3) job into the system. The trace report starts when the NTYPE(3) job enters the system and is suppressed when it exits the system. The reports are printed with the same frequency set for the periodic status report (explained in Appendix B), but include all relevant times in the interval between reports. Trace reports contain nine columns of differentiated information in plain language, depending upon the action being taken. No explanations of column entries are considered necessary.

```
*CHK Z JOB  42 IN QUE  2  CLOCK  20169  D-C-10168  Z= -7.81  Z IN CTR=-19.43  NEXT Z= -20.90
*CHK Z JOB   4 IN QUE  9  CLOCK  20169  D-C-10168  Z= -4.89  Z IN CTR=150.00  NEXT Z=  -7.31
*SETUP JOB  35 IN CTR  9  CLOCK  20169  D-C-10168  Z= -7.31   S MEAN  500     SPREAD   50
*CHK Z JOB  42 IN QUE  2  CLOCK  20170  D-C-10169  Z= -7.81  Z IN CTR=-20.91  NEXT Z= -20.90
*SEND  JOB  46 TO QUE  2  CLOCK  20210  D-C-10209  Z= -7.29   T MEAN 1848.65  ST.DEV 1023.05   Q MEAN  567.00  ST.DEV     .00
*CHK Z JOB  46 IN QUE  2  CLOCK  20210  D-C-10209  Z= -7.29  Z IN CTR=-20.91  NEXT Z= -20.86
*PROC. JOB  35 IN CTR  9  CLOCK  20715  D-C-10714  Z= -7.31   P MEAN  100     SPREAD   10
*EXIT  JOB  35 FROM SHOP  CLOCK  20816  D-A-10815  Z= -7.31  SIZE  100. DUE  10001
*CHK Z JOB   4 IN QUE  9  CLOCK  20816  D-C-10815  Z= -4.89  Z IN CTR=150.00  NEXT Z=  -6.72
*CHK Z JOB   4 IN QUE  9  CLOCK  21000  D-C-10999  Z= -5.16  Z IN CTR= -7.10  NEXT Z=  -6.00
*CHK Z JOB  42 IN QUE  2  CLOCK  21000  D-C-10999  Z=-12.50  Z IN CTR=-20.91  NEXT Z= -20.86
*CHK Z JOB  46 IN QUE  2  CLOCK  21000  D-C-10999  Z=-12.10  Z IN CTR=-20.91  NEXT Z= -20.86
*CHK Z JOB  42 IN QUE  2  CLOCK  21189  D-C-11188  Z=-12.50  Z IN CTR=-21.84  NEXT Z= -21.84
*CHK Z JOB  46 IN QUE  2  CLOCK  21189  D-C-11188  Z=-12.10  Z IN CTR=-21.84  NEXT Z= -21.84
*CHK Z JOB   4 IN QUE  9  CLOCK  21801  D-C-11800  Z= -5.16  Z IN CTR=150.00  NEXT Z=  -6.57
*CHK Z JOB   4 IN QUE  9  CLOCK  22000  D-C-11999  Z= -5.44  Z IN CTR= -7.15  NEXT Z=  -5.16
*CHK Z JOB  42 IN QUE  2  CLOCK  22000  D-C-11999  Z=-13.35  Z IN CTR=-21.84  NEXT Z= -13.89
*CHK Z JOB  46 IN QUE  2  CLOCK  22000  D-C-11999  Z=-12.76  Z IN CTR=-21.84  NEXT Z= -13.89
*CHK Z JOB  42 IN QUE  2  CLOCK  22222  D-C-12221  Z=-13.35  Z IN CTR=-14.87  NEXT Z= -14.87
*CHK Z JOB  46 IN QUE  2  CLOCK  22222  D-C-12221  Z=-12.76  Z IN CTR=-14.87  NEXT Z= -14.87
*SETUP JOB   4 IN CTR  9  CLOCK  22869  D-C-12868  Z= -5.44   S MEAN  500     SPREAD   50
*CHK Z JOB  42 IN QUE  2  CLOCK  23000  D-C-12999  Z=-14.21  Z IN CTR=-14.87  NEXT Z= -13.35
*CHK Z JOB  46 IN QUE  2  CLOCK  23000  D-C-12999  Z=-13.42  Z IN CTR=-14.87  NEXT Z= -13.35
*SETUP JOB  42 IN CTR  2  CLOCK  23213  D-C-13212  Z=-14.21   S MEAN  500     SPREAD   50
*CHK Z JOB  46 IN QUE  2  CLOCK  23213  D-C-13212  Z=-13.42  Z IN CTR=-14.21  NEXT Z= -14.20
*PROC. JOB   4 IN CTR  9  CLOCK  23370  D-C-13369  Z= -5.71   P MEAN  100     SPREAD   10
*SEND  JOB   4 TO QUE  5  CLOCK  23474  D-C-13473  Z= -5.71   T MEAN 2504.47  ST.DEV 2259.38   Q MEAN     .00  ST.DEV     .00
*CHK Z JOB   4 IN QUE  5  CLOCK  23474  D-C-13473  Z= -5.71  Z IN CTR=150.00  NEXT Z= 150.00
*SETUP JOB   4 IN CTR  5  CLOCK  23474  D-C-13473  Z= -5.71   S MEAN  500     SPREAD   50
```

APPENDIX B

THE PERIODIC STATUS REPORT

The periodic status report may be as often as once at the end of each day or suppressed entirely. It is in two parts.

Part 1 contains 14 columns of information about the activities at centers in the system. Second entries are cumulative statistics.

Column	Information
1	Center Number
2	Utilization, Block P
3	Jobs in
4	Jobs out
5	Mean flow time
6	Flow time standard deviation
7	Mean queue time
8	Queue time standard deviation
9	Number of jobs in queue
10	Urgency number of next in line
11	Identification of job in block P
12	Due date of current job
13	Urgency number of current job
14	Centers remaining for current job

Part 2 contains 9 columns of information about the job passing through the system without regard for the machine centers involved. Second entries are again cumulative statistics.

Column	Information
1	Job Size
2	Jobs in
3	Jobs out
4	Mean flow time
5	Flow time standard deviation
6	Mean D-A
7	D-A standard deviation
8	Inter-exit mean
9	Inter-exit standard deviation

****** REPORT FOR LAST 5 DAYS. DATE 555

CTR NO.	UTIL	JOBS IN	JOBS OUT	FLOW MEAN	FLOW ST.DEV	WAIT MEAN	WAIT ST.DEV	IN QUE	Z NEXT	CUR JOB	DUE DATE	Z	CENTERS LEFT
1	.49	5	5	1873.40	675.50	964.00	699.08	7	-.11	27	557635	-.45	1
	.47	505	505	4306.97	3700.38	3402.40	3806.05						
2	.50	5	5	4551.40	3270.80	4393.80	2856.06	5	.42	18	574033	-.08	2 10 9 5 6
	.46	494	494	4280.01	3884.65	3389.09	3996.12						
3	.50	5	5	5795.00	3223.79	4483.20	3489.84	6	.34	34	561794	.45	9
	.48	516	516	4336.51	3939.29	3381.06	3987.45						
4	.49	5	5	5373.20	4241.56	6472.20	4462.78	3	.54	25	598562	.54	4 6 7 9 6 2 10 5 6 8
	.43	462	462	3367.74	3312.57	2465.76	3442.47						
5	.51	5	5	4239.20	3233.47	3330.40	3124.14	1	.35	52	581674	.64	2 9 7 7 6
	.44	474	474	3653.38	3460.24	2726.54	3555.84						
6	.41	4	4	3597.50	2819.99	2503.50	2858.78	1	.51	74	566420	1.57	9
	.45	483	483	3323.20	3356.73	2357.65	3415.37						
7	.40	5	4	1345.00	405.56	279.40	378.11	1	.45	65	563555	.17	3 6
	.46	495	495	4258.03	4017.87	3321.33	4085.87						
8	.51	5	5	3293.40	1016.03	1686.20	1054.41	6	-.47	38	570606	-.53	8 9 4 9 6
	.45	485	485	3428.33	3543.06	2568.05	3728.91						
9	.50	5	5	3784.60	770.20	2256.20	1316.06	6	.39	82	576024	1.75	8 10 8
	.48	519	519	4958.48	4123.52	4436.24	4509.81						
10	.48	5	5	9242.20	4445.49	5683.00	4147.89	10	-.74	63	561160	-.47	1 1
	.43	457	457	3448.11	3543.68	2521.76	3654.03						

JOB TYPE	JOBS IN	JOBS OUT	FLOW MEAN	FLOW ST.DEV	D-A MEAN	D-A ST.DEV	EXIT MEAN	EXIT ST.DEV
SZ= 500.00	9	6	21816.33	14730.43	5561.67	2083.61		
	968	883	30169.83	16622.13	-5915.17	7138.04		
SZ= 100.00	-0	-0	.00	.00	.00	.00		
	0	0	.00	.00	.00	.00		
ZO= .00	9	6	21816.33	14730.43	5561.67	2083.61		
	973	887	30110.13	16611.57	-5953.57	7146.31		
ALL TYPES	9	6	21816.33	14730.43	5561.67	2083.61	1005.50	511.60
	973	887	30110.13	16611.57	-5953.57	7146.31	602.65	568.30

APPENDIX C

STATISTICAL TABLES

These tables are produced at the end of each simulation. There are two types of reports. The first type contains two tables. The first of these displays terminal data on the facilities in the system. Facilities 1 through 10 are blocks S + P. Facilities 21 through 30 are blocks P only. The second table contains terminal information about the queues in the system. The data in this table is not used in this study. Examination of the TOTAL ENTRIES column will show more entries per column in each center than passed through the system. This is because each time z_i is computed and jobs re-sequenced in queues this action is taken as a new entry into the queue.

