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# An empirical study of the utility of a monte carlo model applicable to the determination of interference delays for multiple machine assignments on semiautomatic machines

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# AN EMPIRICAL STUDY
# OF THE UTILITY OF A MONTE CARLO MODEL
# APPLICABLE TO THE DETERMINATION OF INTERFERENCE DELAYS
# FOR MULTIPLE MACHINE ASSIGNMENTS ON SEMIAUTOMATIC MACHINES

by

Leonard A. Sonntag

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CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 18, 1967
(date)

Wallace J Richardson
Professor in Charge

Head of the Department

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## ABSTRACT

One of the most difficult problems that confronts the work measurement engineer, in the establishment of time standards for multiple machine assignments, is the determination of machine interference. Several empirically developed deterministic models have found wide acceptance for use in determining interference solutions for synchronized multiple machine assignments on semiautomatic machines.

A stochastic solution process (Monte Carlo Computer Simulation Model) is considered as a means for improving the portrayal of such a man and machine system. This model was constructed from real world industrial data and its validation was reasonably assured before employment in extensive experimental applications.

The solutions provided by four prominent deterministic models were statistically compared to those supplied by the stochastic simulator. The simulation solutions were found to be significantly different at all levels of experimental operation. However, this significance was found to be immaterial from the practitioner's point of view in all but two instances.

In conclusion, the simulation model was found to have additional utility in the determination of operator delays, the estimation of productivity in particular man and machine systems, and in the evaluation of the effects of proposed changes in equipment and operating procedures.

# 1. INTRODUCTION

The operation of semiautomatic machine tools in various manufacturing processes presents an opportunity for one operator to attend more than one independent machine unit. According to present usage, the term "semiautomatic" is generally applied to machine units which perform a complete cycle of processing without supervision, but require the attention of an operator to remove the part each time one is finished and to present an unfinished part to be processed (2).

There are many types of semiautomatic machine units in commercial operation, such as compression molding presses, lathes, grinders, millers, gear cutters, broaches, die-casting machines, electric welders, drill presses, and programmed test sets. These types of units are the result of the mechanization of the processing and controlling functions of manufacturing activities by our growing industrial complex. The continuous striving of our free enterprise system to reduce costs is necessary for economic growth. Therefore, this trend of technical progress - the development and use of new semiautomatic equipment, will rise and be of considerable importance to the continued growth of our society.

The necessary work required for each semiautomatic unit, consisting of removing the processed material, presenting new material and making possible inspections and adjustments, is seldom enough to occupy all the time of the worker. It is therefore possible to let the same worker service more than one such machine unit.

To establish an understanding of a multiple machine unit assignment, it is important that several terms common to any such relationship be defined.

Systematic Serviced Machines - The unloading, loading and automatic run times of these machines are predictable as to order of occurrence and elapsed time required for both operating and servicing. Solutions to problems involving these machines are determined by systematic analysis and portrayed algebraically with simple linear functions.

Randomly Serviced Machines - The servicing and run times of these machines are unpredictable as to order of occurrence and are completely random. Solutions based on the laws of probability are used for these assignments.

Machine Time - The average of the total time per unit time when the machine is working. It is usually fixed by speed and feed settings and is not controllable by the operator.

Attention (Servicing) Time - The average of the total time per unit time when the operator adjusts, empties, or reloads the machine. This time can be further differentiated between "external work", manual work performed by the operator while the machine is non-productive, and "internal work", manual worked performed during the machine's automatic producing time.

Operation Cycle Time - The total time required to complete one cycle of the operation. (Total of the "external work time" and the "machine time".)

Operator Idle Time - The time that the operator is idle because all the machine units in the assignment are running automatically.

Machine Interference Time - The time that one machine is idle and non-productive because the operator is servicing another unit in the assignment.

When two or more semi-automatic machines are assigned to one operator, it becomes apparent that there may be a loss of output per machine per unit time. This loss is due to an idle machine time caused by one or more of the various machines requiring the operator's attention when that operator is already engaged at another unit. This idle-machine time is commonly referred to as "machine interference".

In establishing time standards for multiple machine assignments, one of the most difficult problems that confronts the work measurement engineer is the determination of the machine interference (21). Dr. K.O.W. Sandberg contends that (16):

> Measurement of machine interference has long been a perplexing manufacturing problem. The lack of an adequate solution has led to strikes, to an investigation by a state governor, and to mediationboard controversies, as well as to internal inadequacies in product costing, pricing and job scheduling. Failure to recognize its existence caused one management and its engineers to overestimate plant capacity during a plant consolidation by 20 to 30 percent.

Sandberg emphasizes the importance of this problem by quoting the words of former governor J. G. Winant while he was serving as chairman of a board of inquiry (1935) for the cotton-textile industry:

> The problem of interference allowances is difficult because of the numerous and often incalculable factors that must be taken into consideration in reaching the proper result.

In practice, machine interference has been found to occur predominantly from 10 to 30 percent of the total working time, with extremes of from 0 to 50 percent (16).

Frequently, time study engineers have spent considerable time taking complete production-time studies of multiple machine assignments attempting to measure accurately the machine running time, attention time and machine interference time. This method of measurement, however, is subject to the limitations of human capabilities and to unfavorable economics. This is true because of difficulties encountered in timing simultaneous events in detail over long and continuous periods and in rating the performance level of the operator. Nevertheless, the direct measurement method has yielded empiric interference data which has taken the form of fitted curves, geometric plots, and algebraic formulas. These empiric time study solutions are usually applicable only in specific situations and extensions to other situations can be misleading (16).

Because of the inherent limitations of direct measurement, research has been conducted in the area of developing methods for preestimating machine interference for a variety of operating conditions which hopefully would provide improved solutions. Wright (21) states that there are four definite advantages of having a preestimating method:

1. It saves a large part of the time required to set standards for multiple unit machines because it eliminates the necessity of taking and analyzing long production time studies.
2. It results in much more accurate time standards in that the errors due to variation in conditions of the work during the

study are eliminated.

3. It makes it possible to set up element standards and formulas for a given class of machines which are entirely general. Without such a formula, standards may safely cover only the machine assignments and conditions for which the interference studies were actually made.

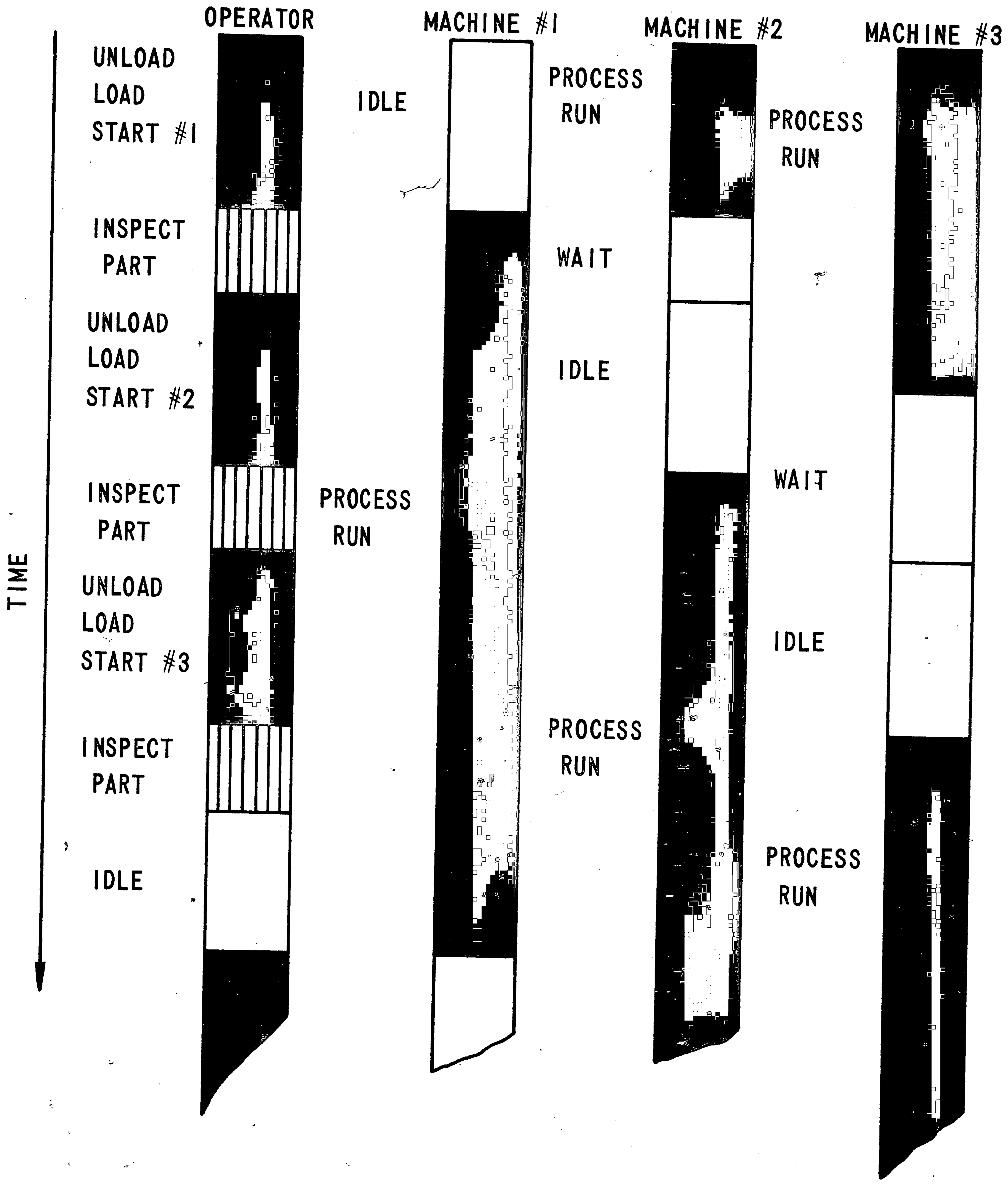
4. Finally, it makes it possible to compute in advance of installation the most economical number of machine units to assign to each operator from the standpoint of labor and machine costs.

Several notable empirical models were developed as a result of investigations conducted specifically to find solutions to this multiple machine problem. These models, which are available for use by the practicing engineer, can be categorized as being either deterministic or probabilistic in their analysis procedure.

The simplest of multiple machine problems has been studied by use of the graphical man and machine chart, such as that shown in Figure 1. Man and machine charts are a graphic means of portraying the separable steps of the work performed by a man and one or more machines and indicating the relationship between the work of each (12). This pictorial model has by nature been deterministic. It must portray the operating times of the system elements as constants and under the conditions of synchronized, or systematic machine servicing, permits solutions by geometric and algebraic methods. The algebraic solution models developed by Jones (8) and Sandberg (16) are based upon this man and machine chart approach. One important disadvantage of this type of model should be noted. It is unable to provide realistic solutions for man-machine systems which include variable attention times and conditions of random servicing.

GRAPHICAL MAN AND MACHINE PROCESS TIME CHART

FIGURE I



A detailed analysis of four of the most prominent deterministic models developed by Jones (8), Sandberg (16), Wright (21), and Duvall (21) is presented in section 4 of this study.

As a result of the limitations associated with deterministic models, a distinct area of investigation was centered on developing solutions for probabilistic problems concerned with strict random servicing. Considerable theoretical work and model development has been done on the pure probabilistic approach. These probability solutions have proceeded from one of three possible approaches: the binominal, the normal curve, or the Poisson-exponential. Contributions employing the use of the binominal solution have been proposed by Jones (8) and Berstein (16). Such authors as Palm (15), Ashcroft (8), Sandberg (16), and Wright (21) have proposed Poisson-exponential and normal-curve solutions. These references also contain a complete bibliography of articles pertaining to probabilistic models.

Further discussion of these pure probabilistic approaches will not be made since they are not the fundamental subject of this study.

## 2. STATEMENT OF THE PROBLEM

The major purpose of this study is the investigation of the feasibility and utility of a stochastic solution process (Monte Carlo Model) as applied to the solution of synchronized multiple machine assignments on semiautomatic machines.

When the time cycles of semiautomatic machines are regular, not random - with regard to operator servicing, it has been found feasible to arrange for a synchronized multiple machine operational work cycle.

Textbooks and published articles covering the determination of machine interference time, arising from this type of assignment, generally have created the impression that interference can be calculated through a set of deterministic mathematical models which give cut-and-dried solutions under all conditions.

Objectively, the manual attention time of such an assignment is never a constant, but the result of a specific chance variable system. The author feels that the real system cannot be studied satisfactorily without considering the variation which is inherent in some of its true variables. It is also believed that the use of a strict deterministic model under these operating conditions renders solutions which are unfeasible. Furthermore, these models do not present their results in terms of confidence intervals which can be more meaningful than the presentation of "single values".

The question of feasibility is of considerable importance since the effect of machine interference delays is to reduce the expected machine output. Consequently, all manufacturing activities concerned with productivity and work measurement must take into account the extent of such reductions.

The stochastic model of this study was developed to apply the probabilistic concept of variable manual attention elements to a synchronized or systematic method of operator servicing with constant machine processing elements. On this point it differs from the pure probabilistic models which all assume operator servicing on a completely random - first finished, first attended basis.

## 3. EXPERIMENTAL PROCEDURE

The problem, as described in section 2, was studied by constructing a Monte Carlo Computer Simulator of the man and machine relationship. The principle of the computer simulator was to build a dynamic manipulatable model of a synchronized multiple machine operation, possessing some stochastic properties, within the high speed memory of a digital computer. Through the use of random sampling from the statistical distributions of the probabilistic components, the model was studied in a stochastic manner under a variety of operating conditions.

The experimental procedure, after formulation of the basic problem, consisted of the following seven major elements.

### 1. Collection and processing of real world data.

Before proceeding with an empirical study, it was desirable to bound the study to an extent that it became manageable but yet remained realistic. The desire for manageability of the study is well understood when considering the numerous factors involved in the multiple machine assignment concept. The area of realism is interpreted from the viewpoint of the practitioner who is interested in the consideration of those factors which are necessary to adequately describe the system of interest.

Consequently, this investigation was confined to an analysis of a typical synchronized three machine assignment model which was developed from real world industrial data.

The data used in the empirical study was obtained from a manufacturing facility of the Western Electric Company, Incorporated. For the usual proprietary reasons, the location of the plant, the exact description of the product, the identification of the operator, and the time period during which the data was compiled must be withheld. However, these restrictions of disclosure do not occlude the validity of the study in any manner.

The actual data collection process involved the use of a memomotion study. Memomotion study is the name given to the technique for the analysis of man activity that involves the use of a motion picture camera which is run at unusually slow speeds (12). This technique is ideally suited for use in studying simultaneously the man work, equipment usage, and flow of materials in an operation for extended periods of time.

The motion pictures were taken using a 16mm Bell & Howell camera connected to a LaFayette Instrument Company motor driven gear train. The speed of the gear train was set at sixty frames per minute (one per second). The camera was equipped with high speed Kodak Tri-X reversal movie film to permit the taking of pictures by natural factory illumination.

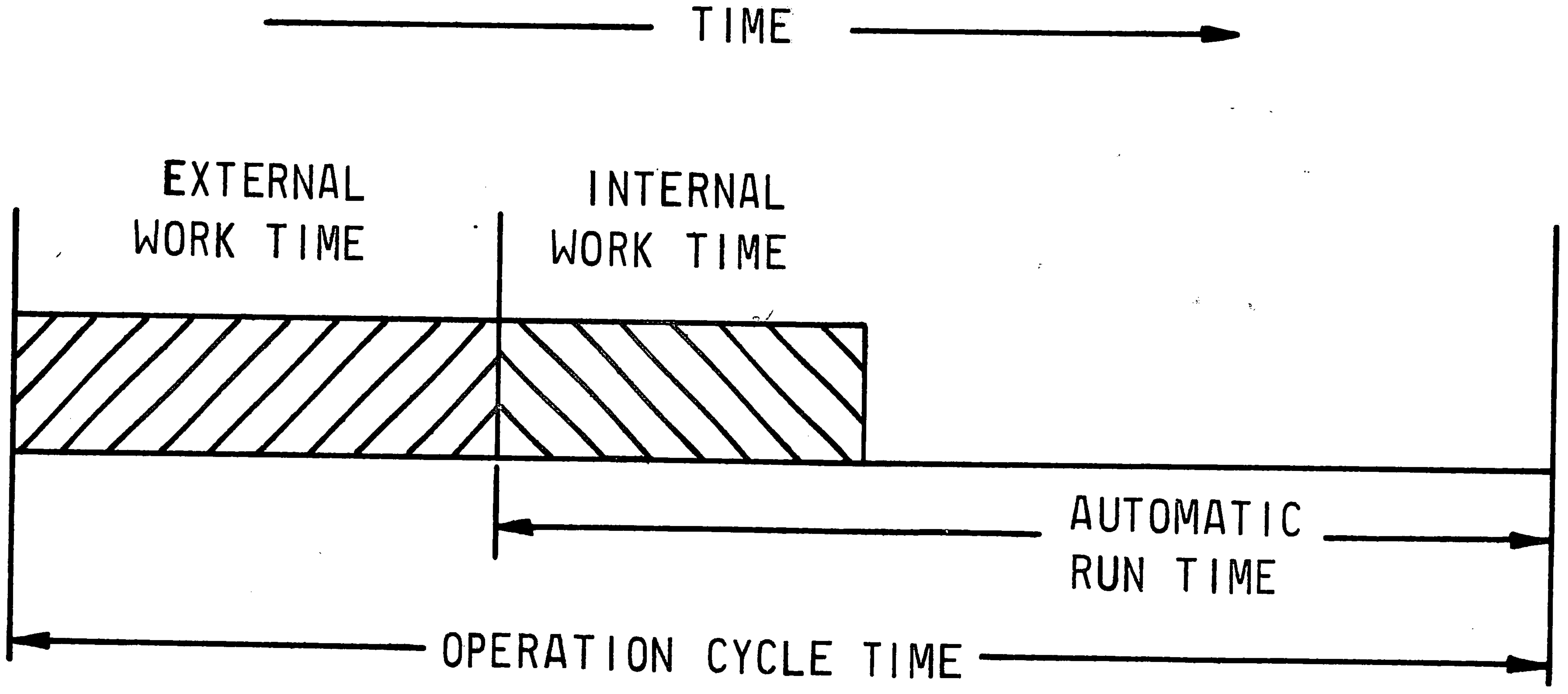
Using this special equipment, one hundred feet of film were exposed on a normal average operator attending three synchronized semiautomatic machine units in an industrial setting.