The second type constitute the primary source of data for this report. Examples of each variable on which terminal statistics are tabulated are shown in numerical order. The following tables are used:

Table Number	Variable
1 - 10	Center flow time
21 - 30	Center idle time
41 - 50	Center queue time
61 - 63	Total flow time by job size

66 - 68	D-A by job size
71 - 73	Total flow time by initial z
76 - 78	D-A by initial z
81	Total flow time
82	D-A
83	Inter-exit time

FACILITY NR	AVERAGE UTILIZATION	NUMBER ENTRIES	AVERAGE TIME/TRANS	TRANS	$TRANS
1	.9112	820	1000.09	72,S	0
2	.9252	835	997.23	18,S	0
3	.9350	844	997.05	59,S	0
4	.8861	800	996.84	44,S	0
5	.9043	815	998.61	61,S	0
6	.9069	817	998.98	0	0
7	.9289	836	1000.00	25,S	0
8	.9089	820	997.56	39,S	0
9	.9716	877	997.07	6,S	0
10	.8999	811	998.69	73,S	0
21	.4552	820	499.56	72,H	0
22	.4619	834	498.47	0	0
23	.4667	843	498.28	0	0
24	.4427	799	498.68	0	0
25	.4506	814	498.19	0	0
26	.4533	817	499.38	0	0
27	.4636	836	499.08	25,H	0
28	.4544	819	499.36	0	0
29	.4832	877	495.87	6,H	0
30	.4493	810	499.23	0	0
41	.0000	1568	.00	0	0

QUEUE NR	MAXIMUM CONTENTS	AVERAGE CONTENTS	TOTAL ENTRIES	ZERO ENTRIES	PERCENT ZEROS	AVERAGE TIME/TRANS	TABLE NUMBER	CURRENT CONTENTS
1	6	.75	3024	83	2.7	223.53	0	1
2	6	.83	3317	60	1.8	224.68	0	1
3	6	.83	3406	59	1.7	219.08	0	1
4	6	.74	2876	84	2.9	230.06	0	1
5	6	.78	3095	65	2.1	226.27	0	1
6	6	.75	2927	84	2.9	231.23	0	0
7	6	.82	3130	63	2.0	235.26	0	1
8	5	.73	2739	88	3.2	240.63	0	1
9	7	.93	3993	22	.6	208.80	0	1
10	5	.75	2855	82	2.9	236.68	0	1
21	14	2.88	5453	0	.0	475.68	0	1
22	16	3.74	7072	0	.0	475.58	0	1
23	15	3.65	6933	1	.0	473.77	0	5
24	14	2.95	5617	0	.0	472.77	0	8
25	15	2.83	5373	1	.0	473.50	0	0
26	16	3.05	5731	1	.0	478.90	0	0
27	9	2.67	5133	1	.0	467.65	0	2
28	13	2.16	4166	0	.0	465.71	0	3
29	23	7.19	13345	2	.0	485.19	0	7
30	17	3.08	5866	0	.0	472.86	0	5
41	61	.00	80031	8320	10.4	.00	0	0

TABLE NUMBER 3

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
825	4385.028	4046.056	NON-WEIGHTED
420300	4303.644	132100.950	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
1000	19000	4.52	4.5	95.5	.228	-.837
2000	171600	40.83	45.3	54.7	.456	-.589
3000	46500	11.06	56.4	43.6	.684	-.342
4000	34000	8.09	64.5	35.5	.912	-.095
5000	22000	5.23	69.7	30.3	1.140	.152
6000	18200	4.33	74.1	25.9	1.368	.399
7000	17500	4.16	78.2	21.8	1.596	.646
8000	15500	3.69	81.9	18.1	1.824	.893
9000	12500	2.97	84.9	15.1	2.052	1.141
10000	12000	2.86	87.7	12.3	2.280	1.388
11000	7000	1.67	89.4	10.6	2.509	1.635
12000	8000	1.90	91.3	8.7	2.737	1.882
13000	10500	2.50	93.8	6.2	2.965	2.129
14000	9500	2.26	96.1	3.9	3.193	2.376
15000	7500	1.78	97.9	2.1	3.421	2.624
16000	4500	1.07	98.9	1.1	3.649	2.871
17000	4500	1.07	100.0	.0	3.877	3.118

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NUMBER 5

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
799	3821.123	3632.483	NON-WEIGHTED
405400	3762.668	116959.225	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
1000	24700	6.09	6.1	93.9	.262	-.777
2000	181600	44.80	50.9	49.1	.523	-.501
3000	52100	12.85	63.7	36.3	.785	-.226
4000	26000	6.41	70.2	29.8	1.047	.049
5000	19000	4.69	74.8	25.2	1.309	.325
6000	15500	3.82	78.7	21.3	1.570	.600
7000	16000	3.95	82.6	17.4	1.832	.875
8000	11000	2.71	85.3	14.7	2.094	1.150
9000	9000	2.22	87.5	12.5	2.355	1.426
10000	10000	2.47	90.0	10.0	2.617	1.701
11000	10000	2.47	92.5	7.5	2.879	1.976
12000	8500	2.10	94.6	5.4	3.140	2.252
13000	7500	1.85	96.4	3.6	3.402	2.527
14000	5500	1.36	97.8	2.2	3.664	2.802
15000	5500	1.36	99.1	.9	3.926	3.077
16000	2000	.49	99.6	.4	4.187	3.353
17000	1500	.37	100.0	.0	4.449	3.628

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NUMBER 21

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
802	596.868	396.576	NON-WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
100	0	.00	.0	100.0	.168	-1.253
200	0	.00	.0	100.0	.335	-1.001
300	0	.00	.0	100.0	.503	-.749
400	0	.00	.0	100.0	.670	-.496
500	362	44.15	44.1	55.9	.838	-.244
600	390	47.56	91.7	8.3	1.005	.008
700	4	.49	92.2	7.8	1.173	.260
800	6	.73	92.9	7.1	1.340	.512
900	3	.37	93.3	6.7	1.508	.764
1000	4	.49	93.8	6.2	1.675	1.017
1100	4	.49	94.3	5.7	1.843	1.269
1200	5	.61	94.9	5.1	2.010	1.521
1300	2	.24	95.1	4.9	2.178	1.773
1400	5	.61	95.7	4.3	2.346	2.025
1500	7	.85	96.6	3.4	2.513	2.277
1600	1	.12	96.7	3.3	2.681	2.529
1700	1	.12	96.8	3.2	2.848	2.782
1800	1	.12	97.0	3.0	3.016	3.034
1900	2	.24	97.2	2.8	3.183	3.286
2000	1	.12	97.3	2.7	3.351	3.538
2100	5	.61	97.9	2.1	3.518	3.790
2200	0	.00	97.9	2.1	3.686	4.042
2300	0	.00	97.9	2.1	3.853	4.295
2400	1	.12	98.0	2.0	4.021	4.547
2500	1	.12	98.2	1.8	4.189	4.799
2600	3	.37	98.5	1.5	4.356	5.051
2700	1	.12	98.7	1.3	4.524	5.303
2800	1	.12	98.8	1.2	4.691	5.555
2900	1	.12	98.9	1.1	4.859	5.808
3000	2	.24	99.1	.9	5.026	6.060
3100	1	.12	99.3	.7	5.194	6.312
3200	2	.24	99.5	.5	5.361	6.564
3300	1	.12	99.6	.4	5.529	6.816
3400	1	.12	99.8	.2	5.696	7.068
3500	2	.24	100.0	.0	5.864	7.320

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NUMBER 42

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
817	3523.820	4074.316	NON-WEIGHTED
415900	3454.700	119271.301	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
0	29500	7.09	7.1	92.9	.000	-.865
500	74600	17.94	25.0	75.0	.142	-.742
1000	72100	17.34	42.4	57.6	.284	-.619
1500	30000	7.21	49.6	50.4	.426	-.497
2000	24000	5.77	55.3	44.7	.568	-.374
2500	11000	2.64	58.0	42.0	.709	-.251
3000	14500	3.49	61.5	38.5	.851	-.129
3500	12100	2.91	64.4	35.6	.993	-.006
4000	13600	3.27	67.7	32.3	1.135	.117
4500	11500	2.77	70.4	29.6	1.277	.240
5000	12000	2.89	73.3	26.7	1.419	.362
5500	9500	2.28	75.6	24.4	1.561	.485
6000	8500	2.04	77.6	22.4	1.703	.608
6500	8000	1.92	79.6	20.4	1.845	.730
7000	7000	1.68	81.2	18.8	1.986	.853
7500	11000	2.64	83.9	16.1	2.128	.976
8000	6500	1.56	85.5	14.5	2.270	1.099
8500	4000	.96	86.4	13.6	2.412	1.221
9000	5000	1.20	87.6	12.4	2.554	1.344
9500	3000	.72	88.3	11.7	2.696	1.467
10000	5500	1.32	89.7	10.3	2.838	1.590
10500	5000	1.20	90.9	9.1	2.980	1.712
11000	5000	1.20	92.1	7.9	3.122	1.835
11500	2000	.48	92.5	7.5	3.264	1.958
12000	5000	1.20	93.7	6.3	3.405	2.080
12500	5000	1.20	95.0	5.0	3.547	2.203
13000	2000	.48	95.4	4.6	3.689	2.326
13500	3000	.72	96.2	3.8	3.831	2.449
14000	3500	.84	97.0	3.0	3.973	2.571
14500	3500	.84	97.8	2.2	4.115	2.694
15000	2500	.60	98.4	1.6	4.257	2.817
15500	2500	.60	99.0	1.0	4.399	2.939
16000	2500	.60	99.6	.4	4.541	3.062
16500	1500	.36	100.0	.0	4.682	3.185

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NUMBER 61

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
1484	30134.296	16668.744	NON-WEIGHTED
756500	29556.591	762051.400	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
1000	3000	.40	.4	99.6	.033	-1.748
2000	21000	2.78	3.2	96.8	.066	-1.688
3000	12000	1.59	4.8	95.2	.100	-1.628
4000	9000	1.19	5.9	94.1	.133	-1.568
5000	15000	1.98	7.9	92.1	.166	-1.508
6000	11500	1.52	9.5	90.5	.199	-1.448
7000	10000	1.32	10.8	89.2	.232	-1.388
8000	10000	1.32	12.1	87.9	.265	-1.328
9000	10000	1.32	13.4	86.6	.299	-1.268
10000	7500	.99	14.4	85.6	.332	-1.208
11000	14500	1.92	16.3	83.7	.365	-1.148
12000	12000	1.59	17.9	82.1	.398	-1.088
13000	15000	1.98	19.9	80.1	.431	-1.028
14000	11500	1.52	21.4	78.6	.465	-.968
15000	15500	2.05	23.5	76.5	.498	-.908
16000	8500	1.12	24.6	75.4	.531	-.848
17000	14500	1.92	26.5	73.5	.564	-.788
18000	15000	1.98	28.5	71.5	.597	-.728
19000	10500	1.39	29.9	70.1	.631	-.668
20000	16000	2.12	32.0	68.0	.664	-.608
21000	13500	1.78	33.8	66.2	.697	-.548
22000	20000	2.64	36.4	63.6	.730	-.488
23000	18500	2.45	38.9	61.1	.763	-.428
24000	12500	1.65	40.5	59.5	.796	-.368
25000	12000	1.59	42.1	57.9	.830	-.308
26000	16000	2.12	44.2	55.8	.863	-.248
27000	14500	1.92	46.1	53.9	.896	-.188
28000	12500	1.65	47.8	52.2	.929	-.128
29000	12000	1.59	49.4	50.6	.962	-.068
30000	14000	1.85	51.2	48.8	.996	-.008
31000	16000	2.12	53.3	46.7	1.029	.052
32000	11500	1.52	54.9	45.1	1.062	.112
33000	13000	1.72	56.6	43.4	1.095	.172
34000	13000	1.72	58.3	41.7	1.128	.232
35000	14000	1.85	60.1	39.9	1.161	.292
36000	12000	1.59	61.7	38.3	1.195	.352
37000	17500	2.31	64.0	36.0	1.228	.412
38000	13000	1.72	65.8	34.2	1.261	.472
39000	15000	1.98	67.7	32.3	1.294	.532
40000	10000	1.32	69.1	30.9	1.327	.592
OVERFLOW	234000	30.93	100.0	.0		

TABLE NUMBER 63

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
4	16930.500	4897.578	NON-WEIGHTED
500	13544.400	157056.670	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
1000	0	.00	.0	100.0	.059	-3.253
2000	100	20.00	20.0	80.0	.118	-3.049
3000	0	.00	20.0	80.0	.177	-2.844
4000	0	.00	20.0	80.0	.236	-2.640
5000	0	.00	20.0	80.0	.295	-2.436
6000	0	.00	20.0	80.0	.354	-2.232
7000	0	.00	20.0	80.0	.413	-2.028
8000	0	.00	20.0	80.0	.473	-1.823
9000	0	.00	20.0	80.0	.532	-1.619
10000	0	.00	20.0	80.0	.591	-1.415
11000	100	20.00	40.0	60.0	.650	-1.211
12000	0	.00	40.0	60.0	.709	-1.007
13000	0	.00	40.0	60.0	.768	-.803
14000	0	.00	40.0	60.0	.827	-.598
15000	0	.00	40.0	60.0	.886	-.394
16000	100	20.00	60.0	40.0	.945	-.190
17000	100	20.00	80.0	20.0	1.004	.014
18000	0	.00	80.0	20.0	1.063	.218
19000	0	.00	80.0	20.0	1.122	.423
20000	0	.00	80.0	20.0	1.181	.627
21000	0	.00	80.0	20.0	1.240	.831
22000	0	.00	80.0	20.0	1.299	1.035
23000	0	.00	80.0	20.0	1.358	1.239
24000	0	.00	80.0	20.0	1.418	1.443
25000	100	20.00	100.0	-.0	1.477	1.648

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NUMBER 66

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
1484	-3920.720	6399.737	NON-WEIGHTED
756500	-3845.564	166161.650	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
-20000	17500	2.31	2.3	97.7	5.101	-2.512
-19000	4000	.53	2.8	97.2	4.846	-2.356
-18000	4000	.53	3.4	96.6	4.591	-2.200
-17000	9000	1.19	4.6	95.4	4.336	-2.044
-16000	8500	1.12	5.7	94.3	4.081	-1.887
-15000	9000	1.19	6.9	93.1	3.826	-1.731
-14000	15000	1.98	8.9	91.1	3.571	-1.575
-13000	13000	1.72	10.6	89.4	3.316	-1.419
-12000	11000	1.45	12.0	88.0	3.061	-1.262
-11000	23000	3.04	15.1	84.9	2.806	-1.106
-10000	22000	2.91	18.0	82.0	2.551	-.950
-9000	20000	2.64	20.6	79.4	2.295	-.794
-8000	23000	3.04	23.7	76.3	2.040	-.637
-7000	26000	3.44	27.1	72.9	1.785	-.481
-6000	17500	2.31	29.4	70.6	1.530	-.325
-5000	36000	4.76	34.2	65.8	1.275	-.169
-4000	46500	6.15	40.3	59.7	1.020	-.012
-3000	62500	8.26	48.6	51.4	.765	.144
-2000	65500	8.66	57.2	42.8	.510	.300
-1000	61500	8.13	65.4	34.6	.255	.456
0	61000	8.06	73.4	26.6	-.000	.613
1000	47000	6.21	79.6	20.4	-.255	.769
2000	38500	5.09	84.7	15.3	-.510	.925
3000	35000	4.63	89.4	10.6	-.765	1.081
4000	33500	4.43	93.8	6.2	-1.020	1.238
5000	20500	2.71	96.5	3.5	-1.275	1.394
6000	8500	1.12	97.6	2.4	-1.530	1.550
7000	6500	.86	98.5	1.5	-1.785	1.706
8000	4000	.53	99.0	1.0	-2.040	1.863
9000	4000	.53	99.5	.5	-2.295	2.019
10000	1000	.13	99.7	.3	-2.551	2.175
11000	500	.07	99.7	.3	-2.806	2.331
12000	500	.07	99.8	.2	-3.061	2.488
13000	500	.07	99.9	.1	-3.316	2.644
14000	0	.00	99.9	.1	-3.571	2.800
15000	500	.07	99.9	.1	-3.826	2.956
16000	0	.00	99.9	.1	-4.081	3.113
17000	0	.00	99.9	.1	-4.336	3.269
18000	500	.07	100.0	.0	-4.591	3.425

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NUMBER 68

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
4	-14430.250	2225.700	NON-WEIGHTED
500	-11544.200	130083.050	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
-20000	0	.00	.0	100.0	1.386	-2.502
-19000	0	.00	.0	100.0	1.317	-2.053
-18000	0	.00	.0	100.0	1.247	-1.604
-17000	0	.00	.0	100.0	1.178	-1.155
-16000	100	20.00	20.0	80.0	1.109	-.705
-15000	100	20.00	40.0	60.0	1.039	-.256
-14000	100	20.00	60.0	40.0	.970	.193
-13000	0	.00	60.0	40.0	.901	.643
-12000	0	.00	60.0	40.0	.832	1.092
-11000	0	.00	60.0	40.0	.762	1.541
-10000	100	20.00	80.0	20.0	.693	1.990
-9000	0	.00	80.0	20.0	.624	2.440
-8000	0	.00	80.0	20.0	.554	2.889
-7000	0	.00	80.0	20.0	.485	3.338
-6000	0	.00	80.0	20.0	.416	3.788
-5000	0	.00	80.0	20.0	.346	4.237
-4000	0	.00	80.0	20.0	.277	4.686
-3000	0	.00	80.0	20.0	.208	5.136
-2000	0	.00	80.0	20.0	.139	5.585
-1000	100	20.00	100.0	-.0	.069	6.034

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NUMBER 71

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
1488	30098.802	16662.293	NON-WEIGHTED
757000	29546.014	761810.490	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
1000	3000	.40	.4	99.6	.033	-1.746
2000	21100	2.79	3.2	96.8	.066	-1.686
3000	12000	1.59	4.8	95.2	.100	-1.626
4000	9000	1.19	6.0	94.0	.133	-1.566
5000	15000	1.98	7.9	92.1	.166	-1.506
6000	11500	1.52	9.5	90.5	.199	-1.446
7000	10000	1.32	10.8	89.2	.233	-1.386
8000	10000	1.32	12.1	87.9	.266	-1.326
9000	10000	1.32	13.4	86.6	.299	-1.266
10000	7500	.99	14.4	85.6	.332	-1.206
11000	14600	1.93	16.3	83.7	.365	-1.146
12000	12000	1.59	17.9	82.1	.399	-1.086
13000	15000	1.98	19.9	80.1	.432	-1.026
14000	11500	1.52	21.4	78.6	.465	-.966
15000	15500	2.05	23.5	76.5	.498	-.906
16000	8600	1.14	24.6	75.4	.532	-.846
17000	14600	1.93	26.5	73.5	.565	-.786
18000	15000	1.98	28.5	71.5	.598	-.726
19000	10500	1.39	29.9	70.1	.631	-.666
20000	16000	2.11	32.0	68.0	.664	-.606
21000	13500	1.78	33.8	66.2	.698	-.546
22000	20000	2.64	36.4	63.6	.731	-.486
23000	18500	2.44	38.9	61.1	.764	-.426
24000	12500	1.65	40.5	59.5	.797	-.366
25000	12100	1.60	42.1	57.9	.831	-.306
26000	16000	2.11	44.3	55.7	.864	-.246
27000	14500	1.92	46.2	53.8	.897	-.186
28000	12500	1.65	47.8	52.2	.930	-.126
29000	12000	1.59	49.4	50.6	.963	-.066
30000	14000	1.85	51.3	48.7	.997	-.006
31000	16000	2.11	53.4	46.6	1.030	.054
32000	11500	1.52	54.9	45.1	1.063	.114
33000	13000	1.72	56.6	43.4	1.096	.174
34000	13000	1.72	58.3	41.7	1.130	.234
35000	14000	1.85	60.2	39.8	1.163	.294
36000	12000	1.59	61.8	38.2	1.196	.354
37000	17500	2.31	64.1	35.9	1.229	.414
38000	13000	1.72	65.8	34.2	1.263	.474
39000	15000	1.98	67.8	32.2	1.296	.534
40000	10000	1.32	69.1	30.9	1.329	.594
OVERFLOW	234000	30.91	100.0	.0		

TABLE NUMBER 81

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
1488	30098.802	16662.293	NON-WEIGHTED
757000	29546.014	761810.490	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
1000	3000	.40	.4	99.6	.033	-1.746
2000	21100	2.79	3.2	96.8	.066	-1.686
3000	12000	1.59	4.8	95.2	.100	-1.626
4000	9000	1.19	6.0	94.0	.133	-1.566
5000	15000	1.98	7.9	92.1	.166	-1.506
6000	11500	1.52	9.5	90.5	.199	-1.446
7000	10000	1.32	10.8	89.2	.233	-1.386
8000	10000	1.32	12.1	87.9	.266	-1.326
9000	10000	1.32	13.4	86.6	.299	-1.266
10000	7500	.99	14.4	85.6	.332	-1.206
11000	14600	1.93	16.3	83.7	.365	-1.146
12000	12000	1.59	17.9	82.1	.399	-1.086
13000	15000	1.98	19.9	80.1	.432	-1.026
14000	11500	1.52	21.4	78.6	.465	-.966
15000	15500	2.05	23.5	76.5	.498	-.906
16000	8600	1.14	24.6	75.4	.532	-.846
17000	14600	1.93	26.5	73.5	.565	-.786
18000	15000	1.98	28.5	71.5	.598	-.726
19000	10500	1.39	29.9	70.1	.631	-.666
20000	16000	2.11	32.0	68.0	.664	-.606
21000	13500	1.78	33.8	66.2	.698	-.546
22000	20000	2.64	36.4	63.6	.731	-.486
23000	18500	2.44	38.9	61.1	.764	-.426
24000	12500	1.65	40.5	59.5	.797	-.366
25000	12100	1.60	42.1	57.9	.831	-.306
26000	16000	2.11	44.3	55.7	.864	-.246
27000	14500	1.92	46.2	53.8	.897	-.186
28000	12500	1.65	47.8	52.2	.930	-.126
29000	12000	1.59	49.4	50.6	.963	-.066
30000	14000	1.85	51.3	48.7	.997	-.006
31000	16000	2.11	53.4	46.6	1.030	.054
32000	11500	1.52	54.9	45.1	1.063	.114
33000	13000	1.72	56.6	43.4	1.096	.174
34000	13000	1.72	58.3	41.7	1.130	.234
35000	14000	1.85	60.2	39.8	1.163	.294
36000	12000	1.59	61.8	38.2	1.196	.354
37000	17500	2.31	64.1	35.9	1.229	.414
38000	13000	1.72	65.8	34.2	1.263	.474
39000	15000	1.98	67.8	32.2	1.296	.534
40000	10000	1.32	69.1	30.9	1.329	.594
OVERFLOW	234000	30.91	100.0	.0		