### 2. Formulation of the mathematical model

A detailed film analysis, utilizing a stop-frame projector equipped with a frame counter, revealed a form of work cycle on each machine as portrayed in figure 2. The operator performed some work while the

FIGURE 2

GRAPHIC DESCRIPTION OF A MACHINE CYCLE



machine was non-productive. This type of work, conventionally called "external work", consisted of the unloading, loading and machine starting elements. The operator then immediately performed some "internal work" after the beginning of the machine's automatic production time.

Determination of this strict work cycle permitted the formulation of a mathematical model which would describe the behaviour of this man and machine system. This model was developed in a general form to depict the operator systematically servicing two or more semi-automatic machine units.

The variables of the model were defined as follows:

Subscripts -

$i$ = $i$ th machine
$j$ = $j$ th cycle
$n$ = number of machines

Cycle Definition - the cycle begins at the moment that the operator begins to unload - load a machine, and ends at the moment when he begins again to unload - load this machine.

Terms -

$C(j)$ = length of the $j$ th cycle.

$P(i,j)$ = machine process time of the $i$ th machine on the $j$ th cycle. (A constant in this model.)

$O(i,j)$ = operator external work time variable on the $i$ th machine on the $j$ th cycle.

$RI(i,j)$ = operator required internal work time variable on the $i$ th machine on the $j$ th cycle.

$AIDLE(i,j)$ = apparatus (machine) idle time on the $i$ th machine on the $j$ th cycle.

$OIDLE(i,j)$ = operator idle time while waiting to service the $i$ th machine on $j$ th cycle.

Model Structure -

(in reference to figure 2)

1. $C(j) = 0(i,j) + P(i,j) + AIDLE(i,j)$

and

2. $C(j) = 0(1,j) + RI(1,j) + OIDLE(2,j) + 0(2,j) + RI(2,j) + \ldots + OIDLE(n,j) + 0(n,j) + RI(n,j) + OIDLE(1,j).$

Analyzing equations number 1. and 2. above for $C(j)$, it can be seen that $AIDLE(1,j)$ and $OIDLE(1,j)$ cannot both be zero on the j th cycle. The machine cannot be waiting for the operator while the operator is waiting for the machine.

This characteristic permits the establishment of a routine to determine the values of both $AIDLE(i,j)$ and $OIDLE(i,j)$.

Let $Z(1,j) = P(1,j) - (OIDLE(2,j) + 0(2,j) + RI(2,j) + \ldots + OIDLE(n,j) + 0(n,j) + RI(n,j))$

$Z(1,j)$ can take on a positive or negative value

If $Z(1,j)$ is positive then $OIDLE(1,j) = Z(1,j)$ and $AIDLE(1,j) = 0$.

If $Z(1,j)$ is negative then $AIDLE(1,j)$ = absolute value of $Z(1,j)$ and $OIDLE(1,j) = 0$.

These relationships form the basis of the general mathematical model describing this system.

## 3. Estimation of parameters of operating characteristics from real world data

Upon completion of the data collection and formulation of the basic mathematical model, the experimental procedure proceeded with an evaluation of the parameters of the operating characteristics from the real world data.

The numerical data gathered from the memomotion study indicated distinct frequency distributions for both the "external" and "internal" operator work elements as shown in Appendix A. Both distributions are identified by a lack of symmetry. They can be classified as right (positively) skewed distributions caused by the extremes in the higher values distorting the curve towards the right.

Statistical measures of the central tendency (the average) and the variation (the standard deviation) were calculated from the numerical data of each distribution. (See Appendix A.)

### Sample Values

"External work element"

Average $\bar{x} = 22.93$ sec.
Standard Deviation $s = 3.27$ sec.
Variance $s^2 = 10.70$ sec.

"Internal work element"

Average $\bar{x} = 11.22$ sec.
Standard Deviation $s = 3.27$ sec.
Variance $s^2 = 12.08$ sec.

These measures, computed from the limited samples of data, were then used to characterize the populations or groups of data from which the samples were taken.

The mean value of a sample of n items is an unbiased estimate of the mean value in the population from which the sample is drawn. Therefore -

the "Expected Value" $E(X) = \bar{x}$

The standard deviation is a biased estimate, tending to underestimate the population value for smaller sample sizes. The factor $\left(\frac{n}{n-1}\right)$, referred to as Bessel's correction, is applied to the sample value as an adjustment for this discrepancy. Therefore -

$$V(X) \text{ or } \hat{\sigma}^2 = \left(\frac{n}{n-1}\right) s^2$$

Using these relationships, the best estimates of the population parameters were calculated.

Population estimates

"External work element"

$$E(X) = \bar{x} = 22.93 \text{ sec.}$$

$$V(X) = \hat{\sigma}^2 = \left(\frac{n}{n-1}\right) s^2 = \left(\frac{83}{82}\right) 10.70 = 10.83 \text{ sec.}$$

"Internal work element"

$$E(X) = \bar{x} = 11.22 \text{ sec.}$$

$$V(X) = \hat{\sigma}^2 = \left(\frac{n}{n-1}\right) s^2 = \left(\frac{122}{121}\right) 12.08 = 12.18 \text{ sec.}$$

Normally, stochastic simulation involves the replacement of an empirically determined distribution by its theoretical counterpart, a universe described by some assumed probability distrubiton, and then sampling from this theoretical population by means of some type of random generator. Therefore, an attempt was made to fit one of the known theoretical distributions tothe empirical distribution obtained from the memomotion study.

The gamma distribution often furnishes a good fit for observations that are intrinsically non-negative and of fairly wide range (positively skewed) (17).

The usual procedure in fitting is the "method of moments" advocated by Karl Pearson and his school (10).

The gamma distribution is described by the following density function

$$f(x) = \frac{\alpha^{k} x^{(k-1)} e^{-\alpha x}}{(k-1)!} \qquad (3\text{-}1)$$

where $\alpha > 0$, $k > 0$, and $x$ are non-negative. The expected value and variance are given by

$$E(X) = \frac{k}{\alpha} \qquad (3\text{-}2)$$

$$V(X) = \frac{k}{\alpha^{2}} \qquad (3\text{-}3)$$

If $k = 1$, the gamma distribution is identical to the exponential distribution. If $k$ is a positive integer, the gamma distribution is identical to the Erlang distribution. As ~~k~~ increases, the gamma distribution approaches a normal distribution asymptotically.

To fit an empirical distribution to a gamma distribution with a given expected value and variance, the following formulas can be used to determine the parameters of $f(x)$ in equation 3-1

$$\alpha = \frac{E(X)}{V(X)} \qquad (3\text{-}4)$$

$$k = \frac{(E(X))^{2}}{V(X)} \qquad (3\text{-}5)$$

The expected value, $E(X)$, and the variance, $V(X)$, determined by the 1st and 2nd moment calculations were used to calculate the remaining parameters $K$ and $\alpha$ of the corresponding gamma distribution.

Fitted Gamma Distributions

"External work element"

$E(X) = 22.93$ sec.

$V(X) = 10.83$ sec.

$$\alpha = \frac{E(X)}{V(X)} = \frac{22.93}{10.83} = 2.12$$

$$k = \frac{(E(X))^2}{V(X)} = \frac{(22.93)^2}{10.83} = 48*$$

*note - k must be an integer to allow computer generation of f(x) (13).

"Internal work element"

$E(X) = 11.22$ sec.

$V(X) = 12.18$ sec.

$$\alpha = \frac{E(X)}{V(X)} = \frac{11.22}{12.18} = .92$$

$$k = \frac{(E(X))^2}{V(X)} = \frac{(11.22)^2}{12.18} = 10$$

## 4. Evaluation of the parameter estimates

Each of the empirical operating characteristics which took the form of a probability distribution were next subjected to a "goodness of fit" test to determine how well the given hypothetical probability distribution fitted the real world data from which it was derived. It is extremely important that a "good fit" exists. A computer model formulated with inadequate operating parameters will not depict the real world situation which is being investigated.

A test to determine the goodness of fit of the actual data to the theoretical distribution has been devised by Karl Pearson (6).

The test involves the calculation of chi-square

$$\text{chi-square} = \left(\frac{(f_o - f)^2}{f}\right)$$

where

$f_o$ = the observed or actual frequencies

$f$ = the theoretical frequencies

By reference to a set of chi-square tables, chi-square may be evaluated. In the tables, N equals the number of "degrees of freedom" based on the number of categories ($N_k$ -1) where $N_k$ represents the total number of categories. The number of degrees of freedom also decreases one for each parameter estimated from the sample. The value indicated in the table (p) is the probability of obtaining a fit, due to chance, as poor as or worse than the one obtained. If this probability is small, the likelihood that the disparities between the theoretical and actual data are due to chance, is small.

The method of determining the theoretical frequencies for a common distribution, such as the normal curve, is a simple matter. It involves the determination of the area under the curve within the desired intervals using specially prepared tables.

Although the cumulative distribution function does not exist in explicit form for the gamma distribution considered in this study, the values of the so-called incomplete gamma function have been tabulated by Pearson (13). Nevertheless, the common practitioner will find that the use of these tables involves a complex statistical procedure.

Therefore, an easily understood method of determining the areas under the fitted gamma distribution was devised. Using the density function of the gamma distribution (eq. 3-1), a short Fortran computer program was developed to generate the areas under the gamma distributions in question. This program uses the trapezoidal rule of approximate integration described by Smail (18) to generate the area under the distribution within the desired intervals. (Appendix B)

Execution of this program resulted in two tables of areas for the fitted external and internal work element distributions. (Appendix C.)

The chi-square test was then used to determine the "goodness of fit" for both distributions. (Appendix D) The values of chi-square in both instances indicated that at the 5 percent level of significance the hypothesis, that the distributions were in fact gamma distributions with parameters k and $\alpha$, should be accepted.

### 5. Formulation of a computer program

The computer simulation program of this investigation was written in general purpose Fortran II language.

The Fortran programming language was selected because it is a widely used computer language that closely resembles the language of mathematics and was designed primarily for scientific and engineering computation. Furthermore, Fortran compilers are now available for nearly all of the computers used most often by industry, colleges and universities.

The mathematical synchronized semiautomatic machine assignment model developed in element 2 of this section was perfectly suited for digital computer computations because of its recursive nature. The major step in the programming of this model involved the development of a procedure which would generate successive random variates describing the external and internal work elements for use in the recursive relationships.

The generation of these random variates is entirely numerical in nature. It consists of a procedure which transforms pseudorandom numbers, representing the uniform random variables in the range 0-1, by means of the inverse cumulative distribution function (13).

The main simulation program, SIMULA, was written following the mathematical model previously established. The operating structure of this main program was designed in a flexible manner to permit the man and machine system to be simulated for different periods of duration under a variety of machine cycle lengths. (See Appendix E)

A subroutine, GAMMA (K,A,X) was written which generated and returned to the main program random variates from the gamma distribution (13). GAMMA (K,A,X) was developed with a general format in order to permit it to generate variates for both the external and internal work elements. (See Appendix E)

In order ~~to~~ function, subroutine GAMMA (K,A,X) required a supply of psuedorandom numbers for transformation. The many methods of generating random numbers on a digital computer have themselves been the subject of extensive studies and investigations. A previous study (20) found that the number 83 used as a multiplier in the multiplicative congruential method provided a sequence of numbers which exhibited satisfactory statistical characteristics of randomness. Subroutine RANDOM (SEED, RAND) was in turn written (using this technique) to generate and return the required psuedorandom numbers to GAMMA (K,A,X) upon demand. (See Appendix E)

The final step in the development of the computer program involved the specification of the desired simulation performance statistics and their output formats. For a given machine cycle length the statistics consisted of -

1. number of machines simulated (echo of the input data)
2. total number of operator service cycles (echo of the input data)
3. elapsed operation time
4. total number of units produced by the system
5. average cycle length
6. average operator idle time/service cycle
7. average apparatus (machine) idle time/service cycle

## 6. Validation of the Computer Simulation Model

Naylor (13) states that:

> The problem of validating computer simulation models is indeed a difficult one because it involves a host of practical, theoretical, statistical, and even philosophical complexities. Validation of simulation experiments is merely part of a more general problem, namely the validation of any kind of model or hypothesis. ....
>
> In general, however, one test seems appropriate for validating simulation models. How well do the simulated values of the endogenous variables compare with known historical data, if historical data is available?

In this investigation, limited historical data was available in the form of the performance data gathered by the original memomotion study.

The memomotion study was taken on a group of three machines, each of which had an automatic processing time of 120 sec. The average manual attention time per unit consisted of 22.93 sec. for the external work element and 11.22 sec. for the internal work element.

Two of the operating parameters of the typical multiple machine assignment are usually expressed as percentages. The first, average manual attention time, can be expressed as a percentage of the total operating cycle and will hereafter be referred to as the "Level of Operation". The second, average machine idle time (interference), is normally expressed as a percentage of the average manual attention time.

Analysis of the memomotion study yielded the following data regarding the two above mentioned parameters -

$$\text{Level of Operation} = \frac{22.93 + 11.22 \text{ sec.}}{22.93 + 11.22 + 120 \text{ sec.}} = 23\%$$

$$\text{Machine Interference} = \frac{.794 \text{ sec.}}{22.93 + 11.22 \text{ sec.}} = 2.32\%$$

An executed computer run (Appendix G) at the 25% level of operation resulted in a machine interference of 2.02%.

Since the results of the simulation at the 25% level compared favorably with the actual limited performance statistics, the computer model was considered valid and capable of predicting the behavior of the real system under other operating conditions.

## 7. Design of the Simulation Experiments

The final step in the experimental procedure, after reasonably determining the validity of the computer model, involved the design of the simulation experiments. These experiments were devised to evaluate the feasibility and utility of the stochastic solution process as applied to the problem.

The investigation involved the evaluation of performance statistics provided by each of four prominent deterministic models (described in Section 4) and the stochastic computer simulator using several sets of basic operating input parameters.

The deterministic models and the computer simulator were evaluated at the following seven different levels of operation.

| Level of Operation | | Associated Automatic Machine Run Time |
|---|---|---|
| 1. | 10% | 319 sec. |
| 2. | 25% | 114 sec. |
| 3. | 35% | 75 sec. |
| 4 | 50% | 45 sec. |
| 5 | 75% | 23 sec. |
| 6 | 100% | 11 sec. |
| 7 | 125% | 4 sec. |

The sample size for one simulation run was set at 155 operator service rounds. This particular sample size was determined from the variability of the available sample data originally obtained by the memomotion study on the manual elements of the operation.

Research in the field of time study and normal rating methods, by such individuals as Mundel, Lazarus, Keim, Lehrer and Carson, indicates that results with an accuracy of ± 5 percent error can be expected (12). The calculations for the required simulation sample size were based on the observed variability of the measurable manual elements using the above accepted work measurement concept. (See Appendix F) The sample size could have been based on the variability of the performance statistics. This procedure would have resulted in a considerably larger sample requirement in order to cause the results to stochastically converge. Had this procedure been employed, it would have provided theoretically greater accuracy in the values of the individual manual elements. However, in practice, this greater accuracy is not obtainable using common work measurement techniques.

The interference solutions provided by the simulator at the seven levels were compared to those supplied by the deterministic models by means of null hypothesis significance testing.

The specific simulation interference statistics were also evaluated by the method of moments to determine their inherent variability at each level of operation.

## 4. DETERMINISTIC MODELS FOR MULTIMACHINE ASSIGNMENTS

The most prominent deterministic models chosen for analysis in this study, which are available for use in evaluating synchronized multimachine assignments and predetermining machine interference, are an outgrowth of algebraic relationships and empirically developed curves.

### 4.1 Dale Jones Algebraic Model

The first model investigated was developed by Dale Jones, of the Sandia Corporation, in 1946 (8). This model is based on an algebraic relationship which is an outgrowth of the basic man-machine chart approach.

Jones depicts the typical semiautomatic machine cycle as illustrated in Figure 2.

The analysis of an assignment using this model requires an understanding of the following terms:

R = Automatic Machine Run Time

WE = Manual External Work Time (performed while the machine is nonproductive)

WI = Manual Internal Work Time (performed during the machine's producing time)

(WE + R) = Attention (service) time (total sum of the manual external work time and the automatic machine run time)

$(WE_i + R_i)$ or (WE + WI) = Battery Cycle Time (in systematically serviced assignments where each machine is serviced but once per cycle; it is the longest of the individual operation-cycle times, or the total of the required operator servicing times per cycle, whichever is greater.)

Basically, there are three conditions that may exist in the relationship between the operator and the machines in a multiple assignment. In the first condition, the operator is found to be fully busy with no idle time and there is no machine interference. Mathematically this is expressed as $\Sigma(WE + WI) = (WE + R)$.

The second condition termed "underassigned," exists when the total attention (servicing) times in the battery is less than the longest operation-cycle. Mathematically this is expressed as $\Sigma(WE + WI) < (WE + R)$.

The third condition termed "overassigned," exists when the total attention (servicing) times for all machines in the battery is greater than the longest operation-cycle. Mathematically this is expressed as $\Sigma(WE + WI) > (WE + R)$.

The significant factor in determining machine interference and operator idle time is the comparison of the operation cycle time $(WE + R)$ with the service time $\Sigma(WE + WI)$. As stated previously, the longest of the individual operation cycles or the summation of the operator service times is the battery cycle time. It is an easy matter to evaluate the interference of any given machine assignment by subtracting the machine's operation cycle $(WE_i + R_i)$ from the battery cycle time.

The degree of inherent operator idle time is calculated by subtracting the total operator servicing time $\Sigma(WE + WI)$ from the battery cycle time.

Battery-cycle time for assignments where one or more machines are serviced more than once per battery cycle is determined by adding the total operator servicing time per battery cycle to the total operator idle time per battery cycle.

## 4.2 Dr. K. O. William Sandberg Algebraic Model

Dr. K. O. William Sandberg, of the General Electric Company, developed a geometric and algebraic model for the solution of machine interference problems (16). This model parallels the Jones' Algebraic Model of section 4.1. However, the formulas which are used in its structure will not apply to situations in which the operator services a machine unit more than once per service cycle.

The analysis of an assignment using this model requires an understanding of the following terms:

N = number of production units per operator
m = total running time of N units
  $m_c$ = time per cycle
  $m_{cl}$ = time of longest cycle

h = total operator hand-servicing time of N units
  $h_c$ = time per cycle
i = total interference delay time of N units
  $i_c$ = time per cycle
  $i_d$ = time per N cycles
p = total operator attention time while machine is running, used for machine attention or other chores. Preoccupied time. May include repairs, cleaning, inspection, etc. if done by operator.
  $p_c$ = time per cycle
  $p_d$ = time per round of operator servicing, of N units.
f = total free time of operator. Also called operator idleness, stand-by, and man interference. Can be used for rest and fatigue allowance.
  $f_d$ = per round
  $f_{d1}$ = value before 'p' introduced
  $f_{d2}$ = value after 'p'

Sandberg states that:

> The significant factor in determining interference and free time values depends on whether or not the longest prime cycle is equal to, or larger than, or smaller than the sum of the operator work load per round.
>
> Preoccupied time adds to the operator work load and tends to create interference delays except when it is absorbed during operator free time periods. Thus, it can occur during free time or overlap free time, or occur without overlap.

Sandberg summarized his model in the form of a table which specifies two general interference formulas for constant time condition. This table provides a rule for choosing between them and for establishing the value of operator free time $f_{d2}$ which remains after preoccupied time is introduced into an assignment. (See Table A)

The choice of the two solutions is determined by the comparison of the work load vs. the longest prime cycle.

A prime disadvantage of this method is the complex mathematical notation which tends to confuse the common practitioner.

| | | | | |
|---|---|---|---|---|
| This comparison | $\Sigma h_c + p_d > h_{c1} + m_{c1}$ | | $h_{c1} + m_{c1} \geq \Sigma h_c + p_d$ | |
| Selects equation for interference | $i_d = N(\Sigma h_c + p_d + f_{d2}) - \Sigma h_c - \Sigma m_c$ | | $i_d = N(h_{c1} + m_{c1} + f_{d2}) - \Sigma h_c - \Sigma m_c$ | |
| This comparison selects values for $f_{d2}$ in $i_d$ | $h_{c1} + m_{c1} > \Sigma h_c$ | $\Sigma h_c \geq h_{c1} + m_{c1}$ | $h_{c1} + m_{c1} > \Sigma h_c$ | $\Sigma h_c = h_{c1} + m_{c1}$ |
| Added selectors for $f_{d2}$ if $p_d$ on $f_d$ overlap is full and $p_d \geq f_{d1}$ —— | $f_{d2} = 0$ | $f_{d2} = 0$ | $f_{d2} = 0$ | $f_{d2} = 0$ |
| full and $p_d < f_{d1}$ —— common situation | $f_{d2} = f_{d1} - p_d = h_{c1} + m_{c1} - \Sigma h_c - p_c$ | - - - - - - - - | $f_{d2} = f_{d1} - p_d$ | $f_{d2} = 0$ |
| partial and $p_d \gtrless f_{d1}$ —— | $f_{d2} = f_{d1}(1\text{-overlap fraction})$ | $f_{d2} = 0$ | $f_{d2} = f_{d1}(1\text{-overlap})$ | $f_{d2} = 0$ |
| zero and $p_d \gtrless f_{d1}$ ⟶ | $f_{d2} = f_{d1} = h_{c1} + m_{c1} - \Sigma h_c$ | $f_{d2} = 0$ | $f_{d2} = f_{d1} = h_{c1} + m_{c1} - \Sigma h_c$ | $f_{d2} = 0$ |
| when $p_d = 0$ —— | - - - - - - - - - - | $\Sigma h_c > h_{c1} + m_{c1}$<br>$f_d = 0$<br>$i_d = (N-1)\Sigma h_c - \Sigma m_c$ | $h_{c1} + m_{c1} \geq \Sigma h_c$<br>$f_d = h_{c1} + m_{c1} - \Sigma h_c$<br>$i_d = N(h_{c1} + m_{c1}) - \Sigma h_c - \Sigma m_c$ | |

TABLE A.

Constant Time Solution Per Round of Servicing for Machine Interference Delay and Operator Free Time

### 4.3 W. R. Wright Algebraic Model

W. R. Wright hypothesized that all machine interference was a matter of chance and believed that a general formula could be developed for it by use of the mathematical theory of probability. He found that Thornton C. Fry, of the Bell Telephone Laboratories, had solved a problem in congestion of telephone lines, the conditions of which were nearly identical to the machine interference problem.

Dr. Fry had developed a formula for "expected delay per call" in connection with telephonic research. The principal conditions assumed in the development of Dr. Fry's formula are as follows: (21)

1. A group of telephone lines having access to one common trunk line are handled in such a manner that if a call requiring the use of this trunk line originates on one line while a call on another line is already making use of the trunk, the second call will be delayed until the first call is finished and will then be given access to the trunk line.
2. All telephone calls are of equal length.
3. The calls which are assigned to the group of channels are distributed individually and collectively at random.

The first condition is obviously identical with the conditions of the machine-interference problem.

The second condition does not apply accurately, but it was realized that if the assumption would give satisfactory results for telephone delay, it should apply to machine interference.

The third condition is not true for small numbers of machines or for high percentages of attention time.

Dr. Fry's solution was converted into terms of machine interference, as follows:

$$I = 50\left( \sqrt{(1 + X - N)^2 + 2N} - (1 + X - N) \right)$$

where

I = interference in percentage of attention time
X = ratio of machine running time to attention time
N = number of units assigned to one operator

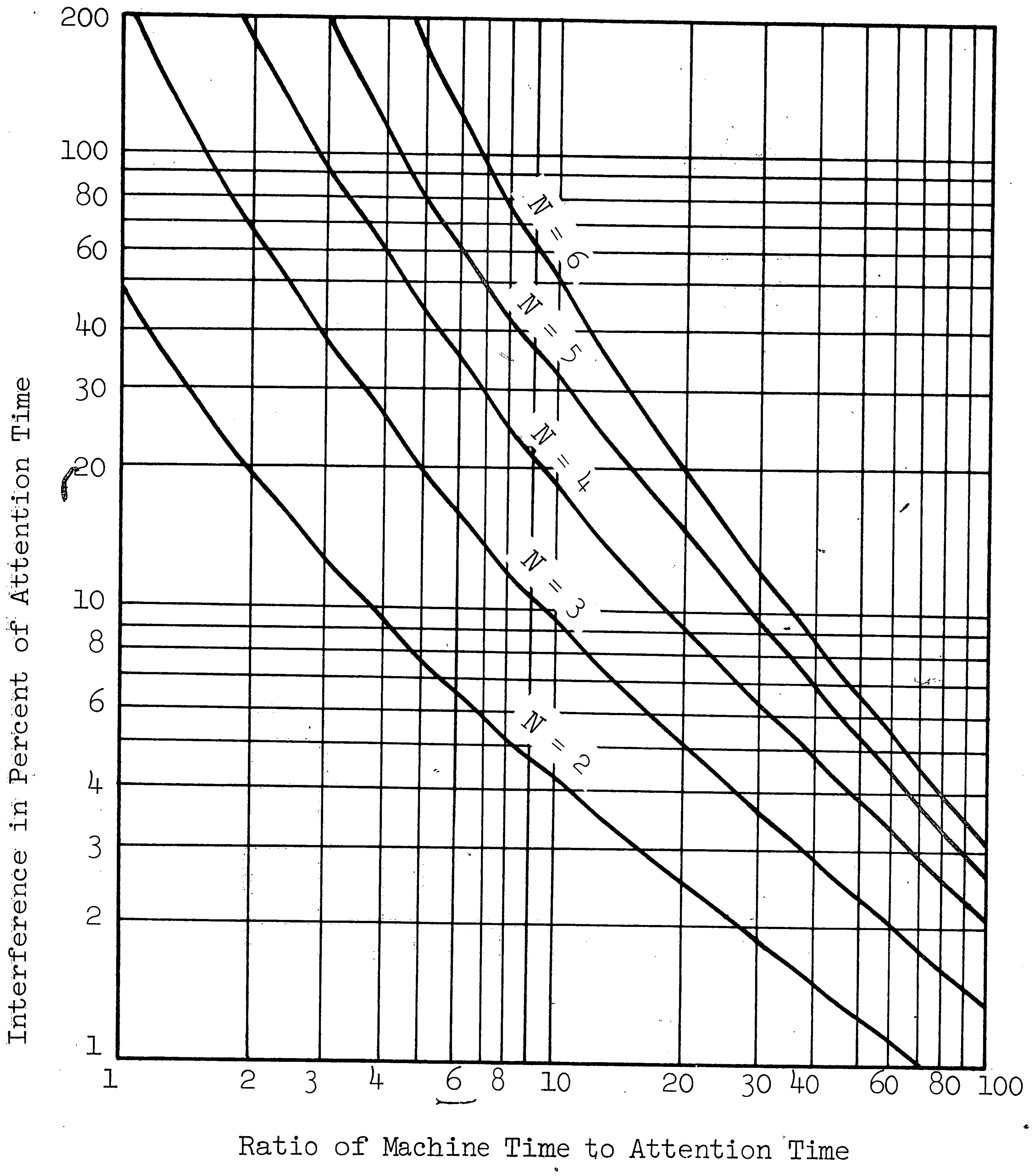
It can be seen that this formula is so simple that it can be applied by any one having a knowledge of algebra. The formula was checked with the analysis of more than eleven hundred hours of actual shop observation during which interference had been measured and recorded. These studies covered the operation of eight entirely different types of machines and were therefore considered entirely general.

It was found that the formula checked accurately with these actual shop studies for assignments of six or more units per operator, but die not agree when the assignment was less than six. It is an interesting fact that the first check of this formula was made with data for a six-unit assignment. If this check had been made with data for a four-unit assignment, the formula would probably have been discarded as not applicable to the machine-interference problem. The discrepancy between the formula and actual performance data for small assignments was due primarily to Dr. Fry's assumption concerning the distribution of "calls." This assumption resulted in an increasing divergence as the assignments became smaller.

A set of empirical curves, Figure 3, was therefore developed from the actual performance data for assignments of from two to six units. With this supplement to the formula, interference values may be determined for any assignment or any multiple-unit job by simply determining the ratio of machine running time to attention time for each unit.

Figure 3

INTERFERENCE ON MULTIPLE-UNIT MACHINES



Showing values of interference in percent of attention time when number of units assigned to one operator is six or less

## 4.4 W. G. Duvall Algebraic Model

W. G. Duvall, of the Western Electric Co., developed an empirical formula to describe interference as a function of several variables (21).

In the formula which he developed, the symbols are defined as follows:

$N$ = number of machine units assigned per operator
$r$ = machine time per machine unit per unit output of product
$W$ = operator's attention time per machine unit per unit output of product
$I$ = interference as a percentage of attention time
$R$ = ratio $r/w$

The operating conditions under which the formula is applicable are as follows:

1. The operation performed on each of the N machine units under one operator's care is identical, the machine units are identical, and are equally well maintained, and the ratio $r/w$ is therefore the same for each machine unit.
2. The operator is equally available to all machine units.
3. The operator is always attending one machine unit as long as there is at least one requiring attention.
4. When any machine unit requires attention while the operator is already engaged, that unit continues to require attention (undergoes interference) until the operator is available, and is then attended by the operator for the full time required.
5. Any time that the operator must spend at one unit, whether other units require attention or not, is attention time in so far as the values of $w$ and $r$ are concerned.
6. Any machine unit undergoing either attention or interference is not liable to the probability of requiring attention until it is again running.
7. The probability of finding the group of N units in any specified condition of interference is independent of the time at which they are noted for that condition.

8. The various units of attention time may or may not be exactly equal; and it is assumed that the probability of a machine unit requiring attention is equal at any instant in the machine running time. This is not literally true, but over a length of operating time, the distribution of attention demands approaches the random distribution.

The general equation measuring interference is

$$I = 100(N-I)e^{-1.4N^{-0.946}R}$$

Duvall stated that he arrived at this form by considering actual interference values plus further reasoning on the nature of interference.

The development of this equation may be summarized as follows: It may be observed that the amount of interference in a given machine assignment will vary inversely with the ratio of machine time to attention time. It may also be observed that when R is constant, the amount of interference will vary directly with N. Duvall concluded that R and N were two factors influencing or controlling the value of I.

# 5. RESULTS AND ANALYSIS

The simulation phase of this experiment consisted of independent simulation runs at seven different operating levels of automatic machine run time. The simulations were run and the desired results were obtained without any serious difficulties. Since each independent simulation required approximately seventeen minutes, the total computer time for the experiment was approximately two hours. The simulation performance statistics that were obtained at each level of operation are shown in Appendix G.

An example of the calculations which were performed to determine the variation of the simulation interference results is shown in Appendix H. Table 1 of Appendix H shows a summary of the means and standard deviations of the simulation results at all levels of operation. By examining the column corresponding to the actual variation, it can be seen that the variation remains almost constant after a point at which the manual attention time reaches 50% of the total cycle time.

Appendix H also includes an example of the computations which were required to evaluate the four deterministic models described in Section 4. Tables 2 and 3 summarize the interference solutions provided by these models and the simulator at each level of operation. Examination of Table 3 indicates that the models of Jones and Sandberg do not recognize machine interference conditions at the low levels of manual attention time. Furthermore, the Wright model ($n < 6$) is not able to provide solutions for levels of operation greater than 50%. Simple inspection of all the solutions indicated that the Jones and Sandberg models seem to fit the actual simulator results most closely.

The solutions provided by the simulator were compared to those supplied by the four deterministic models by means of null hypothesis significance testing. Appendix H contains an example of the application of the two-sided Normal Significance Test. The summary of all the significance tests is shown in Table 4. These results indicate that in all cases, the simulator results differed significantly with the solutions of all the models at the 5% level of significance. Close examination of Table 4 indicates that the models of Jones and Sandberg provided solutions which possessed the smallest significant difference. From the practitioner's point of view, these minimum differences would usually be permissible in incentive pay situations and would certainly be reasonable for scheduling purposes.

An important outgrowth of this investigation has been the presentation of the simulation interference solutions in terms of confidence intervals. (See Table 4) These intervals can be more meaningful to the practitioner than the presentation of the usual tests of significance. Things are rarely black or white; decisions are rarely made on one-shot tests, but usually in conjunction with other information. Confidence intervals give a feeling of the uncertainty of experimental evidence, and give it in the same units as the original observations.

This study has also resulted in the development of a graphic tool which portrays the expected variation for a range of interference solutions. (See Appendix H)

## 6. CONCLUSIONS

The major purpose of this study was the investigation of the feasibility and utility of a stochastic solution process (Monte Carlo Model) as applied to the determination of interference delays for synchronized multiple machine assignments on semiautomatic machines. Throughout the study it was felt by the author that this model would prove to more realistically portray such a man and machine system than the deterministic models which are available.

The stochastic model proved to provide statistically significant results in this particular application. However, this significance is immaterial from the practitioner's point of view in all but two instances. The models of Wright and Duvall provide solutions which are beyond acceptable tolerance limits. Feasible solutions are provided for this type of assignment by the Jones, Sandberg and Stochastic Simulator models.

The author feels that the Stochastic Computer Model, which was constructed for this investigation, has a utility beyond that of determining interference allowances for an incentive system. It can be used with great power to determine operator delays, to estimate the productivity of particular man and machine systems, and to evaluate the effects of proposed changes in equipment and operating procedures.

## 7. AREAS FOR FURTHER STUDY

The results of this study indicate that a portion of any future research effort in this field should be spent on the all important problem of writing computer programs for performing this type of simulation experiment.

The model of this thesis was programmed using the well-known general purpose Fortran language. This approach offered the author maximum flexibility in

1. the design and formulation of the mathematical model of the system.
2. the type and format of output reports generated.

The shortcoming of this approach is the difficulty which is encountered in writing the simulation program. The practitioner can easily become entangled in the complexities of the required sequencing control for the interdependent actions of the model. These complexities provide an opportunity for the occurrence of minor errors which are liable to be obscured.