TABLE NUMBER 82

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
1488	-3948.972	6415.291	NON-WEIGHTED
757000	-3850.649	166140.530	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
-20000	17500	2.31	2.3	97.7	5.065	-2.502
-19000	4000	.53	2.8	97.2	4.811	-2.346
-18000	4000	.53	3.4	96.6	4.558	-2.190
-17000	9000	1.19	4.6	95.4	4.305	-2.034
-16000	8600	1.14	5.7	94.3	4.052	-1.878
-15000	9100	1.20	6.9	93.1	3.798	-1.723
-14000	15100	1.99	8.9	91.1	3.545	-1.567
-13000	13000	1.72	10.6	89.4	3.292	-1.411
-12000	11000	1.45	12.1	87.9	3.039	-1.255
-11000	23000	3.04	15.1	84.9	2.786	-1.099
-10000	22100	2.92	18.0	82.0	2.532	-.943
-9000	20000	2.64	20.7	79.3	2.279	-.787
-8000	23000	3.04	23.7	76.3	2.026	-.631
-7000	26000	3.43	27.1	72.9	1.773	-.476
-6000	17500	2.31	29.4	70.6	1.519	-.320
-5000	36000	4.76	34.2	65.8	1.266	-.164
-4000	46500	6.14	40.3	59.7	1.013	-.008
-3000	62500	8.26	48.6	51.4	.760	.148
-2000	65500	8.65	57.3	42.7	.506	.304
-1000	61600	8.14	65.4	34.6	.253	.460
0	61000	8.06	73.4	26.6	-.000	.616
1000	47000	6.21	79.7	20.3	-.253	.771
2000	38500	5.09	84.7	15.3	-.506	.927
3000	35000	4.62	89.4	10.6	-.760	1.083
4000	33500	4.43	93.8	6.2	-1.013	1.239
5000	20500	2.71	96.5	3.5	-1.266	1.395
6000	8500	1.12	97.6	2.4	-1.519	1.551
7000	6500	.86	98.5	1.5	-1.773	1.707
8000	4000	.53	99.0	1.0	-2.026	1.863
9000	4000	.53	99.5	.5	-2.279	2.018
10000	1000	.13	99.7	.3	-2.532	2.174
11000	500	.07	99.7	.3	-2.786	2.330
12000	500	.07	99.8	.2	-3.039	2.486
13000	500	.07	99.9	.1	-3.292	2.642
14000	0	.00	99.9	.1	-3.545	2.798
15000	500	.07	99.9	.1	-3.798	2.954
16000	0	.00	99.9	.1	-4.052	3.110
17000	0	.00	99.9	.1	-4.305	3.265
18000	500	.07	100.0	.0	-4.558	3.421

REMAINING FREQUENCIES ARE ALL ZERO

TABLE NUMBER 83

ENTRIES IN TABLE	MEAN ARGUMENT	STANDARD DEVIATION	
1488	591.110	563.510	NON-WEIGHTED
756500	580.221	18083.221	WEIGHTED

UPPER LIMIT	OBSERVED FREQUENCY	PERCENT OF TOTAL	CUMULATIVE PERCENTAGE	CUMULATIVE REMAINDER	MULTIPLE OF MEAN	DEVIATION FROM MEAN
50	57600	7.61	7.6	92.4	.085	-.960
100	64000	8.46	16.1	83.9	.169	-.872
150	51000	6.74	22.8	77.2	.254	-.783
200	37500	4.96	27.8	72.2	.338	-.694
250	37000	4.89	32.7	67.3	.423	-.605
300	36600	4.84	37.5	62.5	.508	-.517
350	35100	4.64	42.1	57.9	.592	-.428
400	33500	4.43	46.6	53.4	.677	-.339
450	32000	4.23	50.8	49.2	.761	-.250
500	27000	3.57	54.4	45.6	.846	-.162
550	23600	3.12	57.5	42.5	.930	-.073
600	31000	4.10	61.6	38.4	1.015	.016
650	18000	2.38	64.0	36.0	1.100	.105
700	23500	3.11	67.1	32.9	1.184	.193
750	14500	1.92	69.0	31.0	1.269	.282
800	23000	3.04	72.0	28.0	1.353	.371
850	14000	1.85	73.9	26.1	1.438	.459
900	24000	3.17	77.1	22.9	1.523	.548
950	18000	2.38	79.4	20.6	1.607	.637
1000	20000	2.64	82.1	17.9	1.692	.726
1050	24000	3.17	85.2	14.8	1.776	.814
1100	13000	1.72	87.0	13.0	1.861	.903
1150	9000	1.19	88.2	11.8	1.945	.992
1200	9000	1.19	89.3	10.7	2.030	1.081
1250	6500	.86	90.2	9.8	2.115	1.169
1300	5100	.67	90.9	9.1	2.199	1.258
1350	2500	.33	91.2	8.8	2.284	1.347
1400	5000	.66	91.9	8.1	2.368	1.435
1450	8500	1.12	93.0	7.0	2.453	1.524
1500	6500	.86	93.9	6.1	2.538	1.613
1550	5500	.73	94.6	5.4	2.622	1.702
1600	3000	.40	95.0	5.0	2.707	1.790
1650	1500	.20	95.2	4.8	2.791	1.879
1700	2500	.33	95.5	4.5	2.876	1.968
1750	2500	.33	95.8	4.2	2.961	2.057
1800	2500	.33	96.2	3.8	3.045	2.145
1850	1000	.13	96.3	3.7	3.130	2.234
1900	1500	.20	96.5	3.5	3.214	2.323
1950	3500	.46	97.0	3.0	3.299	2.411
2000	3500	.46	97.4	2.6	3.383	2.500
OVERFLOW	19500	2.58	100.0	.0		

APPENDIX D

COMPUTER PROGRAM

This program is the EXEC II version of GPSS II for processing on the UNIVAC 1107 computer. EXEC II permits GPSS II HELP Blocks and subroutines to be programmed in FORTRAN thus facilitating semi-professional programming as well as better understanding of the program contained in this appendix. GPSS II Program blocks begin on page 109. FORTRAN statements of reader interest include the Data Input Statements, page 99; the ten HELP subroutines, page 100; and subroutine FLOW and UPDATE, page 105.

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**** GLOSSARY *****

ARRAYS AND VARIABLES ASSOCIATED WITH JOB CENTERS

    NCT        NO. OF CENTERS                      MIN 1    MAX 20
    KMIN       MIN NO. OF CENTERS FOR ANY JOB      MIN 1    MAX KMAX
    KMAX       MAX NO. OF CENTERS FOR ANY JOB      MIN KMIN MAX 10
    MEANS(J)   MEAN SET UP TIME FOR CENTER J
    MEANP(J)   MEAN PROCESS TIME/UNIT FOR CENTER J
    CMEAN(J)   AVE. FLOW TIME FOR CENTER J
    CVAR (J)   FLOW TIME VARIANCE FOR CENTER J
          CMEAN AND CVAR ARE UPDATED AT THE END OF EACH DAY.
          INITIAL ESTIMATES ARE USED UNTIL THE NO. OF JOBS THRU A
          CENTER IS .GE. SAMPLE
    SAMPLE     MIN NO. OF JOBS THRU A CENTER BEFORE TABLE MEAN AND
               VAR. ARE USED FOR CENTER FLOW TIMES.

ARRAYS AND VARIABLES ASSOCIATED WITH JOBS

    JOB(I,J)   ROWS ARE CENTER NO.S (ROUTE THRU SHOP FOR JOB I)
    NEXT(I)    INDEX J FOR NEXT CENTER IN JOB(I,J) FOR JOB I
```

```
    Z(I)       Z VALUE FOR JOB I. UPDATED AT END OF EACH DAY
    NDUE(I)    DUE DATE FOR JOB I
         JOBS ARE CLASSIFIED BY SIZE(NO.OF UNITS) AND BY INITIAL Z
         THE SIZE TYPE (1 TO 5) IS IN PARAMETER 4. TYPE 3 JOBS ARE
         TRACED.
         THE INITIAL Z TYPE (1 TO 5) IS IN PARAMETER 3.
    NTYPE(1)   THE NO. OF SIZE TYPES                          MAX 5
    NTYPE(2)   THE NO. OF INITIAL Z TYPES
     SIZE(K)   THE NO. OF UNITS IN A JOB OF SIZE TYPE K
    Z0(K)      THE INITIAL Z FOR A JOB  OF INIT. Z TYPE K
    ISEED      SEED NO.FOR RN GENERATOR USED TO DETERMINE ROUTE.
    JOBIN(K,J) THE NO. OF JOBS ENTERING SHOP BY TYPE
                    J=1 FOR SIZE TYPE K
                    J=2 FOR Z0 TYPE K

ARRAYS AND VARIABLES ASSOCIATED WITH PERIODIC STATUS REPORT

    DAY        NO. OF CLOCK PERIODS IN A DAY.
    NDAY       NO. OF DAYS BETWEEN REPORTS.
         THE FOLLOWING ARRAYS ARE USED TO STORE STATISTICS
         ACCUMULATED UP THRU THE PREVIOUS REPORTING DAY.
    JF(J)      TIME CENTER J WAS IN USE.
    NT(K)      NO. OF ENTRIES IN TABLE K      K=1,83
    TM(K)      SUM OF ENTRIES IN TABLE K
    TSQ(K)     SUM OF SQUARES OF ENTRIES IN TABLE K
    JIN(K,J) THE NO. OF JOBS ENTERING SHOP BY TYPE


 DIMENSION JF(20),MEANS(20),MEANP(20),TYPE(2),NTYPE(2),Z0(5),
1  SIZE(5),Z(501),NDUE(500),JIN(5,2),JOBIN( 5,2),SIZEZ0(5,2)
 DIMENSION FMEAN(5),FVAR(5)
 COMMON/EQ1/JF1( 41)
 COMMON/EQ2/JF2( 41)
 COMMON/EQ3/JF3( 41)
 COMMON/EQ4/JF4( 41)
 COMMON/EQ5/JF5( 41)
 COMMON/EQ6/JF6( 41)
 COMMON/QUE1/JQ1( 45)
 COMMON/QUE2/JQ2( 45)
 COMMON/QUE3/JQ3( 45)
 COMMON/QUE4/JQ4( 45)
 COMMON/QUE5/JQ5( 45)
 COMMON/QUE6/JQ6( 45)
 COMMON/TAB1/JTLOCS(100)
 COMMON/TAB2/JTMODE(100)
 COMMON/TAB3/JLOWRS(100)
 COMMON/TAB4/JTINCS(100)
 COMMON/TAB5/JTLAST(100)
 COMMON/TAB6/JTLNUM(100)
 COMMON/TAB7/TLARG (100)
 COMMON/TAB8/TSQR  (100)
 COMMON/TAB9/TWARG (100)
 COMMON/TAB10/TWSQR(100)
 COMMON/EKSES/JEKS(50)
 COMMON/CENTER/I,JOB(500,10),NEXT(500),CMEAN(20),CVAR(20),KMAX
 COMMON/REPORT/K,NN(6),T(6),D(6),NT(83),TM(83),TSQ(83)
 EQUIVALENCE (SIZEZ0(1,1),SIZE(1)),(SIZEZ0(1,2),Z0(1))
 DATA NTRAN/500/,Z(501)/150./,DAY/1000./
```