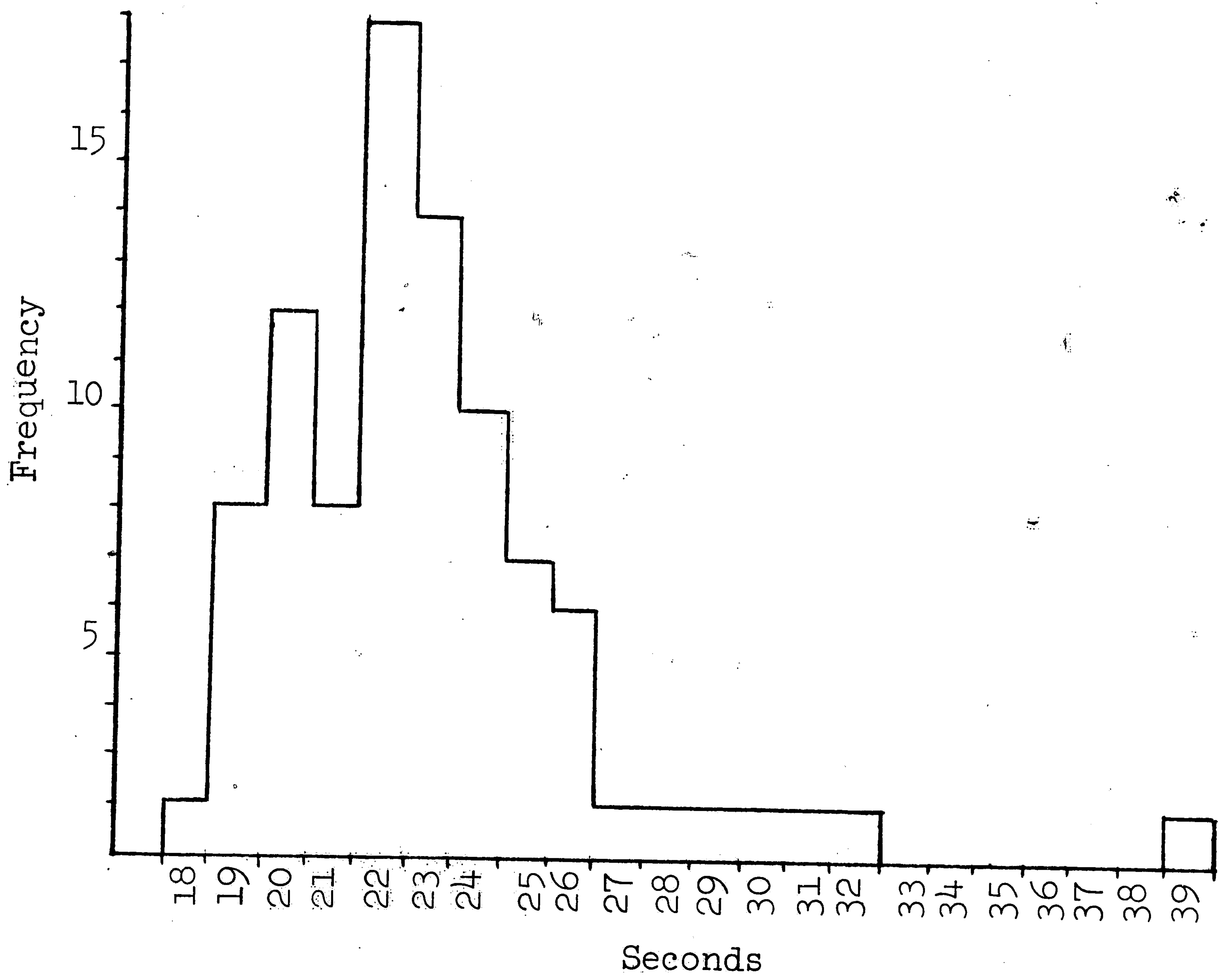
Future investigators should consider the use of one of the more recently developed special purpose simulation languages (SIMSCRIPT, GASP, SIMPAC) that are aimed at simplifying the task of writing simulation programs.

# APPENDIX A

# OPERATOR WORK ELEMENT DISTRIBUTIONS

"External Work Element"
Frequency Distribution

| (Class Interval) Seconds | (Number of Observations) Frequency |
|---|---|
| 17.5-18.5 | 1 |
| 18.5-19.5 | 7 |
| 19.5-20.5 | 11 |
| 20.5-21.5 | 7 |
| 21.5-22.5 | 17 |
| 22.5-23.5 | 13 |
| 23.5-24.5 | 9 |
| 24.5-25.5 | 6 |
| 25.5-26.5 | 5 |
| 26.5-27.5 | 1 |
| 27.5-28.5 | 1 |
| 28.5-29.5 | 1 |
| 29.5-30.5 | 1 |
| 30.5-31.5 | 1 |
| 31.5-32.5 | 1 |
| 32.5-33.5 | 0 |
| 33.5-34.5 | 0 |
| 34.5-35.5 | 0 |
| 35.5-36.5 | 0 |
| 36.5-37.5 | 0 |
| 37.5-38.5 | 0 |
| 38.5-39.5 | 1 |



"External Work Element"
Computation of Average and Standard Deviation

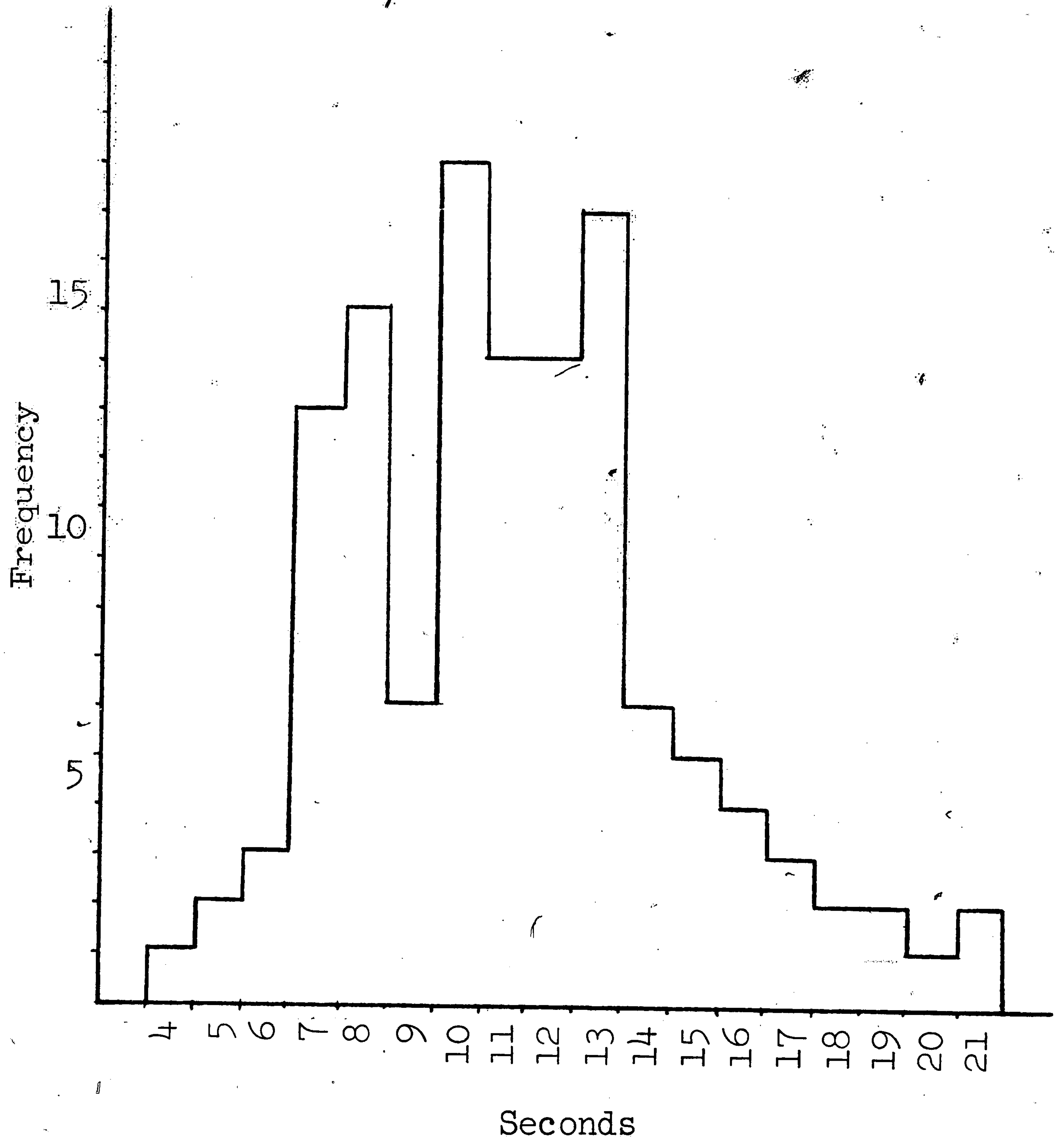
| Class Interval Seconds | Number of Observations Frequency f | Deviation from Assumed Mean d | fd | $f(d)^2$ |
|---|---|---|---|---|
| 17.5-18.5 | 1 | 10 | 10 | 100 |
| 18.5-19.5 | 7 | 9 | 63 | 567 |
| 19.5-20.5 | 11 | 8 | 88 | 704 |
| 20.5-21.5 | 7 | 7 | 49 | 343 |
| 21.5-22.5 | 17 | 6 | 102 | 612 |
| 22.5-23.5 | 13 | 5 | 65 | 325 |
| 23.5-24.5 | 9 | 4 | 36 | 144 |
| 24.5-25.5 | 6 | 3 | 18 | 54 |
| 25.5-26.5 | 5 | 2 | 10 | 20 |
| 26.5-27.5 | 1 | 1 | 1 | 1 |
| 27.5-28.5 | 1 | 0 | 0 | 0 |
| 28.5-29.5 | 1 | -1 | -1 | 1 |
| 29.5-30.5 | 1 | -2 | -2 | 4 |
| 30.5-31.5 | 1 | -3 | -3 | 9 |
| 31.5-32.5 | 1 | -4 | -4 | 16 |
| 32.5-33.5 | 0 | -5 | 0 | 0 |
| 33.5-34.5 | 0 | -6 | 0 | 0 |
| 34.5-35.5 | 0 | -7 | 0 | 0 |
| 35.5-36.5 | 0 | -8 | 0 | 0 |
| 36.5-37.5 | 0 | -9 | 0 | 0 |
| 37.5-38.5 | 0 | -10 | 0 | 0 |
| 38.5-39.5 | 1 | -11 | -11 | 121 |
|  | $\Sigma = 83$ |  | $\Sigma = 421$ | $\Sigma = 3021$ |

$$\bar{x} = AM - \frac{\Sigma fd}{N} = 28.00 - \frac{421}{83} = 22.93 \text{ sec.}$$

$$s = \sqrt{\frac{\Sigma f(d)^2}{N} - \left(\frac{\Sigma fd}{N}\right)^2} = \sqrt{\frac{3021}{83} - \left(\frac{421}{83}\right)^2} = 3.27 \text{ sec.}$$

"Internal Work Element"
Frequency Distribution

| (Class Interval)<br>Seconds | (Number of Observations)<br>Frequency |
|---|---|
| 3.5- 4.5 | 1 |
| 4.5- 5.5 | 2 |
| 5.5- 6.5 | 3 |
| 6.5- 7.5 | 12 |
| 7.5- 8.5 | 14 |
| 8.5- 9.5 | 6 |
| 9.5-10.5 | 17 |
| 10.5-11.5 | 13 |
| 11.5-12.5 | 13 |
| 12.5-13.5 | 16 |
| 13.5-14.5 | 6 |
| 14.5-15.5 | 5 |
| 15.5-16.5 | 4 |
| 16.5-17.5 | 3 |
| 17.5-18.5 | 2 |
| 18.5-19.5 | 2 |
| 19.5-20.5 | 1 |
| 20.5-21.5 | 2 |



## "Internal Work Element"
## Computation of Average and Standard Deviation

| Class Interval Seconds | Number of Observations Frequency f | Deviation from Assumed Mean d | fd | $f(d)^2$ |
|---|---|---|---|---|
| 3.5- 4.5 | 1 | 9 | 9 | 81 |
| 4.5- 5.5 | 2 | 8 | 16 | 128 |
| 5.5- 6.5 | 3 | 7 | 21 | 147 |
| 6.5- 7.5 | 12 | 6 | 72 | 432 |
| 7.5- 8.5 | 14 | 5 | 70 | 350 |
| 8.5- 9.5 | 6 | 4 | 24 | 96 |
| 9.5-10.5 | 17 | 3 | 51 | 153 |
| 10.5-11.5 | 13 | 2 | 26 | 52 |
| 11.5-12.5 | 13 | 1 | 13 | 13 |
| 12.5-13.5 | 16 | 0 | 0 | 0 |
| 13.5-14.5 | 6 | -1 | -6 | 6 |
| 14.5-15.5 | 5 | -2 | -10 | 20 |
| 15.5-16.5 | 4 | -3 | -12 | 36 |
| 16.5-17.5 | 3 | -4 | -12 | 48 |
| 17.5-18.5 | 2 | -5 | -10 | 50 |
| 18.5-19.5 | 2 | -6 | -12 | 72 |
| 19.5-20.5 | 1 | -7 | -7 | 49 |
| 20.5-21.5 | 2 | -8 | -16 | 128 |
|  | $\Sigma =$ 122 |  | $\Sigma =$ 217 | $\Sigma =$ 1861 |

$$\bar{x} = AM - \frac{\Sigma fd}{N} = 13.00 - \frac{217}{122} = 11.22 \text{ sec.}$$

$$s = \sqrt{\frac{\Sigma f(d)^2}{N} - \left(\frac{\Sigma fd}{N}\right)^2} = \sqrt{\frac{1861}{122} - \left(\frac{217}{122}\right)^2} = 3.47 \text{ sec.}$$

# APPENDIX B

# APPROXIMATE INTEGRATION COMPUTER PROGRAM

## Program Variable Name Definitions

K = parameter k of the gamma distribution

A = parameter $\alpha$ of the gamma distribution

X = integration starting point

E = integration ending point

AREA = computed area of the inscribed trapezoid within the interval considered.

SUM = computed cumulative area of the distribution to the last interval point considered.

SOURCE PROGRAM LISTING

```
 TITLEAREA
C         THIS PROGRAM USES THE TRAPEZOIDAL RULE OF APPROXIMATE
C         INTEGRATION TO DETERMINE THE AREA UNDER A GAMMA
C         DISTRIBUTION WITH PARAMETERS K AND A .
      READ 1, K,A,X,E
    1 FORMAT (I8,F8.2,F8.2,F8.2)
      PRINT 2
    2 FORMAT (1H1)
      PRINT 3
    3 FORMAT (11X,31H TABLE OF AREAS UNDER THE GAMMA,-
     1 12H DISTRIBUTION,/)
      PRINT 4, K,A
    4 FORMAT (16X,2HK=,1X,I2,10X,2HA=,1X,F6.2,/)
      PRINT 5, X,E
    5 FORMAT (16X,3HX1=,1X,F6.2,10X,3HX2=,1X,F6.2,/)
      PRINT 6
    6 FORMAT (4X,20HINTEGRATION INTERVAL,5X,13HINTERVAL AREA,
     1 5X,9HCUM. AREA,/)
      C = K
      S = X
      V = 0.0
      P = 0.0
      Z = 0.0
      Y = 0.0
      AREA = 0.0
      TOT = 0.0
      SUM = 0.0
      N = K - 1
      DIV = 1.0
      B = 1.0
      DO 7 I= 1,N
      DIV = DIV * B
      B = B + 1.0
    7 CONTINUE
    8 Z = (( A**C)*( EXPF (-A*X))) / DIV
      Y = Z*(X**(C-1.0))
      IF (X-S) 10, 9, 10
   10 AREA = (.5)*(W+Y)*(.02)
    9 W = Y
      X = X + .02
      V = V + 1.0
      TOT = TOT + AREA
      IF (V-50.) 8, 11, 11
   11 SUM = SUM + TOT
      P = X- 1.0
      PRINT 12, P, X, TOT, SUM
   12 FORMAT (6X,F6.2,3H - ,F6.2,7X,E18.9,1X,E18.9,/)
      P = 0.0
```

```
   V = 0.0
   TOT = 0.0
   IF (X-E) 8, 13,13
13 STOP
   END
```

# APPENDIX C

# COMPUTER GENERATED AREA TABLES

## Table of Areas Under the Gamma Distribution

K = 48 A = 2.12

$X_1$ = 16.50 $X_2$ = 40.50

| Integration Interval | Interval Area | Cum. Area |
|---|---|---|
| 16.50 - 17.50 | .265064400E-01 | .265064400E-01 |
| 17.50 - 18.50 | .472092300E-01 | .737156700E-01 |
| 18.50 - 19.50 | .718280200E-01 | .145543600E-00 |
| 19.50 - 20.50 | .960706200E-01 | .241614200E+00 |
| 20.50 - 21.50 | .114354400E+00 | .355968600E+00 |
| 21.50 - 22.50 | .122435500E+00 | .478404100E+00 |
| 22.50 - 23.50 | .119013800E+00 | .597417900E+00 |
| 23.50 - 24.50 | .105888000E+00 | .703305900E+00 |
| 24.50 - 25.50 | .868451000E-01 | .790151000E+00 |
| 25.50 - 26.50 | .660758700E-01 | .856226800E+00 |
| 26.50 - 27.50 | .469022600E-01 | .903129000E+00 |
| 27.50 - 28.50 | .312152100E-01 | .934344200E+00 |
| 28.50 - 29.50 | .195653500E-01 | .953909500E+00 |
| 29.50 - 30.50 | .115972000E-01 | .965506700E+00 |
| 30.50 - 31.50 | .652398100E-02 | .972030600E+00 |
| 31.50 - 32.50 | .349451400E-02 | .975525100E+00 |
| 32.50 - 33.50 | .178772000E-02 | .977312800E+00 |
| 33.50 - 34.50 | .875829200E-03 | .978188600E+00 |
| 34.50 - 35.50 | .411966600E-03 | .978600500E+00 |
| 35.50 - 36.50 | .186466800E-03 | .978786900E+00 |
| 36.50 - 37.50 | .813874300E-04 | .978868200E+00 |
| 37.50 - 38.50 | .343207900E-04 | .978902500E+00 |
| 38.50 - 39.50 | .140083400E-04 | .978916500E+00 |
| 39.50 - 40.50 | .554316200E-05 | .978922000E+00 |