```
DATA TYPE(1)/6HSZ=    /,TYPE(2)/6HZ0=    /

DATA SWITCH/0./

THE FOLLOWING DATA IS VARIABLE INPUT DATA
THE DATA CARDS MAY BE CHANGED

DATA ISEED /1354171/

DATA NCT/10/,KMAX/10/,KMIN/ 1/,SAMPLE/ 5./

DATA NDAY/5/

DATA NTYPE(1)/2/,NTYPE(2)/1/

DATA (SIZE(J),J=1,5)/500.,100.,100.,0.,0./

DATA (Z0(J),J=1,3)/0.,0.,0./

DATA(MEANS(J),J=1,10)/500,500,500,500,500,500,500,500,500,500/

DATA(MEANP(J),J=1,10)/1,1,1,1,1,1,1,1,1,1/

DATA (CMEAN(J),J=1,10)/500,500,500,500,500,500,500,500,500,500/
```

```
      DATA (CVAR(J),J=1,10)/833,833,833,833,833,833,833,833,833,833/


      DATA (FMEAN(J),J=1,5)/500,100,100,0,0/


      DATA (FVAR(J),J=1,5)/833,33,33,0,0/
C


 500  FORMAT(I4,F6.2,I6,I5,2F9.2,1X2F9.2,I5,F7.2,I5,I7,F7.2,1X,10I3/
     1 90X,10I3)
 501  FORMAT(4X,F6.2,I6,I5,2F9.2,1X,2F9.2/)
 502  FORMAT(1X,A3,F7.2,I5,I5,2F9.2,1X,2F9.2)
 503  FORMAT(10X,I6,I5,2F9.2,1X,2F9.2/)
 504  FORMAT(10H ALL TYPES,I6,I5,2F9.2,1X,2F9.2,4X2F9.2)
 505  FORMAT(10X,I6,I5,2F9.2,1X,2F9.2,4X,2F9.2/)
 506  FORMAT(  24H1******  REPORT FOR LAST  ,I3,6H DAYS.,9X4HDATE,I4//
     1 21H  CTR UTIL  JOBS JOBS ,4X4HFLOW5X4HFLOW6X4HWAIT5X4HWAIT3X2HIN
     1 5X1HZ
     2 4X3HCUR2X3HDUE6X1HZ4X7HCENTERS/2X3HNO.8X2HIN3X3HOUT4X,4HMEAN4X
     3 6HST.DEV5X4HMEAN4X6HST.DEV2X3HQUE2X4HNEXT3X3HJOB2X4HDATE10X
     4 4HLEFT )
 507  FORMAT(2X3HJOB7X9HJOBS JOBS4X4HFLOW5X4HFLOW6X3HD-A6X3HD-A10X4HEXIT
     1 5X4HEXIT/2X4HTYPE7X2HIN3X3HOUT4X4HMEAN4X6HST.DEV5X4HMEAN4X
     2 6HST.DEV8X4HMEAN4X6HST.DEV)
 701  FORMAT(/11H *ENTER JOBI4,17H INTO SHOP  CLOCKI7,2X3HD-CI6,2X2HZ=
     1F6.2,2X4HSIZE,F6.0,1X3HDUEI7,2X5HROUTE,10I3/90X,10I3)
 702  FORMAT(/  11H *SEND  JOBI4, 7H TO QUEI3,2X5HCLOCKI7,2X3HD-CI6,2X
     12HZ=F6.2,3X6HT MEANF8.2,2X6HST.DEVF8.2,3X6HQ MEANF8.2,2X6HST.DEV
     2F8.2)
 703  FORMAT(/  11H *EXIT  JOBI4,17H FROM SHOP  CLOCKI7,2X3HD-AI6,2X2HZ=
     1F6.2,2X4HSIZE,F6.0,1X3HDUEI7)
 706  FORMAT(/  11H *CHK Z JOBI4, 7H IN QUEI3,2X5HCLOCKI7,2X3HD-CI6,2X
     12HZ=F6.2,2X9HZ IN CTR=F6.2,2X7HNEXT Z=F7.2)
 708  FORMAT(/  11H *SETUP JOBI4, 7H IN CTRI3,2X5HCLOCKI7,2X3HD-CI6,2X
     12HZ=F6.2,3X 6HS MEANI5,5X6HSPREADI5)
 709  FORMAT(/  11H *PROC. JOBI4, 7H IN CTRI3,2X5HCLOCKI7,2X3HD-CI6,2X
     12HZ=F6.2,3X 6HP MEANI5,5X6HSPREADI5)
 1003 FORMAT(/30H RESET TABLES TO ZERO AT CLOCK ,I7/)
C
C
C     THERE ARE TEN ENTRY POINTS AT STATEMENTS 1 THRU 10
C
      GO TO (1,2,3,4,5,6,7,8,9,10),JX
C
C
C     HELP1 ASSIGNS JOB NO., ROUTE, AND DUE DATE
C
 1    I=JF1(41)
C     STORE TRANS. NO IN SAVEX 41
      JEKS(41)=I
C     THE NO. OF CENTERS FOR THIS JOB =KMAX-KCT+1, UNIFORMLY DISTRIBUTED
C     FROM KMIN TO KMAX.
      CALL RANDM(NEWSED,RN)
```

```
      KCT=RN*SPREAD+1.
      NEXT(I)=KCT
C     ASSIGN CENTERS UNIFORMLY FROM 1 TO NCT.
      DO 12 J=KCT,KMAX
      CALL RANDM(NEWSED,RN)
 12   JOB(I,J)=XNCT*RN+1.
 13   Z(I)=Z0(JZ)
C     CALCULATE DUE DATE FOR JOB I.
      XC=FLOAT(KMAX-KCT+1)
      XN=FLOAT(JTLNUM(JMOD+60))
      IF(XN.LT.SAMPLE) GO TO 14
      SMEAN=TLARG(JMOD+60)/XN
      SVAR=TSQR(JMOD+60)/XN-SMEAN*SMEAN
      FMEAN(JMOD)=2.*SMEAN/(XNCT+1.)
      FVAR(JMOD)=2.*SVAR/(XNCT+1.)
 14   NDUE(I)= Z(I)*SQRT(ABS(FVAR(JMOD)*XC))+FMEAN(JMOD)*XC+FLOAT(JMEAN)
      JOBIN(JMOD,1)=JOBIN(JMOD,1)+1
      JOBIN(JZ,2)=JOBIN(JZ,2)+1
      IF(JMOD.NE.3) RETURN
C
C     WRITE TRACE LINE FOR JOBS OF SIZE TYPE 3.
      NDC=NDUE(I)-JMEAN
      WRITE(6,701)I,JMEAN,NDC,Z(I), SIZE(JMOD),NDUE(I),(JOB(I,J),
     1 J=KCT,KMAX)
      RETURN
C
C
C     HELP2 OBTAINS THE NEXT CENTER FOR THIS JOB.
C     IF JOB IS FINISHED NBA IS BLOCK 28, OTHERWISE NBA= BLOCK 15
C
  2   KCT=NEXT(JZ)
C     STORE NBA IN SAVEX 42. STORE NEXT CENTER NO. IN SAVEX 43
      JEKS(42)=28
      IF(KCT.GT.KMAX) RETURN
      JEKS(43)=JOB(JZ,KCT)
      JEKS(42)=15
      IF(JMOD.NE.3) RETURN
C
C     WRITE TRACE LINE FOR JOBS OF SIZE TYPE 3.
      J=JEKS(43)
      NDC=NDUE(JZ)-JMEAN
      DEV=SQRT(ABS(CVAR(J)))
      IF(JTLNUM(J+40).EQ.0) GO TO 21
      SMEAN=TLARG(J+40)/FLOAT(JTLNUM(J+40))
      SVAR=SQRT(ABS(TSQR(J+40)/FLOAT(JTLNUM(J+40))-SMEAN*SMEAN))
      WRITE(6,702) JZ,J,JMEAN,NDC,Z(JZ),CMEAN(J),DEV,SMEAN,SVAR
      RETURN
 21   WRITE(6,702) JZ,J,JMEAN,NDC,Z(JZ),CMEAN(J),DEV
      RETURN
C
C
C     HELP3 OBTAINS D-A (DUE DATE - CLOCK TIME). STORE IN SAVEX 44
C
  3   JEKS(44)=NDUE(JZ)-JMEAN
      IF(JMOD.NE.3) RETURN
C
C     WRITE TRACE LINE FOR JOBS OF SIZE TYPE 3.
      NDC=NDUE(JZ)-JMEAN
```

```
      WRITE(6,703) JZ,JMEAN,NDC,Z(JZ), SIZE(JMOD),NDUE(JZ)
      RETURN
C
C
C     HELP4 UPDATES THE MEAN AND VAR. OF THE FLOW TIME FOR EACH CENTER
C     AND UPDATES THE VALUE OF Z FOR EACH JOB IN SHOP.
C     HELP4 IS ENTERED AT THE END OF EACH DAY.
C
 4    DO 41 J=1,NCT
      XN=FLOAT(JTLNUM(J))
C     USE INITIAL ESTIMATES UNTIL THE NO.OF JOBS COMPLETED IN THIS
C     CENTER = SAMPLE.
      IF(XN.LT.SAMPLE)GO TO 41
C     FLOW TIME  FOR CENTER J IS  TABULATED IN TABLE J
C     JTLNUM, TLARG, TSQR = NO.OF ENTRIES, SUM OF ENTRIES, SUM OF
C     SQUARES OF ENTRIES IN TABLE.
      CMEAN(J)=TLARG(J)/XN
      CVAR(J)=TSQR(J)/XN-CMEAN(J)*CMEAN(J)
 41   CONTINUE
C     RE-CALCULATE Z VALUE.
      DO 43 I=1,NTRAN
      IF(NEXT(I).GT.KMAX) GO TO 43
      CALL FLOW(I,SMEAN,SVAR)
 42   Z(I)=(FLOAT(NDUE(I)-JZ)-SMEAN)/SVAR
 43   CONTINUE
      NDATE=JZ/IFIX(DAY)
      C1=JZ
      JEKS(46)=5
      IDAY=IDAY+1
C     TEST FOR END OF REPORTING PERIOD.
      IF(IDAY.GE.NDAY) JEKS(46)=80
      RETURN
C
C
C     HELP5 IS ENTERED ONCE FOR INITIALIZATION.
C
 5    CALL RSTART(ISEED)
      XNCT=FLOAT(NCT)
      JEKS(50)=NCT
      XC1=DAY*FLOAT(NDAY)
      SPREAD=KMAX-KMIN+1
      DO 50 I=1,NTRAN
 50   NEXT(I)=KMAX+1
      DO 51 I=1,83
      NT(I)=0
      TM(I)=0.
 51   TSQ(I)=0.
      DO 52 I=1,NCT
 52   JF(I)=0
      DO 53 I=1,5
      DO 53 J=1,2
      JOBIN(I,J)=0
 53   JIN(I,J)=0
      IDAY=0
      RETURN
C
C
C     HELP6 ASSIGNS AN INTEGER PRIORITY ACCORDING TO THE JOBS Z VALUE
```

```
C
    6 JEKS(45)=15000-IFIX(100.*Z(JZ))
      IF(JMOD.NE.3) RETURN
C
C     WRITE TRACE LINE FOR JOBS OF SIZE TYPE 3.
      NDC=NDUE(JZ)-JMEAN
      KCT=NEXT(JZ)
      J=JOB(JZ,KCT)
      JC=JF1(J)
C     IF CENTER IS IDLE, SET DUMMY JOB NO.=501, Z(501)=150.
      IF(JC.LE.0) JC=501
      ZN= .01*FLOAT(15000-JEKS(J))
      WRITE(6,706) JZ,J,JMEAN,NDC,Z(JZ),Z(JC),ZN
      RETURN
C
C
C     HELP7 OUTPUTS THE STATUS REPORT EVERY NDAY DAYS.
C     HELP7 IS ENTERED ONCE FOR EACH CENTER VIA TRANSACTION CONTROL LOOP
C
C     WRITE HEADING FOR STATUS REPORT.
 7    IF(IDAY.NE.0) WRITE(6,506) NDAY,NDATE
      IDAY=0
      DO 71 K=1,2
C     I=TABLE NO.  FLOW TIME FOR CENTER J IS IN TABLE J
C                  QUE  TIME FOR CENTER J IS IN TABLE 40+J
      I=40*(K-1)+JZ
      CALL UPDATE(K,I)
C     SUBROUTINE UPDATE CALCULATES THE MEAN AND STD.DEV OF  THE VARIABLE
C     IN TABLE NO. I FOR THE REPORTING PERIOD AND FOR THE TOTAL TIME TO
C     DATE
 71   CONTINUE
      NQ=JMEAN+JMOD
      UTIL=FLOAT(JF2(JZ+20)-JF(JZ))/XC1
      JF(JZ)=JF2(JZ+20)
      I=JF1(JZ)
      QZ= .01*FLOAT(15000-JEKS(JZ))
      IF(I.EQ.0)GO TO 73
      KCT=NEXT(I)
      WRITE(6,500)JZ,UTIL,NN(2),NN(1),(T(K),D(K),K=1,2),NQ,QZ,I,NDUE(I),
     1Z(I),(JOB(I,J),J=KCT,KMAX)
      GO TO 74
 73   WRITE(6,500)JZ,UTIL,NN(2),NN(1),(T(K),D(K),K=1,2),NQ
 74   UTIL=FLOAT(JF2(JZ+20))/C1
      WRITE(6,501) UTIL,NN(5),NN(4),(T(K),D(K),K=4,5)
      JEKS(46)=80
C     TEST FOR LAST CENTER.  IF FINISHED NBA=BLOCK 5, OTHERWISE NBA=80
      IF(JZ.LT.NCT) RETURN
C
      JEKS(46)=5
      WRITE(6,507)
      DO 76 K1=1,2
      K3=NTYPE(K1)
      DO 76 K2=1,K3
      DO 75 K=1,2
      I=60+10*(K1-1)+5*(K-1)+K2
C     I=TABLE NO.  FLOW TIME FOR SIZE TYPE J IS IN TABLE 60+J
C                  D-A  TIME FOR SIZE TYPE J IS IN TABLE 65+J
C                  FLOW TIME FOR Z0   TYPE J IS IN TABLE 70+J
```

```
C                    D-A  TIME FOR Z0   TYPE J IS IN TABLE 75+J
      CALL UPDATE(K,I)
 75   CONTINUE
      IN=JOBIN(K2,K1)-JIN(K2,K1)
      JIN(K2,K1)=JOBIN(K2,K1)
      WRITE(6,502) TYPE(K1),SIZEZ0(K2,K1),IN,NN(1),(T(K),D(K),K=1,2)
 76   WRITE(6,503) JOBIN(K2,K1),NN(4),(T(K),D(K),K=4,5)
      IN=JF6(41)-NJF6
      NJF6=JF6(41)
      DO 77 K=1,3
      I=80+K
C     I=TABLE NO.  FLOW TIME FOR ALL JOBS    IS IN TABLE 81
C                  D-A  TIME FOR ALL JOBS    IS IN TABLE 82
C                  INTER EXIT TIME FOR ALL JOBS IN TABLE 83
      CALL UPDATE(K,I)
 77   CONTINUE
      WRITE(6,504) IN,NN(1),(T(K),D(K),K=1,3)
      WRITE(6,505) NJF6   ,NN(4),(T(K),D(K),K=4,6)
      RETURN
C
C
C     HELP8 PUTS MEAN SETUP TIME FOR CENTER(JMEAN) IN SAVEX 42, AND
C           PUTS SPREAD IN SAVEX 43
C
 8    JEKS(42)=MEANS(JMEAN)
      JEKS(43)=JEKS(42)/10
      IF(JMOD.NE.3) RETURN
C
C     WRITE TRACE LINE FOR JOBS OF SIZE TYPE 3.
      NDC=NDUE(JZ)-JF3(JMEAN)
      WRITE(6,708) JZ,JMEAN,JF3(JMEAN),NDC,Z(JZ),JEKS(42),JEKS(43)
      RETURN
C
C
C     HELP9 PUTS MEAN PROCESS TIME IN SAVEX 42 AND SPREAD IN SAVEX 43
C
 9    JEKS(42)=MEANP(JMEAN)*IFIX(SIZE(JMOD))
      JEKS(43)=JEKS(42)/10
      NEXT(JZ)=NEXT(JZ)+1
      IF(JMOD.NE.3) RETURN
C
C     WRITE TRACE LINE FOR JOBS OF SIZE TYPE 3.
      NDC=NDUE(JZ)-JEKS(49)
      WRITE(6,709) JZ,JMEAN,JEKS(49),NDC,Z(JZ),JEKS(42),JEKS(43)
      RETURN
C
C
C     HELP10 RESETS TABLES TO ZERO
C
 10   DO 1001 I=1,83
      NT(I)=0
      TM(I)=0.
      TSQ(I)=0.
      JTLNUM(I)=0
      TWARG(I)=0.
      TWSQR(I)=0.
      TLARG(I)=0.
 1001 TSQR(I)=0.
```

```
WRITE(6,1003) JZ
RETURN
END

SUBROUTINE FLOW CALCULATES MEAN AND ST.DEV. OF FLOW TIME THRU
CENTERS REMAINING FOR JOB I.

SUBROUTINE FLOW(I,SMEAN,SVAR)

COMMON/CENTER/I,JOB(500,10),NEXT(500),CMEAN(20),CVAR(20),KMAX
N1=NEXT(I)
SMEAN=0.
SVAR=0.
DO 101 K=N1,KMAX
JCTR=JOB(I,K)
SMEAN=SMEAN+CMEAN(JCTR)
SVAR=SVAR+CVAR(JCTR)
SVAR=SQRT(ABS(SVAR))
RETURN
END
NN(K)=JTLNUM(I)-NT(I)
T(K)=TLARG(I)-TM(I)
D(K)=TSQR(I)-TSQ(I)
IF(NN(K).EQ.0) GO TO 201
XNT=NN(K)
NT(I)=JTLNUM(I)
TM(I)=TLARG(I)
TSQ(I)=TSQR(I)
T(K)=T(K)/XNT
D(K)=SQRT(ABS(D(K)/XNT-T(K)*T(K)))
NN(K+3)=JTLNUM(I)
T(K+3)=0.
D(K+3)=0.
IF(JTLNUM(I).EQ.0) RETURN
XNT=JTLNUM(I)
T(K+3)=TLARG(I)/XNT
D(K+3)=SQRT(ABS(TSQR(I)/XNT-T(K+3)*T(K+3)))
RETURN
END

SUBROUTINE UPDATE CALCULATES THE MEAN AND STD.DEV OF  THE VARIABLE
IN TABLE NO. I FOR THE REPORTING PERIOD AND FOR THE TOTAL TIME TO
DATE

SUBROUTINE UPDATE(K,I)

I=TABLE NO.
K=INDEX FOR TEMP STORAGE ARRAYS NN(K),T(K),D(K)
  WHERE NN,T,D ARE THE NO. OF ENTRIES,MEAN, AND DEVIATION
  K=1 FOR FLOW TIME OVER REPORT PERIOD
  K=2 FOR D-A  TIME OVER REPORT PERIOD
  K=3 FOR EXIT TIME OVER REPORT PERIOD
  K=4 FOR FLOW TIME OVER TOTAL  PERIOD
  K=5 FOR D-A  TIME OVER TOTAL  PERIOD
  K=6 FOR EXIT TIME OVER TOTAL  PERIOD
NT(I)=TM(I),TSQ(I) ARE THE NO. OF ENTRIES, SUM OF ENTRIES, AND THE
  SUM OF SQUARES OF ENTRIES IN TABLE NO I AT THE END OF THE
  PREVIOUS REPORTING PERIOD.
COMMON/REPORT/K,NN(6),T(6),D(6),NT(83),TM(83),TSQ(83)
COMMON/TAB6/JTLNUM(100)
COMMON/TAB7/TLARG(100)
COMMON/TAB8/TSQR(100)
```