### Table of Areas Under the Gamma Distribution

K = 10 A = 0.92

$X_1$ = 2.50 $X_2$ = 22.50

| Integration Interval | Interval Area | Cum. Area |
|---|---|---|
| 2.50 - 3.50 | 0.162443914E-02 | 0.162443914E-02 |
| 3.50 - 4.50 | 0.809950025E-02 | 0.972393938E-02 |
| 4.50 - 5.50 | 0.234948367E-01 | 0.332187761E-01 |
| 5.50 - 6.50 | 0.479442045E-01 | 0.811629806E-01 |
| 6.50 - 7.50 | 0.763975060E-01 | 0.157560487E+00 |
| 7.50 - 8.50 | 0.101380227E+00 | 0.258940713E+00 |
| 8.50 - 9.50 | 0.116879812E+00 | 0.375820525E+00 |
| 9.50 - 10.50 | 0.120543105E+00 | 0.496363630E+00 |
| 10.50 - 11.50 | 0.113578637E+00 | 0.609942267E+00 |
| 11.50 - 12.50 | 0.993080321E-01 | 0.709250299E+00 |
| 12.50 - 13.50 | 0.815409699E-01 | 0.790791269E+00 |
| 13.50 - 14.50 | 0.634601889E-01 | 0.854251458E+00 |
| 14.50 - 15.50 | 0.471587458E-01 | 0.901410204E+00 |
| 15.50 - 16.50 | 0.336622595E-01 | 0.935072463E+00 |
| 16.50 - 17.50 | 0.231932156E-01 | 0.958265679E+00 |
| 17.50 - 18.50 | 0.154871012E-01 | 0.973752780E+00 |
| 18.50 - 19.50 | 0.100563796E-01 | 0.983809160E+00 |
| 19.50 - 20.50 | 0.636825612E-02 | 0.990177416E+00 |
| 20.50 - 21.50 | 0.394248245E-02 | 0.994119898E+00 |
| 21.50 - 22.50 | 0.239113590E-02 | 0.996511034E+00 |

# APPENDIX D

# CHI-SQUARE "GOODNESS OF FIT" TESTS

## CHI-SQUARE TEST FOR GOODNESS OF FIT

"External Work Element"

Gamma Distribution Fit ( K= 48, A= 2.12)

| Cell Interval (Seconds) | Actual Frequency ($f_o$) | Theoretical Frequency ($f$) | $(f_o-f)$ | $(f_o-f)^2$ | $\frac{(f_o-f)^2}{f}$ |
|---|---|---|---|---|---|
| 17.5-18.5 | 1 | 3.9 | -1.9 | 3.58 | .362 |
| 18.5-19.5 | 7 | 6.0 | | | |
| 19.5-20.5 | 11 | 8.0 | 3.0 | 9.00 | 1.125 |
| 20.5-21.5 | 7 | 9.5 | -2.5 | 6.25 | .675 |
| 21.5-22.5 | 17 | 10.2 | 6.8 | 46.24 | 4.540 |
| 22.5-23.5 | 13 | 9.9 | 3.1 | 9.61 | .972 |
| 23.5-24.5 | 9 | 8.8 | .2 | .04 | .005 |
| 24.5-25.5 | 6 | 7.2 | -1.2 | 1.44 | .200 |
| 25.5-26.5 | 5 | 5.5 | - .5 | .25 | .046 |
| 26.5-27.5 | 1 | 3.9 | -3.1 | 9.61 | .950 |
| 27.5-28.5 | 1 | 2.6 | | | |
| 28.5-29.5 | 1 | 1.6 | | | |
| 29.5-30.5 | 1 | 1.0 | | | |
| 30.5-31.5 | 1 | .5 | | | |
| 31.5-32.5 | 1 | .3 | | | |
| 32.5-33.5 | 0 | .1 | | | |
| 33.5-34.5 | 0 | .1 | | | |
| 34.5-35.5 | 0 | 0 | | | |
| 35.5-36.5 | 0 | 0 | | | |
| 36.5-37.5 | 0 | 0 | | | |
| 37.5-38.5 | 0 | 0 | | | |
| 38.5-39.5 | 1 | 0 | | | |

CHI-SQUARE = 8.875

Degrees of freedom = 9 intervals - 1 - 4 (number of parameters estimated from sample)

Degrees of freedom = 4

From table (5), CHI-SQUARE = 9.49

Since the observed value of 8.88 is smaller than 9.49, we accept, at the 5 percent level of significance, the hypothesis that the distribution is a gamma distribution with parameters K = 48, A = 2.12 .

## CHI-SQUARE TEST FOR GOODNESS OF FIT

"Internal Work Element"

Gamma Distribution Fit (K = 10, A = .92)

| Cell Interval (Seconds) | Actual Frequency ($f_o$) | Theoretical Frequency ($f$) | $(f_o-f)$ | $(f_o-f)^2$ | $\frac{(f_o-f)^2}{f}$ |
|---|---|---|---|---|---|
| 3.5- 4.5 | 1 | 1.0 | - .9 | .81 | .208 |
| 4.5- 5.5 | 2 | 2.9 | | | |
| 5.5- 6.5 | 3 | 5.8 | -2.8 | 7.84 | 1.350 |
| 6.5- 7.5 | 12 | 9.3 | 2.7 | 7.29 | .784 |
| 7.5- 8.5 | 14 | 12.4 | 1.6 | 2.56 | .206 |
| 8.5- 9.5 | 6 | 14.2 | 8.2 | 67.24 | 4.730 |
| 9.5-10.5 | 17 | 14.7 | 2.3 | 5.29 | .360 |
| 10.5-11.5 | 13 | 13.8 | - .8 | .64 | .046 |
| 11.5-12.5 | 13 | 12.1 | .9 | .81 | .067 |
| 12.5-13.5 | 16 | 10.0 | 6.0 | 36.00 | 3.600 |
| 13.5-14.5 | 6 | 7.7 | -1.7 | 2.89 | .376 |
| 14.5-15.5 | 5 | 5.7 | - .7 | .49 | .086 |
| 15.5-16.5 | 4 | 4.1 | - .1 | .01 | .002 |
| 16.5-17.5 | 3 | 2.8 | .2 | .04 | .014 |
| 17.5-18.5 | 2 | 1.9 | .1 | .01 | .005 |
| 18.5-19.5 | 2 | 1.2 | 2.5 | 6.25 | 2.500 |
| 19.5-20.5 | 1 | .8 | | | |
| 20.5-21.5 | 2 | .5 | | | |

CHI-SQUARE = 14.334

Degrees of freedom = 15 intervals - 1 - 4 (number of parameters estimated from sample)

Degrees of freedom = 0

From table (5), CHI-SQUARE = 18.31

Since the observed value of 14.33 is smaller than 18.31, we accept, at the 5 per cent level of significance, the hypothesis that the distribution is a gamma distribution with parameters K = 10, A = .92.

# APPENDIX E

# SYNCHRONIZED MULTIPLE MACHINE ASSIGNMENT SIMULATION COMPUTER PROGRAM

)

## Subroutine and Main Program
## Variable Name Definitions

Subroutine RANDOM (SEED, RAND)

SEED = input-transfer of control variable

RAND = input-initial random number to begin sequence (43839901)

output-next computed random number

Subroutine GAMMA (K, A, X)

RAND = input-computed random number by Subroutine RANDOM (SEED, RAND)

K = parameter k of the gamma distribution

A = parameter $\alpha$ of the gamma distribution

X = output - computed gamma variate

Main Program SIMULA

All terms defined on source program listing

# SOURCE PROGRAM LISTING

```
      SUBROUTINE RANDOM (SEED, RAND)
C        THIS SUBROUTINE GENERATES A SEQUENCE OF PSEUDO-RANDOM NUMBERS
C        USING A MULTIPLICATIVE CONGRUENTIAL METHOD
C        CALLING SEQUENCE
C           SEED   INPUT  TRANSFER OF CONTROL VARIABLE
C                         IF SEED = ZERO, RANDOM WILL SET SEED = 1.0
C                         RANDOM WILL THEN READ A CARD TO DETERMINE AN
C                         INITIAL VALUE FOR RAND AND THEN COMPUTE RAND.
C                         IF SEED DOES NOT EQUAL ZERO, RANDOM WILL
C                         COMPUTE THE NEXT RAND IN THE SEQUENCE
C           RAND   INPUT  INITIAL VALUE WHEN SEED EQUALS ZERO
C                  OUTPUT RANDOM NUMBER
      COMMON SEED, K, A, X, RAND
      IF (SEED) 3, 1, 3
    1 SEED = 1.0
      READ 2, RAND
    2 FORMAT (F10.8)
    3 RAND = RAND * 83.
      RN = INTF (RAND)
      RAND = RAND - RN
      RETURN
      END
```

# SOURCE PROGRAM LISTING

```
      SUBROUTINE GAMMA (K,A,X)
C        THIS SUBROUTINE GENERATES A STOCHASTIC GAMMA VARIATE FROM THE
C        CONTINUOUS GAMMA PROBABILITY DISTRIBUTION WITH PARAMETERS K
C        AND A.
      COMMON SEED, K, A, X, RAND
      TR = 1.0
      DO 2 I=1,K
      CALL RANDOM (SEED,RAND)
    2 TR = TR * RAND
      X = -LOGF (TR)/A
      RETURN
      END
```

# SOURCE PROGRAM LISTING

```
 TITLESIMULA
C    THIS PROGRAM SIMULATES THE OPERATION OF A STOCHASTIC MODEL FOR
C    SYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE ASSIGNMENTS.
C    A. STOCHASTIC MODEL TERMS
C        SUBSCRIPT (I)= ITH MACHINE (N)= TOTAL NO. OF MACHINES
C                  (J)= JTH CYCLE
C       CYCLE DEFINITION - THE CYCLE BEGINS AT THE MOMENT THAT THE
C        OPERATOR BEGINS TO UNLOAD-LOAD MACHINE NO. 1 AND ENDS AT
C        THE MOMENT WHEN HE BEGINS AGAIN TO UNLOAD-LOAD THIS MACHINE.
C          C(J)= LENGTH OF CYCLE
C        P(I,J)= MACHINE PROCESS TIME (CONSTANT)
C        O(I,J)= OPERATOR UNLOAD-LOAD TIME VARIABLE
C       RI(I,J)= REQUIRED INTERNAL WORK TIME VARIABLE (STARTED AT
C                THE BEGINNING OF THE MACHINE PROCESS TIME.)
C       AIDLE(I,J)= APPARATUS(MACHINE) IDLE TIME
C       OIDLE(I,J)= OPERATOR IDLE TIME
C    B. STOCHASTIC MODEL STRUCTURE (RECURSIVE RELATIONSHIP)
C         C(J)= O(1,J) + P(1,J) + AIDLE(1,J)
C          AND
C         C(J)= O(1,J)+RI(1,J)+OIDLE(2,J)+O(2,J)+RI(2,J)+...+
C                OIDLE(N,J)+)(N,J)+RI(N,J)+OIDLE(1,J)
C    C. PROGRAM INITIALIZATION
C         SET (SEED), RANDOM SUBROUTINE TRANSFER OF CONTROL VARIABLE,
C             TO ZERO.
C         CLEAR ALL OPERATION TIME ACCUMULATORS AND COUNTERS
C             EOT = ELAPSED OPERATION RUN TIME
      COMMON SEED ,K,A,X, RAND
      DIMENSION AIDLE (25),OIDLE(25),RI(25),O(25),Z(25),AAIDLE(25),
     1PERAA(25), PERAAT(25)
    5 ERASE (AIDLE,OIDLE,RI,O,Z,AAIDLE,PERAA,PERAAT)
      SEED = 0.0
      EOT = 0.0
      OIDLET = 0.0
      NUP = 0.0
      PERC = 0.0
      EOTC = 0.0
      ACL = 0.0
      TOTAL = 0.0
      AMIT = 0.0
      PAMIT = 0.0
      PERCT = 0.0
      WAIT = 0.0
      READ 10, PER, N
   10 FORMAT (A3, 1X, I2)
      IF END OF FILE 220, 15
   15 PRINT 20
   20 FORMAT (1H1)
      PRINT 30
```

```
   30 FORMAT (22X,22HMONTE CARLO SIMULATION)
      PRINT 40
   40 FORMAT (6X,43HSYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE,
     111H ASSIGNMENT//)
      PRINT 45
   45 FORMAT (26X,14HRUN STATISTICS/)
      PRINT 50
   50 FORMAT(5X,17HSIMULATION LEVEL-)
      PRINT 60, PER
   60 FORMAT (10X,A3,1X,37H PERCENT OPERATOR ATTENTION TIME/TOTAL,
     16HCYCLE/)
      PRINT 61
   61 FORMAT (10X, 39HAVERAGE MACHINE IDLE TIME/SERVICE CYCLE/)
C       D. 1ST CYCLE SIMULATION
      J= 1
      READ 70, KE, AE, KI,AI, M
   70 FORMAT (I4,2X,F6.2,2X,I4,2X,F6.2,2X,I6)
      READ 80, P
   80 FORMAT (F6.2)
      K = KI
      A = AI
      CALL GAMMA (K,A,X)
      RI(1) = X
      EOT = EOT + RI(1)
      DO 90 I = 2, N
      OIDLE (I) = 0.0
      K = KE
      A = AE
      CALL GAMMA (K,A,X)
      O(I) = X
      EOT = EOT + O(I)
      K = KI
      A = AI
      CALL GAMMA (K,A,X)
      RI(I) = X
   90 EOT = EOT + RI(I)
C       E. MAJOR PROGRAM - REITERATE FOR M CYCLES
  100 DO 160 I = 1, N
      Z(I) = P
      SUB = 0.0
      DO 120 L = 1, N
      IF (L-I) 110, 120, 110
  110 SUB = SUB + OIDLE(L) + O(L) + RI(L)
  120 CONTINUE
      Z(I) = Z(I) - RI(I) - SUB
      IF (Z(I)) 130, 145, 140
  130 Z(I) = -Z(I)
      WAIT = WAIT + Z(I)
      AIDLE(I) = AIDLE(I) + Z(I)
      OIDLE (I) = 0.0
      GO TO 150
```

```
140 OIDLET = OIDLET + Z(I)
    EOT = EOT + Z(I)
    OIDLE(I) = Z(I)
    GO TO 150
145 OIDLE(I) = 0.0
150 K = KE
    A = AE
    CALL GAMMA (K, A, X)
    O(I) = X
    EOT = EOT + O(I)
    K = KI
    A = AI
    CALL GAMMA (K, A, X)
    RI(I) = X
    EOT = EOT + RI(I)
160 CONTINUE
    VAR = FLOATF (N)
    AVE = (WAIT/VAR)
    PRINT 161, J, AVE
161 FORMAT (15X, I3, 2X, F12.5,1X, 4HSEC.,/)
    IF (M-J) 170, 180, 170
170 J = J + 1
    WAIT = 0.0
    GO TO 100
C     C. SUMMARY OF COMPLETED SIMULATION RUN
180 EOTC = EOT/3600.
    PRINT 181, N
181 FORMAT (5X,19HNUMBER OF MACHINES =,26X,I2,/)
    PRINT 182, M
182 FORMAT (5X,40HTOTAL NUMBER OF OPERATOR SERVICE CYCLES=,
   11X,I6,/)
    PRINT 183, EOTC
183 FORMAT (5X,23HELAPSED OPERATION TIME=,15X,F12.5,2X,3HHR.,/)
    Y = FLOATF (M)
    ACL = EOT/Y
    NUP = M * N
    PRINT 184, NUP
184 FORMAT (5X,31HTOTAL NUMBER OF UNITS PRODUCED=,6X,I10,/)
    PRINT 185, ACL
185 FORMAT (5X,21HAVERAGE CYCLE LENGTH=,17X,F12.5,2X,4HSEC.,/)
    AOIDLE = OIDLET/Y
    PERC = (AOIDLE/ACL)*100.
    PRINT 186, AOIDLE
186 FORMAT (5X,33HAVERAGE OPERATOR IDLE TIME/CYCLE=,5X,F12.5,2X,
   12X,4HSEC.,/)
    PRINT 187, PERC
187 FORMAT (5X,41HPERCENT AVERAGE OPERATOR IDLE TIME/CYCLE=,
   12X,F7.2,/)
    PERCT = (OIDLET/EOT) * 100.
    PRINT 188, PERCT
```

```
188 FORMAT (5X,31HPERCENT OPERATOR IDLE TIME/RUN=,12X,F7.2,/)
    PRINT 189
189 FORMAT (5X,42HMACHINE IDLE TIME/INDIVIDUAL MACHINE/CYCLE,/)
    PRINT 190
190 FORMAT (31X,10HSEC./CYCLE,6X,13HPERCENT/CYCLE)
    DO 205 I = 1, N
    AAIDLE(I) = AIDLE(I)/Y
    PERAA(I) = (AAIDLE(I)/ACL)*100.
205 PRINT 210, I, AAIDLE(I), PERAA(I)
210 FORMAT (12X,11HMACHINE NO.,1X,I2,3X,F12.5,7X,F7.2)
    PRINT 211
211 FORMAT (1H2)
    PRINT 212
212 FORMAT (5X,36HPERCENT MACHINE IDLE TIME/INDIVIDUAL,
  112HMACHINE/RUN)
    DO 213 I= 1,N
    PERAAT(I) = (AIDLE(I)/EOT) * 100.
213 PRINT 214, I,PERAAT(I)
214 FORMAT (12X,11HMACHINE NO.,1X,I2,5X,F7.2)
    PRINT 215
215 FORMAT (1H2)
    DO 216 I=1,N
216 TOTAL = TOTAL + AAIDLE(I)
    W = FLOATF(N)
    AMIT = (TOTAL/W)
    PAMIT = (AMIT/ACL) * 100.
    PRINT 217, AMIT
217 FORMAT (5X,40HAVERAGE MACHINE IDLE TIME/MACHINE/CYCLE=,
  1,1X,F12.5,1X,4HSEC.,/)
    PRINT 218, PAMIT
218 FORMAT (5X,48HPERCENT AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE=,
  11X,F7.2)
    GO TO 5
220 STOP
    END
```

## Ordering of Job Deck for Computer Run

## (Fortran II - Honeywell 400 System)

1. EXECUTE Primary Control Card
2. Main Program SIMULA Binary Deck
3. PREFERRED Secondary Control Card
4. Subroutine GAMMA (K, A, X) Binary Deck
5. Subroutine RANDOM (SEED, RAND) Binary Deck
6. JOBEND Secondary Control Card
7. Input Data Deck
    - a. Simulation Level, No. of Machines
    - b. External & Internal Values of K & A, Number of simulation cycles
    - c. Machine Process Time
    - d. Initial Random Number
8. FINIS Control Card

# APPENDIX F

# CALCULATION OF SIMULATION SAMPLE SIZE

# CALCULATION OF SIMULATION SAMPLE SIZE

This computation is made to achieve assurance of 95 in 100 that the population average element time lies within ±5 per cent of the estimated observed value $\bar{x}$ from a sample size of N.

$$2\sigma_{\bar{x}} = 0.050\ \bar{x}$$

$$\sigma_{\bar{x}} = \frac{\sigma'_x}{N}$$

$$\frac{\sigma'_x}{\sqrt{N}} = \frac{0.050\ \bar{x}}{2}$$

$$N = \left(\frac{2\ \sigma'_x}{.050\ \bar{x}}\right)^2$$

External Manual Element

$V(X) = 10.83 \qquad \sigma'_x = 3.44 \qquad \bar{x} = 22.93$ sec.

$$N = \left(\frac{2 \times 3.44}{.050 \times 22.93}\right)^2 = 36 \text{ samples}$$

Internal Manual Element

$V(X) = 12.18 \qquad \sigma'_x = 3.49 \qquad \bar{x} = 11.22$ sec.

$$N = \left(\frac{2 \times 3.49}{.050 \times 11.22}\right)^2 = 155 \text{ samples}$$

The selected sample size must be the larger of these two calculations (155).

# APPENDIX G

# COMPUTER SIMULATION PERFORMANCE STATISTICS

# MONTE CARLO SIMULATION

## SYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE ASSIGNMENT

## RUN STATISTICS

SIMULATION LEVEL -

10 PERCENT OPERATOR ATTENTION TIME/TOTAL CYCLE

AVERAGE MACHINE IDLE TIME/SERVICE CYCLE

| | |
|---|---|
| 1 | 0.26520 SEC. |
| 2 | 0.84138 SEC. |
| 3 | 0.92061 SEC. |
| 4 | 1.65991 SEC. |
| 5 | 2.98338 SEC. |
| 6 | 1.65368 SEC. |
| 7 | 0.37459 SEC. |
| 8 | 0.00000 SEC. |
| 9 | 0.00000 SEC. |
| 10 | 0.73064 SEC. |
| 11 | 0.06576 SEC. |
| 12 | 1.41882 SEC. |
| 13 | 0.72507 SEC. |
| 14 | 0.28471 SEC. |
| 15 | 0.00000 SEC. |
| 16 | 0.84989 SEC. |
| 17 | 0.00000 SEC. |
| 18 | 0.00000 SEC. |
| 19 | 0.00000 SEC. |
| 20 | 1.86180 SEC. |
| 21 | 0.14774 SEC. |
| 22 | 1.19775 SEC. |
| 23 | 2.73652 SEC. |
| 24 | 0.00000 SEC. |
| 25 | 0.47378 SEC. |
| 26 | 0.00000 SEC. |
| 27 | 0.00000 SEC. |
| 28 | 0.72639 SEC. |
| 29 | 0.00000 SEC. |
| 30 | 0.00000 SEC. |
| 31 | 0.00000 SEC. |
| 32 | 0.00000 SEC. |
| 33 | 0.00000 SEC. |
| 34 | 0.00000 SEC. |
| 35 | 0.00000 SEC. |
| 36 | 0.00000 SEC. |
| 37 | 0.00000 SEC. |
| 38 | 0.00000 SEC. |

| | |
|---|---|
| 39 | 0.00000 SEC. |
| 40 | 0.34780 SEC. |
| 41 | 1.15782 SEC. |
| 42 | 0.42267 SEC. |
| 43 | 0.00000 SEC. |
| 44 | 0.00000 SEC. |
| 45 | 0.00000 SEC. |
| 46 | 0.00000 SEC. |
| 47 | 0.00000 SEC. |
| 48 | 0.00000 SEC. |
| 49 | 0.00000 SEC. |
| 50 | 0.00000 SEC. |
| 51 | 0.00000 SEC. |
| 52 | 0.00000 SEC. |
| 53 | 0.00000 SEC. |
| 54 | 0.00000 SEC. |
| 55 | 0.00000 SEC. |
| 56 | 0.00000 SEC. |
| 57 | 0.00000 SEC. |
| 58 | 0.00000 SEC. |
| 59 | 0.00000 SEC. |
| 60 | 0.00000 SEC. |
| 61 | 0.00000 SEC. |
| 62 | 0.00000 SEC. |
| 63 | 0.00000 SEC. |
| 64 | 0.00000 SEC. |
| 65 | 0.00000 SEC. |
| 66 | 0.00000 SEC. |
| 67 | 0.00000 SEC. |
| 68 | 0.00000 SEC. |
| 69 | 0.00000 SEC. |
| 70 | 0.00000 SEC. |
| 71 | 0.03371 SEC. |
| 72 | 0.00000 SEC. |
| 73 | 0.00000 SEC. |
| 74 | 0.00000 SEC. |
| 75 | 0.00000 SEC. |
| 76 | 0.00000 SEC. |
| 77 | 0.00000 SEC. |
| 78 | 0.00000 SEC. |
| 79 | 0.00000 SEC. |
| 80 | 0.00000 SEC. |
| 81 | 0.00000 SEC. |
| 82 | 0.00000 SEC. |
| 83 | 0.18280 SEC. |
| 84 | 1.63892 SEC. |
| 85 | 3.96470 SEC. |
| 86 | 1.45870 SEC. |
| 87 | 0.00000 SEC. |
| 88 | 0.00000 SEC. |

| | |
|---|---|
| 89 | 0.00000 SEC. |
| 90 | 0.00000 SEC. |
| 91 | 1.33966 SEC. |
| 92 | 2.52459 SEC. |
| 93 | 0.00000 SEC. |
| 94 | 0.00000 SEC. |
| 95 | 0.00000 SEC. |
| 96 | 0.00000 SEC. |
| 97 | 0.00000 SEC. |
| 98 | 0.00000 SEC. |
| 99 | 0.00000 SEC. |
| 100 | 0.00000 SEC. |
| 101 | 0.33878 SEC. |
| 102 | 0.00000 SEC. |
| 103 | 0.00000 SEC. |
| 104 | 0.00000 SEC. |
| 105 | 1.55707 SEC. |
| 106 | 2.20211 SEC. |
| 107 | 2.09133 SEC. |
| 108 | 0.00000 SEC. |
| 109 | 0.00000 SEC. |
| 110 | 0.00000 SEC. |
| 111 | 0.00000 SEC. |
| 112 | 0.00000 SEC. |
| 113 | 0.00000 SEC. |
| 114 | 0.00000 SEC. |
| 115 | 0.00000 SEC. |
| 116 | 0.00000 SEC. |
| 117 | 0.00000 SEC. |
| 118 | 0.00000 SEC. |
| 119 | 0.00000 SEC. |
| 120 | 0.00000 SEC. |
| 121 | 0.00000 SEC. |
| 122 | 0.00000 SEC. |
| 123 | 0.00000 SEC. |
| 124 | 0.00000 SEC. |
| 125 | 0.00000 SEC. |
| 126 | 0.00000 SEC. |
| 127 | 0.00000 SEC. |
| 128 | 0.00000 SEC. |
| 129 | 0.00000 SEC. |
| 130 | 0.00000 SEC. |
| 131 | 0.00000 SEC. |
| 132 | 0.00000 SEC. |
| 133 | 0.00000 SEC. |
| 134 | 0.00000 SEC. |
| 135 | 0.00000 SEC. |
| 136 | 0.00000 SEC. |
| 137 | 0.00000 SEC. |
| 138 | 0.00000 SEC. |

```
          139              0.00000 SEC.
          140              0.00000 SEC.
          141              0.00000 SEC.
          142              0.00000 SEC.
          143              0.00000 SEC.
          144              0.00000 SEC.
          145              0.00000 SEC.
          146              0.00000 SEC.
          147              0.00000 SEC.
          148              0.00000 SEC.
          149              0.00000 SEC.
          150              0.00000 SEC.
          151              0.00000 SEC.
          152              0.00000 SEC.
          153              0.00000 SEC.
          154              0.00000 SEC.
          155              0.00000 SEC.

NUMBER OF MACHINES =                                      3

TOTAL NUMBER OF OPERATOR SERVICE CYCLES =               155

ELAPSED OPERATION TIME =                           14.74089  HR.

TOTAL NUMBER OF UNITS PRODUCED =                        465

AVERAGE CYCLE LENGTH =                            342.36901  SEC.

AVERAGE OPERATOR IDLE TIME/CYCLE =                241.68986  SEC.

PERCENT AVERAGE OPERATOR IDLE TIME/CYCLE =            70.59

PERCENT OPERATOR IDLE TIME/RUN =                      70.59

MACHINE IDLE TIME/INDIVIDUAL MACHINE/CYCLE

                           SEC./CYCLE             PERCENT/CYCLE
   MACHINE NO.  1           0.00000                   0.00
   MACHINE NO.  2           0.22493                   0.07
   MACHINE NO.  3           0.53336                   0.16

PERCENT MACHINE IDLE TIME/INDIVIDUAL MACHINE/RUN

   MACHINE NO.  1           0.00
   MACHINE NO.  2           0.07
   MACHINE NO.  3           0.16

AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =                 0.25276 SEC.

PERCENT AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =            0.07
```

# MONTE CARLO SIMULATION

## SYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE ASSIGNMENT

## RUN STATISTICS

SIMULATION LEVEL -

25 PERCENT OPERATOR ATTENTION TIME/TOTAL CYCLE

AVERAGE MACHINE IDLE TIME/SERVICE CYCLE

| | |
|---|---|
| 1 | 0.26520 SEC. |
| 2 | 0.84138 SEC. |
| 3 | 0.92061 SEC. |
| 4 | 1.65991 SEC. |
| 5 | 2.98338 SEC. |
| 6 | 1.65368 SEC. |
| 7 | 0.37459 SEC. |
| 8 | 0.00000 SEC. |
| 9 | 0.00000 SEC. |
| 10 | 0.73064 SEC. |
| 11 | 0.06576 SEC. |
| 12 | 1.41882 SEC. |
| 13 | 0.72507 SEC. |
| 14 | 0.28471 SEC. |
| 15 | 0.00000 SEC. |
| 16 | 0.84989 SEC. |
| 17 | 0.00000 SEC. |
| 18 | 0.00000 SEC. |
| 19 | 0.00000 SEC. |
| 20 | 1.86180 SEC. |
| 21 | 0.14774 SEC. |
| 22 | 1.19775 SEC. |
| 23 | 2.73652 SEC. |
| 24 | 0.00000 SEC. |
| 25 | 0.47378 SEC. |
| 26 | 2.08149 SEC. |
| 27 | 0.00000 SEC. |
| 28 | 0.72639 SEC. |
| 29 | 0.00000 SEC. |
| 30 | 0.00000 SEC. |
| 31 | 0.00000 SEC. |
| 32 | 0.00000 SEC. |
| 33 | 0.00000 SEC. |
| 34 | 0.00000 SEC. |
| 35 | 0.00000 SEC. |
| 36 | 0.00000 SEC. |
| 37 | 1.38222 SEC. |
| 38 | 0.00000 SEC. |
| 39 | 0.00000 SEC. |

| | |
|---|---|
| 40 | 0.34780 SEC. |
| 41 | 1.15782 SEC. |
| 42 | 1.94421 SEC. |
| 43 | 0.00000 SEC. |
| 44 | 0.00000 SEC. |
| 45 | 2.22216 SEC. |
| 46 | 0.00000 SEC. |
| 47 | 5.45405 SEC. |
| 48 | 0.00000 SEC. |
| 49 | 0.00000 SEC. |
| 50 | 0.00000 SEC. |
| 51 | 0.00000 SEC. |
| 52 | 0.00000 SEC. |
| 53 | 0.85081 SEC. |
| 54 | 0.78741 SEC. |
| 55 | 2.36796 SEC. |
| 56 | 0.00000 SEC. |
| 57 | 0.03592 SEC. |
| 58 | 0.14693 SEC. |
| 59 | 0.79177 SEC. |
| 60 | 0.00000 SEC. |
| 61 | 3.74037 SEC. |
| 62 | 0.58983 SEC. |
| 63 | 1.99852 SEC. |
| 64 | 0.00000 SEC. |
| 65 | 0.00000 SEC. |
| 66 | 0.00000 SEC. |
| 67 | 0.00000 SEC. |
| 68 | 0.00000 SEC. |
| 69 | 3.28372 SEC. |
| 70 | 0.00000 SEC. |
| 71 | 1.28158 SEC. |
| 72 | 0.00000 SEC. |
| 73 | 0.00000 SEC. |
| 74 | 0.00000 SEC. |
| 75 | 0.23917 SEC. |
| 76 | 0.00000 SEC. |
| 77 | 0.18974 SEC. |
| 78 | 0.00000 SEC. |
| 79 | 0.00000 SEC. |
| 80 | 0.00000 SEC. |
| 81 | 0.00000 SEC. |
| 82 | 0.00000 SEC. |
| 83 | 0.61171 SEC. |
| 84 | 1.63892 SEC. |
| 85 | 3.96470 SEC. |
| 86 | 1.55657 SEC. |
| 87 | 4.29860 SEC. |
| 88 | 3.35180 SEC. |
| 89 | 0.00000 SEC. |

| | |
|---|---|
| 90 | 0.00000 SEC. |
| 91 | 3.50209 SEC. |
| 92 | 2.52459 SEC. |
| 93 | 0.00000 SEC. |
| 94 | 0.00000 SEC. |
| 95 | 0.00000 SEC. |
| 96 | 2.78849 SEC. |
| 97 | 0.00000 SEC. |
| 98 | 0.00000 SEC. |
| 99 | 0.00000 SEC. |
| 100 | 0.00000 SEC. |
| 101 | 1.20597 SEC. |
| 102 | 0.00000 SEC. |
| 103 | 0.68967 SEC. |
| 104 | 0.00000 SEC. |
| 105 | 1.55707 SEC. |
| 106 | 2.20211 SEC. |
| 107 | 3.99803 SEC. |
| 108 | 2.65131 SEC. |
| 109 | 0.00000 SEC. |
| 110 | 3.24913 SEC. |
| 111 | 0.00000 SEC. |
| 112 | 0.00000 SEC. |
| 113 | 0.00000 SEC. |
| 114 | 0.00000 SEC. |
| 115 | 0.00000 SEC. |
| 116 | 0.00000 SEC. |
| 117 | 0.00000 SEC. |
| 118 | 0.00000 SEC. |
| 119 | 0.00000 SEC. |
| 120 | 1.15643 SEC. |
| 121 | 0.00000 SEC. |
| 122 | 0.00000 SEC. |
| 123 | 0.00000 SEC. |
| 124 | 1.09335 SEC. |
| 125 | 0.00000 SEC. |
| 126 | 0.00000 SEC. |
| 127 | 0.00000 SEC. |
| 128 | 0.00000 SEC. |
| 129 | 0.00000 SEC. |
| 130 | 0.00000 SEC. |
| 131 | 0.00000 SEC. |
| 132 | 0.00000 SEC. |
| 133 | 0.00000 SEC. |
| 134 | 0.00000 SEC. |
| 135 | 0.00000 SEC. |
| 136 | 2.56813 SEC. |
| 137 | 0.00000 SEC. |
| 138 | 0.00000 SEC. |
| 139 | 0.00000 SEC. |

```
        140           2.36947 SEC.
        141           0.00000 SEC.
        142           0.00000 SEC.
        143           0.85564 SEC.
        144           0.15858 SEC.
        145           0.00000 SEC.
        146           0.00000 SEC.
        147           0.02567 SEC.
        148           0.00000 SEC.
        149           1.89234 SEC.
        150           0.00000 SEC.
        151           0.00000 SEC.
        152           0.00000 SEC.
        153           0.00000 SEC.
        154           0.00000 SEC.
        155           0.00000 SEC.

NUMBER OF MACHINES =                                      3

TOTAL NUMBER OF OPERATOR SERVICE CYCLES =               155

ELAPSED OPERATION TIME =                            5.92632  HR.

TOTAL NUMBER OF UNITS PRODUCED =                        465

AVERAGE CYCLE LENGTH =                            137.64354  SEC.

AVERAGE OPERATOR IDLE TIME/CYCLE =                 36.96439  SEC.

PERCENT AVERAGE OPERATOR IDLE TIME/CYCLE =            26.86

PERCENT OPERATOR IDLE TIME/RUN =                      26.86

MACHINE IDLE TIME/INDIVIDUAL MACHINE/CYCLE

                           SEC./CYCLE          PERCENT/CYCLE
     MACHINE NO.  1         0.53828                0.39
     MACHINE NO.  2         0.60328                0.44
     MACHINE NO.  3         0.80789                0.59

PERCENT MACHINE IDLE TIME/INDIVIDUAL MACHINE/RUN

     MACHINE NO.  1         0.39
     MACHINE NO.  2         0.44
     MACHINE NO.  3         0.59

AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =              0.64982 SEC.

PERCENT AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =           0.47
```