```
C                      GPSS II   VERSION C
C      THE FIRST FILE CONTAINS THE GPSS II, VERSION C, OPERATING
C      SYSTEM IN RELOCATABLE CODE FOR 1107 AND 1108 65K SYSTEMS.
C      THE SECOND FILE CONTAINS THE SYMBOLIC ELEMENT GPSS2, AS
C      PARTIALLY REPRODUCED HERE, TOGETHER WITH THE SYMBOLIC ELEMENT
C      NTAB$ FOR THIS SYSTEM.  USE CUR TO LIST OR PUNCH EITHER ELEMENT.
C      THE GENERAL PURPOSE SYSTEMS SIMULATOR II USERS MANUAL IS
C      U4470.17, AND THE GPSS II CODING FORMS ARE UD1-1007, BOTH
C      OBTAINABLE FROM UNIVAC DPC TECHNICAL SUPPORT DEPT, SPERRY
C      RAND BUILDING, N.Y. 19, N.Y. SSFR (BUG) REPORTS SHOULD BE
C      MAILED TO MARVIN HUROWITZ, UNIVAC SYSTEMS PROGRAMMING,
C      SPERRY RAND BUILDING, N.Y. 19, N.Y.
C*****THE FOLLOWING FEATURES ARE NOT AVAILABLE IN VERSION C *****
C          STANDARD FEATURES
C               1. BLOCK MACRO GENERATOR (WILL NOT BE IMPLEMENTED)
C          NEW FEATURES- SEE PREFACE IN MANUAL FOR LIST
C               1. ABILITY TO INCREASE NUMBER OF PARAMETERS ABOVE
C                  EIGHT (WHEN IMPLEMENTED, MAXIMUM WILL BE THIRTY)
C*****THE FOLLOWING FEATURES APPEAR IN VERSION C, BUT ARE NOT
C      DESCRIBED IN THE USERS MANUAL *****
C          1. SETTING JUMP SWITCH NUMBER 1 TO ON WILL CAUSE AN
C             IMMEDIATE GPSS ERROR TERMINATION.  OPERATORS SHOULD
C             ALWAYS DO SO WHEN ABOUT TO ABORT FOR ANY REASON
C          2. EACH TIME AN OVERLAY OCCURS A WARNING TO THIS EFFECT
C             IS PRINTED, BUT EXECUTION IS NOT INHIBITED
C          3. THE MANUAL LIMITATION OF ONE LEVEL OF FN AND V IS
C             EXTENDED TO FOUR LEVELS OF FN AND V
C          4. IF JOBTAPE AND WRITE ARE USED THE NUMBER OF TRANS-
C             ACTIONS ON TAPE MUST BE AT LEAST ONE GREATER THAN
C             THE NUMBER REQUIRED FOR THE EXECUTION OF THE JOB
C          5. EXECUTION USING XQT GPSS2 RESULTS IN AN ALL-CORE
C             SYSTEM WITH STANDARD LIMITS AS PER THE MANUAL
C          6. EXECUTION USING XQT MAPGPS RESULTS IN A SEGMENTING
C             OF THE SYSTEM PERMITTING A MODEL APPROXIMATELY 2/3
C             LARGER THAN THE STANDARD LIMITS. (THE PERMISSIBLE
C             SIZE OF THE MODEL WILL BE INCREASED IN SUBSEQUENT
C             VERSIONS.)  LIMITS MAY BE CHANGED BY CHANGING THE
C             DIMENSIONS OF THE APPROPRIATE TABLES (ARRAYS) OF THE
C             SYMBOLIC ELEMENT GPSS2 AS DESCRIBED IN THE MANUAL.
C             GPSS2 IS DENOTED IN THE MANUAL AS THE CONTROL PROGRAM.
C      THE BALANCE OF THIS ELEMENT CONSISTS OF TABLES AND CODING.
C      BLOCK          TABLES  NEXT  5 CARDS  DIMENSION IDENTICALLY
       COMMON/NODE1/JN1(100)
       COMMON/NODE2/JN2(100)
       COMMON/NODE3/JN3(100)
       COMMON/NODE4/JN4(100)
       COMMON/NODE5/JN5(100)
C      FACILITY       TABLES  NEXT  6 CARDS  DIMENSION IDENTICALLY
       COMMON/EQ1/JF1(41)
       COMMON/EQ2/JF2(41)
       COMMON/EQ3/JF3(41)
       COMMON/EQ4/JF4(41)
       COMMON/EQ5/JF5(41)
       COMMON/EQ6/JF6(41)
C      STORAGE        TABLES  NEXT  7 CARDS  DIMENSION IDENTICALLY
       COMMON/STOR1/JS1(1)
       COMMON/STOR2/JS2(1)
       COMMON/STOR3/JS3(1)
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```
      COMMON/STOR4/JS4(1)
      COMMON/STOR5/JS5(1)
      COMMON/STOR6/JS6(1)
      COMMON/STOR7/JS7(1)
C     QUEUE             TABLES  NEXT  6 CARDS  DIMENSION IDENTICALLY
      COMMON/QUE1/JQ1( 45)
      COMMON/QUE2/JQ2( 45)
      COMMON/QUE3/JQ3( 45)
      COMMON/QUE4/JQ4( 45)
      COMMON/QUE5/JQ5( 45)
      COMMON/QUE6/JQ6( 45)
C     LOGIC SWITCH TABLE              1 CARD
      COMMON/LOGIX/JL1(25)
C     SAVEX TABLE                     1 CARD
      COMMON/EKSES/JEKS(50)
C     FUNCTION          TABLES  NEXT  4 CARDS  DIMENSION IDENTICALLY
      COMMON/FN1/JYLOCS(5)
      COMMON/FN2/JXLOCS(5)
      COMMON/FN3/JSLOCS(5)
      COMMON/FN4/JFNPAN(5)
C     TABLE AND QTABLE  TABLES  NEXT 10 CARDS  DIMENSION IDENTICALLY
      COMMON/TAB1/JTLOCS(100)
      COMMON/TAB2/JTMODE(100)
      COMMON/TAB3/JLOWRS(100)
      COMMON/TAB4/JTINCS(100)
      COMMON/TAB5/JTLAST(100)
      COMMON/TAB6/JTLNUM(100)
      COMMON/TAB7/TLARG (100)
      COMMON/TAB8/TSQR  (100)
      COMMON/TAB9/TWARG (100)
      COMMON/TAB10/TWSQR(100)
C     VARIABLE STATEMENT TABLE        1 CARD
      COMMON/VARS/JVLOCS(10)
C     COMMON CORE AREA                1 CARD
      COMMON/WORDS/JWORDS(4500)
C     TRANSACTION       TABLES  NEXT  9 CARDS  DIMENSION IDENTICALLY
      COMMON/TRAN1/JNDT(500)
      COMMON/TRAN2/JCHAIN(500)
      COMMON/TRAN3/JMOVE(500)
      COMMON/TRAN4/JNNWD(500)
      COMMON/TRAN5/JC1(500)
      COMMON/TRAN6/JC2(500)
      COMMON/TRAN7/JC3(500)
      COMMON/TRAN8/JC4(500)
      COMMON/TRAN9/JC5(500)
C     DO NOT REDIMENSION ANY OF THE FOLLOWING CARDS
      COMMON/TRAN10/JC6(1)
      COMMON/TRAN12/JC7(1)
      COMMON/TRAN14/JC8(1)
      COMMON/TRAN16/JC9(1)
      COMMON/TRAN18/JC10(1)
      COMMON/TRAN20/JC11(1)
      COMMON/TRAN22/JC12(1)
      COMMON/TRAN24/JC13(1)
      COMMON/TRAN26/JC14(1)
      COMMON/TRAN28/JC15(1)
      COMMON/TRAN30/JC16(1)
      COMMON K(100)
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      COMMON LPRI(8)
      COMMON LPRIOR(8),ICHAR(70),KTYPE(41),KGATE(12),KCONTR(7),KSV(17),
     1 KCOMP(6),KSELEC(7),LX(6)
      DIMENSION FWORDS(1)
      EQUIVALENCE(JWORDS(1),FWORDS(1))
      EQUIVALENCE(K(1),KASYM1),(K(2),KASYM2),(K(3),KNODES),(K(4),KEQS),
     1 (K(5),KSTORS),(K(6),KQUES),(K(7),KVARS),(K(8),KLOGIX),
     2 (K(9),KEKSES),(K(10),KFNS),(K(11),KTABS),(K(12),KWORDS),
     3 (K(13),KTRANS),(K(14),KRAND),(K(15),KASMBL),(K(16),KIT),
     4 (K(17),KOT)
      EQUIVALENCE(K(78),KPARAM),(K(71),INDFLO),(K(72),INDEND),
     1 (K(55),IFATAL)
          KPARAM = 8
      KIT = 5
      KOT = 6
      KRAND = 1220703125
      KNODES = MDIFF(JN2(1),JN1(1))
      KEQS   = MDIFF(JF2(1),JF1(1))
      KSTORS = MDIFF(JS2(1),JS1(1))
      KQUES  = MDIFF(JQ2(1),JQ1(1))
          KVARS = MDIFF(JWORDS(1),JVLOCS(1))
          KLOGIX = MDIFF(JEKS(1),JL1(1))
          KEKSES = MDIFF(JYLOCS(1),JEKS(1))
      KFNS   = MDIFF(JXLOCS(1),JYLOCS(1))
      KTABS  = MDIFF(JTMODE(1),JTLOCS(1))
          KWORDS = MDIFF(JNDT(1),JWORDS(1))
      KTRANS = MDIFF(JCHAIN(1),JNDT(1))
          CALL BLOCKD
   10     CALL INPROC($20,$30)
   20 IF (INDFLO .NE. 0) CALL FLOW
      IF (IFATAL .NE. 0) GO TO 10
      IF (INDEND .NE. 0) GO TO 10
          CALL EXECUT
          CALL PUTOUT
          GO TO 10
   30     CALL ASSEMB
          GO TO 10
      END
```

```
LOC  NAME        X      Y      Z     SEL   NBA   NBB   MEAN  MOD   REMARKS

     JOB         116013570615JOB SHOP, PROB 66-354,SESCD(DUNLAP)
*
*
* GENERATE ONE TRANS. AT TIME 0 FOR INITIALIZATION
*
 1   GENERATE           1                2
 2   HELP        K5            K1        5           K1    K1
 5   TERMINATE
*
*    THE X FIELD OF GENERATE BLOCK 96 IS THE CLOCK TIME AT
*    WHICH TABLES ARE RESET TO ZERO.
*
 96  GENERATE    20001 1                 97
 97  HELP        K10           C1        5           K1    K1
*
*
*
*
*    CONTROL LOOP FOR QUEUE DISCIPLINE
*    THE Y FIELD OF BLOCK 60 = NO. OF CENTERS.  (NCT.
*    GENERATE ONE CONTROL TRANS. FOR EACH CENTER
*
 60  GENERATE    1      10     1         61
 61  SAVEX       48+    K1               67                      PUT CTR NO.
 67  ASSIGN      2      X48              62                      IN P2
 62  GATE        LS*2                    63
 63  BUFFER                              64                      WAIT FOR QUES
*    RESET X(J) TO ZERO                                          TO RE-CYCLE
 64  SAVEX       *2     K0               65
*    RESET SWITCH J AND SWITCH 22
 65  LOGIC       R*2                     66
 66  LOGIC       R22                     62
*
*
* GENERATE ONE CONTROL TRANS. AT THE END OF EACH DAY TO UPDATE THE Z
* VALUE OF EVERY JOB IN THE SHOP AND CHECK EVERY Q FOR SMALLEST Z
*
 3   ORIGINATE   1000                    4           1000        1000CLOCK=1 DA
 4   BUFFER                              70                      WAIT DAYS ENDD
*    HELP4 UPDATES THE MEAN AND VAR. OF THE FLOW TIME FOR EACH CENTER
*    AND UPDATES THE VALUE OF Z FOR EACH JOB IN SHOP.
 70  HELP        K4            C1        75          K1    K1
 75  ASSIGN      2      X50              76                      X50=NO OF CTR
*
* LOOP TO OPEN GATE TO RE-CYCLE EACH Q.
*
 76  LOGIC       S*2                     77                      SET SWITCH J
 77  LOOP        2                       76    78                J=1,NCT
 78  LOGIC       S22                     79
 79  BUFFER                              83                      WAIT RECYCLE Q
*
* LOOP THRU BLOCKS 80-83, ONCE FOR EACH CTR. TO OUTPUT REPORT LINE FOR
* THAT CENTER.
*
```