## MONTE CARLO SIMULATION

## SYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE ASSIGNMENT

## RUN STATISTICS

SIMULATION LEVEL =

35 PERCENT OPERATOR ATTENTION TIME/TOTAL CYCLE

AVERAGE MACHINE IDLE TIME/SERVICE CYCLE

| | |
|---|---|
| 1 | 1.22967 SEC. |
| 2 | 6.41329 SEC. |
| 3 | 1.98443 SEC. |
| 4 | 1.80463 SEC. |
| 5 | 7.38163 SEC. |
| 6 | 6.98834 SEC. |
| 7 | 14.08509 SEC. |
| 8 | 2.58354 SEC. |
| 9 | 8.18324 SEC. |
| 10 | 5.40481 SEC. |
| 11 | 11.82850 SEC. |
| 12 | 16.34485 SEC. |
| 13 | 3.37607 SEC. |
| 14 | 0.70954 SEC. |
| 15 | 6.56021 SEC. |
| 16 | 4.77389 SEC. |
| 17 | 3.72931 SEC. |
| 18 | 0.53638 SEC. |
| 19 | 5.39950 SEC. |
| 20 | 3.88434 SEC. |
| 21 | 0.98766 SEC. |
| 22 | 3.09182 SEC. |
| 23 | 11.73507 SEC. |
| 24 | 8.98762 SEC. |
| 25 | 3.63913 SEC. |
| 26 | 13.46171 SEC. |
| 27 | 5.23669 SEC. |
| 28 | 9.94297 SEC. |
| 29 | 4.73437 SEC. |
| 30 | 2.88685 SEC. |
| 31 | 1.94204 SEC. |
| 32 | 5.13201 SEC. |
| 33 | 3.32221 SEC. |
| 34 | 3.69118 SEC. |
| 35 | 1.56515 SEC. |
| 36 | 1.57810 SEC. |
| 37 | 4.07479 SEC. |
| 38 | 2.51531 SEC. |

| | |
|---|---|
| 39 | 3.67878 SEC. |
| 40 | 2.22244 SEC. |
| 41 | 1.49384 SEC. |
| 42 | 14.15518 SEC. |
| 43 | 6.36072 SEC. |
| 44 | 1.25346 SEC. |
| 45 | 11.93800 SEC. |
| 46 | 1.31370 SEC. |
| 47 | 14.87121 SEC. |
| 48 | 0.18625 SEC. |
| 49 | 0.54665 SEC. |
| 50 | 5.09061 SEC. |
| 51 | 5.01559 SEC. |
| 52 | 3.26507 SEC. |
| 53 | 6.19134 SEC. |
| 54 | 7.41831 SEC. |
| 55 | 5.83611 SEC. |
| 56 | 4.22340 SEC. |
| 57 | 7.76104 SEC. |
| 58 | 16.96331 SEC. |
| 59 | 6.99118 SEC. |
| 60 | 6.69930 SEC. |
| 61 | 12.89247 SEC. |
| 62 | 24.15236 SEC. |
| 63 | 13.89545 SEC. |
| 64 | 4.13362 SEC. |
| 65 | 9.97853 SEC. |
| 66 | 5.09610 SEC. |
| 67 | 0.44247 SEC. |
| 68 | 5.64022 SEC. |
| 69 | 9.52609 SEC. |
| 70 | 4.76001 SEC. |
| 71 | 6.21827 SEC. |
| 72 | 5.10647 SEC. |
| 73 | 3.16111 SEC. |
| 74 | 16.10790 SEC. |
| 75 | 12.99279 SEC. |
| 76 | 2.08537 SEC. |
| 77 | 2.44894 SEC. |
| 78 | 2.76539 SEC. |
| 79 | 5.57062 SEC. |
| 80 | 5.34433 SEC. |
| 81 | 12.89346 SEC. |
| 82 | 5.14987 SEC. |
| 83 | 3.22450 SEC. |
| 84 | 3.49641 SEC. |
| 85 | 7.17474 SEC. |
| 86 | 4.21053 SEC. |
| 87 | 5.03204 SEC. |
| 88 | 8.87668 SEC. |

| | |
|---|---|
| 89 | 2.59967 SEC. |
| 90 | 8.76810 SEC. |
| 91 | 4.27941 SEC. |
| 92 | 9.06520 SEC. |
| 93 | 5.66866 SEC. |
| 94 | 2.17483 SEC. |
| 95 | 0.66605 SEC. |
| 96 | 3.54282 SEC. |
| 97 | 2.12446 SEC. |
| 98 | 3.33028 SEC. |
| 99 | 4.68868 SEC. |
| 100 | 0.98458 SEC. |
| 101 | 6.42387 SEC. |
| 102 | 2.43618 SEC. |
| 103 | 9.64569 SEC. |
| 104 | 1.23748 SEC. |
| 105 | 3.54730 SEC. |
| 106 | 2.79490 SEC. |
| 107 | 9.13436 SEC. |
| 108 | 7.90575 SEC. |
| 109 | 4.80734 SEC. |
| 110 | 17.38988 SEC. |
| 111 | 5.03042 SEC. |
| 112 | 3.28206 SEC. |
| 113 | 2.46150 SEC |
| 114 | 3.07839 SEC. |
| 115 | 1.96988 SEC. |
| 116 | 3.66449 SEC. |
| 117 | 2.25333 SEC. |
| 118 | 7.98555 SEC. |
| 119 | 7.65181 SEC. |
| 120 | 11.27286 SEC. |
| 121 | 2.02580 SEC. |
| 122 | 0.21032 SEC. |
| 123 | 3.98132 SEC. |
| 124 | 9.02878 SEC. |
| 125 | 3.28390 SEC. |
| 126 | 6.25527 SEC. |
| 127 | 4.51268 SEC. |
| 128 | 8.13302 SEC. |
| 129 | 9.65763 SEC. |
| 130 | 2.61283 SEC. |
| 131 | 3.36735 SEC. |
| 132 | 1.05220 SEC. |
| 133 | 6.34618 SEC. |
| 134 | 4.55979 SEC. |
| 135 | 2.72567 SEC. |
| 136 | 9.21615 SEC. |
| 137 | 6.29015 SEC. |
| 138 | 2.48251 SEC. |

| | |
|---|---|
| 139 | 3.20995 SEC. |
| 140 | 8.27575 SEC. |
| 141 | 3.19857 SEC. |
| 142 | 0.33169 SEC. |
| 143 | 3.74677 SEC. |
| 144 | 7.93760 SEC. |
| 145 | 9.20217 SEC. |
| 146 | 1.27992 SEC. |
| 147 | 7.80533 SEC. |
| 148 | 2.74183 SEC. |
| 149 | 12.28603 SEC. |
| 150 | 11.35668 SEC. |
| 151 | 14.20377 SEC. |
| 152 | 0.21155 SEC. |
| 153 | 2.75140 SEC. |
| 154 | 5.68657 SEC. |
| 155 | 5.40615 SEC. |

NUMBER OF MACHINES = 3

TOTAL NUMBER OF OPERATOR SERVICE CYCLES = 155

ELAPSED OPERATION TIME = 4.46387 HR.

TOTAL NUMBER OF UNITS PRODUCED = 465

AVERAGE CYCLE LENGTH = 103.67699 SEC.

AVERAGE OPERATOR IDLE TIME/CYCLE = 2.99783 SEC.

PERCENT AVERAGE OPERATOR IDLE TIME/CYCLE = 2.89

PERCENT OPERATOR IDLE TIME/RUN = 2.89

MACHINE IDLE TIME/INDIVIDUAL MACHINE/CYCLE

| | SEC./CYCLE | PERCENT/CYCLE |
|---|---|---|
| MACHINE NO. 1 | 5.64107 | 5.44 |
| MACHINE NO. 2 | 5.64310 | 5.44 |
| MACHINE NO. 3 | 5.84133 | 5.63 |

PERCENT MACHINE IDLE TIME/INDIVIDUAL MACHINE/RUN

| | |
|---|---|
| MACHINE NO. 1 | 5.44 |
| MACHINE NO. 2 | 5.44 |
| MACHINE NO. 3 | 5.63 |

AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE = 5.70850 SEC.

PERCENT AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE = 5.51

## MONTE CARLO SIMULATION

## SYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE ASSIGNMENT

## RUN STATISTICS

SIMULATION LEVEL -

50 PERCENT OPERATOR ATTENTION TIME/TOTAL CYCLE

AVERAGE MACHINE IDLE TIME/SERVICE CYCLE

| | |
|---|---|
| 1 | 31.22967 SEC. |
| 2 | 36.41329 SEC. |
| 3 | 28.03700 SEC. |
| 4 | 31.11499 SEC. |
| 5 | 37.03681 SEC. |
| 6 | 36.98834 SEC. |
| 7 | 44.08509 SEC. |
| 8 | 29.93656 SEC. |
| 9 | 32.99646 SEC. |
| 10 | 35.40481 SEC. |
| 11 | 41.82850 SEC. |
| 12 | 46.34485 SEC. |
| 13 | 33.37607 SEC. |
| 14 | 28.83715 SEC. |
| 15 | 35.62401 SEC. |
| 16 | 34.01009 SEC. |
| 17 | 32.87097 SEC. |
| 18 | 26.69665 SEC. |
| 19 | 28.74076 SEC . |
| 20 | 31.93413 SEC. |
| 21 | 26.98293 SEC. |
| 22 | 28.13270 SEC. |
| 23 | 40.01291 SEC. |
| 24 | 38.98762 SEC. |
| 25 | 28.61015 SEC. |
| 26 | 40.94721 SEC. |
| 27 | 31.21295 SEC. |
| 28 | 39.94297 SEC. |
| 29 | 34.73437 SEC. |
| 30 | 32.28217 SEC. |
| 31 | 27.25923 SEC. |
| 32 | 28.00442 SEC. |
| 33 | 32.13587 SEC. |
| 34 | 30.64404 SEC. |
| 35 | 28.54895 SEC. |
| 36 | 24.97479 SEC. |
| 37 | 31.07636 SEC. |
| 38 | 29.10084 SEC. |

| | |
|---|---|
| 39 | 30.77819 SEC. |
| 40 | 30.08071 SEC. |
| 41 | 28.21557 SEC. |
| 42 | 43.05148 SEC. |
| 43 | 36.36072 SEC, |
| 44 | 31.17180 SEC. |
| 45 | 41.77469 SEC. |
| 46 | 30.23881 SEC. |
| 47 | 42.72207 SEC. |
| 48 | 28.70365 SEC. |
| 49 | 24.33933 SEC. |
| 50 | 24.06395 SEC. |
| 51 | 35.01559 SEC. |
| 52 | 22.88510 SEC. |
| 53 | 32.66280 SEC. |
| 54 | 37.41831 SEC. |
| 55 | 27.66656 SEC. |
| 56 | 33.05673 SEC. |
| 57 | 35.42770 SEC. |
| 58 | 46.96331 SEC. |
| 59 | 32.54839 SEC. |
| 60 | 35.72771 SEC. |
| 61 | 37.96905 SEC. |
| 62 | 54.15236 SEC. |
| 63 | 43.89545 SEC. |
| 64 | 30.71534 SEC. |
| 65 | 33.69730 SEC. |
| 66 | 35.09610 SEC. |
| 67 | 25.09833 SEC. |
| 68 | 33.19460 SEC. |
| 69 | 26.55740 SEC. |
| 70 | 34.76001 SEC. |
| 71 | 36.21827 SEC. |
| 72 | 34.54616 SEC. |
| 73 | 30.41349 SEC. |
| 74 | 46.10790 SEC. |
| 75 | 42.99279 SEC. |
| 76 | 27.44539 SEC. |
| 77 | 27.17019 SEC. |
| 78 | 26.10315 SEC. |
| 79 | 28.95608 SEC. |
| 80 | 25.48021 SEC. |
| 81 | 41.38574 SEC. |
| 82 | 35.14987 SEC. |
| 83 | 33.11137 SEC. |
| 84 | 25.42470 SEC. |
| 85 | 35.56206 SEC. |
| 86 | 31.72628 SEC. |
| 87 | 34.24665 SEC. |
| 88 | 38.48398 SEC. |

| | |
|---|---|
| 89 | 29.91445 SEC. |
| 90 | 35.01419 SEC. |
| 91 | 28.02749 SEC. |
| 92 | 35.93924 SEC. |
| 93 | 35.53288 SEC. |
| 94 | 31.18384 SEC. |
| 95 | 26.39852 SEC. |
| 96 | 30.42122 SEC. |
| 97 | 29.44922 SEC. |
| 98 | 28.65872 SEC. |
| 99 | 31.73301 SEC. |
| 100 | 29.10483 SEC. |
| 101 | 35.14395 SEC. |
| 102 | 32.43618 SEC. |
| 103 | 39.64569 SEC. |
| 104 | 30.33704 SEC. |
| 105 | 31.10846 SEC. |
| 106 | 30.41297 SEC. |
| 107 | 38.10289 SEC. |
| 108 | 37.90575 SEC. |
| 109 | 34.80734 SEC. |
| 110 | 47.38988 SEC. |
| 111 | 32.41337 SEC. |
| 112 | 30.63963 SEC. |
| 113 | 29.79370 SEC. |
| 114 | 32.37441 SEC. |
| 115 | 25.22880 SEC. |
| 116 | 33.66449 SEC. |
| 117 | 26.83224 SEC. |
| 118 | 37.89855 SEC. |
| 119 | 37.61346 SEC. |
| 120 | 34.24570 SEC. |
| 121 | 26.43550 SEC. |
| 122 | 22.94041 SEC. |
| 123 | 32.84318 SEC. |
| 124 | 38.94744 SEC. |
| 125 | 30.31519 SEC. |
| 126 | 30.31784 SEC. |
| 127 | 24.40425 SEC. |
| 128 | 30.06436 SEC. |
| 129 | 39.65763 SEC. |
| 130 | 28.24220 SEC. |
| 131 | 25.59240 SEC. |
| 132 | 20.74644 SEC. |
| 133 | 27.97951 SEC. |
| 134 | 33.37684 SEC. |
| 135 | 31.96582 SEC. |
| 136 | 39.04152 SEC. |
| 137 | 24.52615 SEC. |

| | |
|---|---|
| 138 | 24.12934 SEC. |
| 139 | 33.05504 SEC. |
| 140 | 38.27575 SEC. |
| 141 | 20.46291 SEC. |
| 142 | 24.78081 SEC. |
| 143 | 28.48364 SEC. |
| 144 | 37.93760 SEC. |
| 145 | 37.27316 SEC. |
| 146 | 26.56056 SEC. |
| 147 | 36.08264 SEC. |
| 148 | 27.96101 SEC. |
| 149 | 38.23675 SEC. |
| 150 | 41.35668 SEC. |
| 151 | 44.20377 SEC. |
| 152 | 21.86726 SEC. |
| 153 | 18.69859 SEC. |
| 154 | 34.98246 SEC. |
| 155 | 35.40615 SEC. |

NUMBER OF MACHINES = 3

TOTAL NUMBER OF OPERATOR SERVICE CYCLES = 155

ELAPSED OPERATION TIME = 4.33480 HR.

TOTAL NUMBER OF UNITS PRODUCED = 465

AVERAGE CYCLE LENGTH = 100.67916 SEC.

AVERAGE OPERATOR IDLE TIME/CYCLE = 0.00000 SEC.

PERCENT AVERAGE OPERATOR IDLE TIME/CYCLE = 0.00

PERCENT OPERATOR IDLE TIME/RUN = 0.00

MACHINE IDLE TIME/INDIVIDUAL MACHINE/CYCLE

| | SEC./CYCLE | PERCENT/CYCLE |
|---|---|---|
| MACHINE NO. 1 | 32.64323 | 32.42 |
| MACHINE NO. 2 | 32.64527 | 32.43 |
| MACHINE NO. 3 | 32.84349 | 32.62 |

PERCENT MACHINE IDLE TIME/INDIVIDUAL MACHINE/RUN

| | |
|---|---|
| MACHINE NO. 1 | 32.42 |
| MACHINE NO. 2 | 32.43 |
| MACHINE NO. 3 | 32.62 |

AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE = 32.71066 SEC.