```
 80    ASSIGN      3+    K1                   81                        P3= CTR NO.
 81    ASSIGN      4     V1                   82                        P4= CTR+20
*      HELP7 OUTPUTS THE STATUS REPORT EVERY NDAY DAYS.
*      HELP7 IS ENTERED ONCE FOR EACH CENTER VIA TRANSACTION CONTROL LOOP
 82    HELP        K7          P3             83          Q*3    Q*4
* SET NBA=80 IF THIS IS THE END OF A REPORTING PERIOD, OTHERWISE NBA=5
 83    ASSIGN      5     X46                  *5                        X46= NBA
*
*
*
*
*
*
*      GENERATE JOBS TO LOAD QUEUES
 95    GENERATE    5     20    1              7
*
*
* ORIGINATE JOBS FOR SHOP. PARAMETERS ARE USED AS FOLLOWS
*  P1= JOB NO.
*  P2= NEXT CENTER NO.
*  P3= Z0 TYPE (INTEGER 1 TO 5)
*  P4= SIZE TYPE (INTEGER 1 TO 5)
*  P5= PRIORITY WHEN IN Q. MEAN TIME WHEN IN CENTER
*  P6= NEXT CTR NO.+ 20 WHEN IN Q.  SPREAD FOR SERVICE TIME WHEN IN CTR.
*  P7= FOR INDIRECT SPECIFICATION OF TABLE NO.
*  P8= MARK TIME
*
 6     ORIGINATE   600         1              7           600    FN4
 7     ASSIGN      4     FN2                  8                         SIZE TYPE
 8     ASSIGN      3     FN3                  9                         INITIAL Z  TYP
 9     SEIZE       41                         10                        DUMMY FACILITY
*      HELP1 OBTAINS JOB NO. AND GENERATES ROUTE AND DUE DATE
 10    HELP        K1          P3             11          C1     P4
 11    RELEASE     41                         12
 12    ASSIGN      1     X41                  13                        P1= JOB NO.
*
*      HELP2 PUTS NBA IN X42 AND NEXT CTR IN X43
*            NBA= BLOCK 28 IF JOB IS FINISHED, OTHERWISE NBA= BLOCK 15
 13    HELP        K2          P1             14          C1     P4
 14    ASSIGN      2     X42                  *2                        P2= NBA
 15    ASSIGN      2     X43                  16                        P2= NEXT CTR.
 16    ASSIGN      6     V8                   46                        P6=CTR NO+20
 46    MARK        8                          47                        P8=MARK TIME
*
*      BLOCKS 47 THRU 56 ESTABLISH QUEUE DISCIPLINE FOR EACH CENTER J
*         IN THE SET OF JOBS WAITING FOR CENTER J
*         THE JOB WITH THE HIGHEST PRIORITY (LOWEST Z)
*         IS SENT TO QUEUE J, THE REST ARE SENT TO QUEUE J+20
*         WHEN A JOB LEAVES CTR J, THE JOB IN QUEUE J ENTERS THE CENTER
*         AND QUEUE J+20 IS RE-CYCLED (SEARCHED FOR HIGHEST P)
*         ALL QUEUES ARE RE-CYCLED AT THE END OF EACH DAY WHEN THE Z
*         VALUES ARE UPDATED.
*
*      HELP6 PUTS PRIORITY IN X45. WHERE P= 15000 - 100*Z(I)
 47    HELP        K6          P1             48          C1     P4     GET PRIORITY
 48    ASSIGN      5     X45                  49                        P5=PRIORITY
 49    QUEUE       41                         50                        DUMMY QUE
 50    GATE        LR*2              BOTH     51    52                  NORMALLY RESET
```

```
 51    COMPARE      P5     LE    X*2            55
*      STORE THE HIGHEST PRIORITY TO DATE IN X(J)
 52    SAVEX        *2     P5                   53                          QUE J HAS JOB
 53    QUEUE        *2                  ALL     71     73                   OF HIGHEST PRI
 71    COMPARE      P5     L     X*2            55
 72    GATE         LS22                        47                          SW 22 DUMPS QJ
 55    QUEUE        *6                          56                          Q J+20 HAS RES
 56    GATE         LS*2                        47                          RECYCLE WHEN
*                                                                           CTR J RELEASED
*                                                                           AND AT END DAY
*      ENTER CENTER J
*
 73    SEIZE        *2                          19                          SEIZE CTR J
 19    ASSIGN       7      V3                   20                          P7=CTR +40
 20    ASSIGN       5      FN1                  44                          P5=SIZE
 44    TABULATE     *7     P5                   39                          TAB Q TIME
*      HELP8 PUTS MEAN SETUP TIME IN X42 AND SPREAD IN X43
 39    HELP         K8           P1             21            P2     P4
 21    ASSIGN       5      X42                  22                          SETUP MEAN
 22    ASSIGN       6      X43                  37            *5     *6     SETUP SPREAD
*      FINSH SET UP
 37    ASSIGN       7-     K20          BOTH    42     40                     P7  =CTR+20
 42    COMPARE      V4     G     K0             38                          CHECK IDLE TIM
 38    TABULATE     *7                          40                          TAB IDLE TIME
*      SAVE CLOCK TIME FOR TRACE IN HELP9
 40    SAVEX        49     C1                   41
*      HELP9 PUTS MEAN PROCESS TIME IN X42 AND SPREAD IN X43
 41    HELP         K9           P1             23            P2     P4
 23    ASSIGN       5      X42                  24                          PROCESS MEAN
 24    ASSIGN       6      X43                  43                          PROCESS SPREAD
 43    HOLD         *7                          25            *5     *6     PROCESS JOB
*
*      LEAVE CENTER J
*
 25    RELEASE      *2                          26                          RELEASE CTR J
*      SAVE RELEASE TIME FOR CTR J IN X(J+20) FOR IDLE TIME TABULATION
 26    SAVEX        *7     C1                   27
 27    ASSIGN       5      FN1                  45                          P5=SIZE
 45    TABULATE     *2     P5                   58                          CTR FLOW TIMES
*      SET SWITCH J TO OPEN GATE TO RE-CYCLE QUEUE FOR CTR J
*      GO BACK TO GET NEXT CENTER NO.
 58    LOGIC        S*2                         13                          SET SWITCH J
*
*
*      JOB IS FINISHED. TABULATE STATISTICS AND TERMINATE
*
 28    ASSIGN       6      V2                   29                          P6=SZ TYPE+60
 29    ASSIGN       5      FN1                  98                          P5=SIZE
 98    TABULATE     *6     P5                   30                          FLOW/SIZE TYPE
*      HELP3 OBTAINS D-A (DUE DATE - CLOCK TIME). STORE IN SAVEX 44
 30    HELP         K3           P1             31            C1     P4
 31    ASSIGN       6+     K5                   32                          INCRE. TBL NO
 32    TABULATE     *6     P5                   85                          D-C/SIZE TYPE
 85    ASSIGN       6      V9                   86                          P6=ZO TYPE+70
 86    TABULATE     *6     P5                   87                          FLOW/ZO TYPE
 87    ASSIGN       6+     K5                   88                          INCRE. TBL NO
 88    TABULATE     *6     P5                   33                          D-C/ZO TYPE
 33    TABULATE     81     P5                   34                          TOTAL TIME
```

```
 34    TABULATE     82     P5                 35                       DUE DATE-C
 35    TABULATE     83     P5                 36                       IA TIME
 36    TERMINATE
*
*
 1     VARIABLE     P3+K20                                             Z0 TYPE+20
 2     VARIABLE     P4+K60                                             SIZE TYPE+60
 3     VARIABLE     P2+K40                                             CTR NO +40
 4     VARIABLE     C1-X*7                                             IDLE TIME
 5     VARIABLE     C1-P8
 6     VARIABLE     V5(K16384
 8     VARIABLE     P2+K20                                             CTR NO +20
 9     VARIABLE     P3+K70                                             Z0 TYPE +70
*      FUNCTION 1 GIVES THE NO. OF UNITS IN EACH SIZE TYPE
*
*
 1     FUNCTION     P4     D5           JOB SIZE BY SIZE TYPE
1      500    2     100    3      100   4      0     5      0
*
*      FUNCTION 2 GIVES THE DESIRED MIX OF JOBS BY SIZE TYPE
*
 2     FUNCTION     RN1    D2           JOB TYPE BY SIZE    TYPE=1,2,...5
0.     1      1     1
*
*      FUNCTION 3 GIVES THE DESIRED MIX OF JOBS BY Z0(INITIAL Z) TYPE
 3     FUNCTION     RN1    D2           JOB TYPE BY INITIAL Z  TYPE=1,2,...5
0.     1      1.    1
*
*
*
*DEFINE EXPONENTIAL DISTRIBUTION
*
 4     FUNCTION     RN1    C26          EXPONENTIAL DISTRIBUTION
 0     0      .05   .051   .1     .105  .2     .223  .3     .357  .4     .511
 .5    .693   .6    .916   .7     1.204 .75    1.386 .8     1.609 .84    1.833
 .88   2.12   .9    2.303  .92    2.526 .94    2.813 .95    2.996 .96    3.219
 .97   3.507  .98   3.912  .99    4.605 .995   5.298 .998   6.215 .999   6.908
 .99978.112   .9999 9.210
*
*
*
*      TOTAL FLOW TIME FOR CENTER J IS TABULATED IN TABLE J
 1     TABLE        V6     1000   1000  W21
 2     TABLE        V6     1000   1000  W21
 3     TABLE        V6     1000   1000  W21
 4     TABLE        V6     1000   1000  W21
 5     TABLE        V6     1000   1000  W21
 6     TABLE        V6     1000   1000  W21
 7     TABLE        V6     1000   1000  W21
 8     TABLE        V6     1000   1000  W21
 9     TABLE        V6     1000   1000  W21
 10    TABLE        V6     1000   1000  W21
*
*      IDLE TIME FOR CENTER J IS TABULATED IN TABLE 20+J
 21    TABLE        V4     100    100   41
 22    TABLE        V4     100    100   41
 23    TABLE        V4     100    100   41
 24    TABLE        V4     100    100   41
```

```
 25    TABLE        V4    100    100    41
 26    TABLE        V4    100    100    41
 27    TABLE        V4    100    100    41
 28    TABLE        V4    100    100    41
 29    TABLE        V4    100    100    41
 30    TABLE        V4    100    100    41
*
*      QUEUE TIME FOR CENTER J IS TABULATED IN TABLE 40+J
 41    TABLE        V6    0      500    W41
 42    TABLE        V6    0      500    W41
 43    TABLE        V6    0      500    W41
 44    TABLE        V6    0      500    W41
 45    TABLE        V6    0      500    W41
 46    TABLE        V6    0      500    W41
 47    TABLE        V6    0      500    W41
 48    TABLE        V6    0      500    W41
 49    TABLE        V6    0      500    W41
 50    TABLE        V6    0      500    W41
*
*      FLOW TIME THRU SHOP FOR SIZE TYPE K IS TABULATED IN TABLE 60+K
 61    TABLE        M1    1000   1000   W41
 62    TABLE        M1    1000   1000   W41
 63    TABLE        M1    1000   1000   W41
*
*      D-A TIME FOR SIZE TYPE K IS TABULATED INTABLE 65+K
 66    TABLE        X44   -200001000    W42
 67    TABLE        X44   -200001000    W42
 68    TABLE        X44   -200001000    W42
*
*      FLOW TIME THRU SHOP FOR Z0 TYPE K IS TABULATED INTABLE 70+K
 71    TABLE        M1    1000   1000   W41
 72    TABLE        M1    1000   1000   W41
 73    TABLE        M1    1000   1000   W41
*
*      D-A TIME FOR Z0 TYPE K IS TABULATED IN TABLE 75+K
 76    TABLE        X44   -200001000    W42
 77    TABLE        X44   -200001000    W42
 78    TABLE        X44   -200001000    W42
*
*      FLOW TIME FOR ALL JOBS IS TABULATED IN TABLE 81
 81    TABLE        M1    1000   1000   W41
*
*      D-A TIME FOR ALL JOBS IN TABLE 82
 82    TABLE        X44   -200001000    W42
*
*      INTER-EXIT TIMES FOR ALL JOBS IN TABLE 83
 83    TABLE        IA    50     50     W41
 99    GENERATE     10001 5      1             100
 100   ASSIGN       4     K3                   8
       START                     900000
```

VITA

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Candidate for the Degree of

Doctor of Philosophy

Thesis: THE EFFECT OF ORDER SIZE ON THE OPERATION OF A HYPOTHETICAL JOB SHOP MANUFACTURING SYSTEM

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