PERCENT AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE = 32.49

## MONTE CARLO SIMULATION

## SYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE ASSIGNMENT

## RUN STATISTICS

SIMULATION LEVEL -

75 PERCENT OPERATOR ATTENTION TIME/TOTAL CYCLE

AVERAGE MACHINE IDLE TIME/SERVICE CYCLE

| | |
|---|---|
| 1 | 53.22967 SEC. |
| 2 | 58.41329 SEC. |
| 3 | 50.03700 SEC. |
| 4 | 53.11499 SEC. |
| 5 | 59.03681 SEC. |
| 6 | 58.98834 SEC. |
| 7 | 66.08509 SEC. |
| 8 | 51.93656 SEC. |
| 9 | 54.99646 SEC. |
| 10 | 57.40481 SEC. |
| 11 | 63.82850 SEC. |
| 12 | 68.34485 SEC. |
| 13 | 55.37607 SEC. |
| 14 | 50.83715 SEC. |
| 15 | 57.62401 SEC. |
| 16 | 56.01009 SEC. |
| 17 | 54.87097 SEC. |
| 18 | 48.69665 SEC. |
| 19 | 50.74076 SEC. |
| 20 | 53.93413 SEC. |
| 21 | 48.98293 SEC. |
| 22 | 50.13270 SEC. |
| 23 | 62.01291 SEC. |
| 24 | 60.98762 SEC. |
| 25 | 50.61015 SEC. |
| 26 | 62.94721 SEC. |
| 27 | 53.21295 SEC. |
| 28 | 61.94297 SEC. |
| 29 | 56.73437 SEC. |
| 30 | 54.28217 SEC. |
| 31 | 49.25923 SEC. |
| 32 | 50.00442 SEC. |
| 33 | 54.13587 SEC. |
| 34 | 52.64404 SEC. |
| 35 | 50.54895 SEC. |
| 36 | 46.97479 SEC. |
| 37 | 53.07636 SEC. |
| 38 | 51.10084 SEC. |

| | |
|---|---|
| 39 | 52.77819 SEC. |
| 40 | 52.08071 SEC. |
| 41 | 50.21557 SEC. |
| 42 | 65.05148 SEC. |
| 43 | 58.36072 SEC. |
| 44 | 53.17180 SEC. |
| 45 | 63.77469 SEC. |
| 46 | 52.23881 SEC. |
| 47 | 64.72207 SEC. |
| 48 | 50.70365 SEC. |
| 49 | 46.33933 SEC. |
| 50 | 46.06395 SEC. |
| 51 | 57.01559 SEC. |
| 52 | 44.88510 SEC. |
| 53 | 54.66280 SEC. |
| 54 | 59.41831 SEC. |
| 55 | 49.66656 SEC. |
| 56 | 55.05673 SEC. |
| 57 | 57.42770 SEC. |
| 58 | 68.96331 SEC. |
| 59 | 54.54839 SEC. |
| 60 | 57.72771 SEC. |
| 61 | 59.96905 SEC. |
| 62 | 76.15236 SEC. |
| 63 | 65.89545 SEC. |
| 64 | 52.71534 SEC. |
| 65 | 55.69730 SEC. |
| 66 | 57.09610 SEC. |
| 67 | 47.09833 SEC. |
| 68 | 55.19460 SEC. |
| 69 | 48.55740 SEC. |
| 70 | 56.76001 SEC. |
| 71 | 58.21827 SEC. |
| 72 | 56.54616 SEC. |
| 73 | 52.41349 SEC. |
| 74 | 68.10790 SEC. |
| 75 | 64.99279 SEC. |
| 76 | 49.44539 SEC. |
| 77 | 49.17019 SEC. |
| 78 | 48.10315 SEC. |
| 79 | 50.95608 SEC. |
| 80 | 47.48021 SEC. |
| 81 | 63.38574 SEC. |
| 82 | 57.14987 SEC. |
| 83 | 55.11137 SEC. |
| 84 | 47.42470 SEC. |
| 85 | 57.56206 SEC. |
| 86 | 53.72628 SEC. |
| 87 | 56.24665 SEC. |
| 88 | 60.48398 SEC. |

| | |
|---|---|
| 89 | 51.91445 SEC. |
| 90 | 57.01419 SEC. |
| 91 | 50.02749 SEC. |
| 92 | 57.93924 SEC. |
| 93 | 57.53288 SEC. |
| 94 | 53.18384 SEC. |
| 95 | 48.39852 SEC. |
| 96 | 52.42122 SEC. |
| 97 | 51.44922 SEC. |
| 98 | 50.65872 SEC. |
| 99 | 53.73301 SEC. |
| 100 | 51.10483 SEC. |
| 101 | 57.14395 SEC. |
| 102 | 54.43618 SEC. |
| 103 | 61.64569 SEC. |
| 104 | 52.33704 SEC. |
| 105 | 53.10846 SEC. |
| 106 | 52.41297 SEC. |
| 107 | 60.10289 SEC. |
| 108 | 59.90575 SEC. |
| 109 | 56.80734 SEC. |
| 110 | 69.38988 SEC. |
| 111 | 54.41337 SEC. |
| 112 | 52.63963 SEC. |
| 113 | 51.79370 SEC. |
| 114 | 54.37441 SEC. |
| 115 | 47.22880 SEC. |
| 116 | 55.66449 SEC. |
| 117 | 48.83224 SEC. |
| 118 | 59.89855 SEC. |
| 119 | 59.61346 SEC. |
| 120 | 56.24570 SEC. |
| 121 | 48.43550 SEC. |
| 122 | 44.94041 SEC. |
| 123 | 54.84318 SEC. |
| 124 | 60.94744 SEC. |
| 125 | 52.31519 SEC. |
| 126 | 52.31784 SEC. |
| 127 | 46.40425 SEC. |
| 128 | 52.06436 SEC. |
| 129 | 61.65763 SEC. |
| 130 | 50.24220 SEC. |
| 131 | 47.59240 SEC. |
| 132 | 42.74644 SEC. |
| 133 | 49.97951 SEC. |
| 134 | 55.37684 SEC. |
| 135 | 53.96582 SEC. |
| 136 | 61.04152 SEC. |
| 137 | 46.52615 SEC. |
| 138 | 46.12934 SEC. |

```
        139              55.05504 SEC.
        140              60.27575 SEC.
        141              42.46291 SEC.
        142              46.78081 SEC.
        143              50.48364 SEC.
        144              59.93760 SEC.
        145              59.27316 SEC.
        146              48.56056 SEC.
        147              58.08264 SEC.
        148              49.96101 SEC.
        149              60.23675 SEC.
        150              63.35668 SEC.
        151              66.20377 SEC.
        152              43.86726 SEC.
        153              40.69859 SEC.
        154              56.98246 SEC.
        155              57.40615 SEC.

NUMBER OF MACHINES =                                          3

TOTAL NUMBER OF OPERATOR SERVICE CYCLES =                   155

ELAPSED OPERATION TIME =                                4.33480  HR.

TOTAL NUMBER OF UNITS PRODUCED =                            465

AVERAGE CYCLE LENGTH =                                100.67916  SEC.

AVERAGE OPERATOR IDLE TIME/CYCLE =                      0.00000  SEC.

PERCENT AVERAGE OPERATOR IDLE TIME/CYCLE =                 0.00

PERCENT OPERATOR IDLE TIME/RUN =                           0.00

MACHINE IDLE TIME/INDIVIDUAL MACHINE/CYCLE

                               SEC./CYCLE            PERCENT/CYCLE
        MACHINE NO.  1          54.64323                 54.27
        MACHINE NO.  2          54.64527                 54.28
        MACHINE NO.  3          54.84349                 54.47

PERCENT MACHINE IDLE TIME/INDIVIDUAL MACHINE/RUN

        MACHINE NO.  1          54.27
        MACHINE NO.  2          54.28
        MACHINE NO.  3          54.47

AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =              54.71066 SEC.

PERCENT AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =      54.34
```

## MONTE CARLO SIMULATION

## SYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE ASSIGNMENT

## RUN STATISTICS

SIMULATION LEVEL -

100 PERCENT OPERATOR ATTENTION TIME/TOTAL CYCLE

AVERAGE MACHINE IDLE TIME/SERVICE CYCLE

| | |
|---|---|
| 1 | 65.22967 SEC. |
| 2 | 70.41329 SEC. |
| 3 | 62.03700 SEC. |
| 4 | 65.11499 SEC. |
| 5 | 71.03681 SEC. |
| 6 | 70.98834 SEC. |
| 7 | 78.08509 SEC. |
| 8 | 63.93656 SEC. |
| 9 | 66.99646 SEC. |
| 10 | 69.40481 SEC. |
| 11 | 75.82850 SEC. |
| 12 | 80.34485 SEC. |
| 13 | 67.37607 SEC. |
| 14 | 62.83715 SEC. |
| 15 | 69.62401 SEC. |
| 16 | 68.01009 SEC. |
| 17 | 66.87097 SEC. |
| 18 | 60.69665 SEC. |
| 19 | 62.74076 SEC. |
| 20 | 65.93413 SEC. |
| 21 | 60.98293 SEC. |
| 22 | 62.13270 SEC. |
| 23 | 74.01291 SEC. |
| 24 | 72.98762 SEC. |
| 25 | 62.61015 SEC. |
| 26 | 74.94721 SEC. |
| 27 | 65.21295 SEC. |
| 28 | 73.94297 SEC. |
| 29 | 68.73437 SEC. |
| 30 | 66.28217 SEC. |
| 31 | 61.25923 SEC. |
| 32 | 62.00442 SEC. |
| 33 | 66.13587 SEC. |
| 34 | 64.64404 SEC. |
| 35 | 62.54895 SEC. |
| 36 | 58.97479 SEC. |
| 37 | 65.07636 SEC. |
| 38 | 63.10084 SEC. |

| | |
|---|---|
| 39 | 64.77819 SEC. |
| 40 | 64.08071 SEC. |
| 41 | 62.21557 SEC. |
| 42 | 77.05148 SEC. |
| 43 | 70.36072 SEC. |
| 44 | 65.17180 SEC. |
| 45 | 75.77469 SEC. |
| 46 | 64.23881 SEC. |
| 47 | 76.72207 SEC. |
| 48 | 62.70365 SEC. |
| 49 | 58.33933 SEC. |
| 50 | 58.06395 SEC. |
| 51 | 69.01559 SEC. |
| 52 | 56.88510 SEC. |
| 53 | 66.66280 SEC. |
| 54 | 71.41831 SEC. |
| 55 | 61.66656 SEC. |
| 56 | 67.05673 SEC. |
| 57 | 69.42770 SEC. |
| 58 | 80.96331 SEC. |
| 59 | 66.54839 SEC. |
| 60 | 69.72771 SEC. |
| 61 | 71.96905 SEC. |
| 62 | 88.15236 SEC. |
| 63 | 77.89545 SEC. |
| 64 | 64.71534 SEC. |
| 65 | 67.69730 SEC. |
| 66 | 69.09610 SEC. |
| 67 | 59.09833 SEC. |
| 68 | 67.19460 SEC. |
| 69 | 60.55740 SEC. |
| 70 | 68.76001 SEC. |
| 71 | 70.21827 SEC. |
| 72 | 68.54616 SEC. |
| 73 | 64.41349 SEC. |
| 74 | 80.10790 SEC. |
| 75 | 76.99279 SEC. |
| 76 | 61.44539 SEC. |
| 77 | 61.17019 SEC. |
| 78 | 60.10315 SEC. |
| 79 | 62.95608 SEC. |
| 80 | 59.48021 SEC. |
| 81 | 75.$\overset{5}{3}$8574 SEC. |
| 82 | 69.14987 SEC. |
| 83 | 67.11137 SEC. |
| 84 | 59.42470 SEC. |
| 85 | 69.56206 SEC. |
| 86 | 65.72628 SEC. |
| 87 | 68.24665 SEC. |
| 88 | 72.48398 SEC. |

| | |
|---|---|
| 89 | 63.91445 SEC. |
| 90 | 69.01419 SEC. |
| 91 | 62.02749 SEC. |
| 92 | 69.93924 SEC. |
| 93 | 69.53288 SEC. |
| 94 | 65.18384 SEC. |
| 95 | 60.39852 SEC. |
| 96 | 64.42122 SEC. |
| 97 | 63.44922 SEC. |
| 98 | 62.65872 SEC. |
| 99 | 65.73301 SEC. |
| 100 | 63.10483 SEC. |
| 101 | 69.14395 SEC. |
| 102 | 66.43618 SEC. |
| 103 | 73.64569 SEC. |
| 104 | 64.33704 SEC. |
| 105 | 65.10846 SEC. |
| 106 | 64.41297 SEC. |
| 107 | 72.10289 SEC. |
| 108 | 71.90575 SEC. |
| 109 | 68.80734 SEC. |
| 110 | 81.38988 SEC. |
| 111 | 66.41337 SEC. |
| 112 | 64.63963 SEC. |
| 113 | 63.79370 SEC. |
| 114 | 66.37441 SEC. |
| 115 | 59.22880 SEC. |
| 116 | 67.66449 SEC. |
| 117 | 60.83224 SEC. |
| 118 | 71.89855 SEC. |
| 119 | 71.61346 SEC. |
| 120 | 68.24570 SEC. |
| 121 | 60.43550 SEC. |
| 122 | 56.94041 SEC. |
| 123 | 66.84318 SEC. |
| 124 | 72.94744 SEC. |
| 125 | 64.31519 SEC. |
| 126 | 64.31784 SEC. |
| 127 | 58.40425 SEC. |
| 128 | 64.06436 SEC. |
| 129 | 73.65763 SEC. |
| 130 | 62.24220 SEC. |
| 131 | 59.59240 SEC. |
| 132 | 54.74644 SEC. |
| 133 | 61.97951 SEC. |
| 134 | 67.37684 SEC. |
| 135 | 65.96582 SEC. |
| 136 | 73.04152 SEC. |
| 137 | 58.52615 SEC. |
| 138 | 58.12934 SEC. |

```
            139              67.05504 SEC.
            140              72.27575 SEC.
            141              54.46291 SEC.
            142              58.78081 SEC.
            143              62.48364 SEC.
            144              71.93760 SEC.
            145              71.27316 SEC.
            146              60.56056 SEC.
            147              70.08264 SEC.
            148              61.96101 SEC.
            149              72.23675 SEC.
            150              75.35668 SEC.
            151              78.20377 SEC.
            152              55.86726 SEC.
            153              52.69859 SEC.
            154              68.98246 SEC.
            155              69.40615 SEC.

     NUMBER OF MACHINES =                                          3

     TOTAL NUMBER OF OPERATOR SERVICE CYCLES =                   155

     ELAPSED OPERATION TIME =                                  4.33480  HR.

     TOTAL NUMBER OF UNITS PRODUCED =                            465

     AVERAGE CYCLE LENGTH =                                  100.67916  SEC.

     AVERAGE OPERATOR IDLE TIME/CYCLE =                        0.00000  SEC.

     PERCENT AVERAGE OPERATOR IDLE TIME/CYCLE =                   0.00

     PERCENT OPERATOR IDLE TIME/RUN =                             0.00

     MACHINE IDLE TIME/INDIVIDUAL MACHINE/CYCLE

                                  SEC./CYCLE                PERCENT/CYCLE
          MACHINE NO.  1            66.64323                    66.19
          MACHINE NO.  2            66.64527                    66.20
          MACHINE NO.  3            66.84349                    66.39

     PERCENT MACHINE IDLE TIME/INDIVIDUAL MACHINE/RUN

          MACHINE NO.  1            66.19
          MACHINE NO.  2            66.20
          MACHINE NO.  3            66.39

     AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =                 66.71066 SEC.

     PERCENT AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =         66.26
```

MONTE CARLO SIMULATION

SYNCHRONIZED MULTIPLE-SEMIAUTOMATIC-MACHINE ASSIGNMENT

RUN STATISTICS

SIMULATION LEVEL -

125 PERCENT OPERATOR ATTENTION TIME/TOTAL CYCLE

AVERAGE MACHINE IDLE TIME/SERVICE CYCLE

| | |
|---|---|
| 1 | 72.22967 SEC. |
| 2 | 77.41329 SEC. |
| 3 | 69.03700 SEC. |
| 4 | 72.11499 SEC. |
| 5 | 78.03681 SEC. |
| 6 | 77.98834 SEC. |
| 7 | 85.08509 SEC. |
| 8 | 70.93656 SEC. |
| 9 | 73.99646 SEC. |
| 10 | 76.40481 SEC. |
| 11 | 82.82850 SEC. |
| 12 | 87.34485 SEC. |
| 13 | 74.37607 SEC. |
| 14 | 69.83715 SEC. |
| 15 | 76.62401 SEC. |
| 16 | 75.01009 SEC. |
| 17 | 73.87097 SEC. |
| 18 | 67.69665 SEC. |
| 19 | 69.74076 SEC. |
| 20 | 72.93413 SEC. |
| 21 | 67.98293 SEC. |
| 22 | 69.13270 SEC. |
| 23 | 81.01291 SEC. |
| 24 | 79.98762 SEC. |
| 25 | 69.61015 SEC. |
| 26 | 81.94721 SEC. |
| 27 | 72.21295 SEC. |
| 28 | 80.94297 SEC. |
| 29 | 75.73437 SEC. |
| 30 | 73.28217 SEC. |
| 31 | 68.25923 SEC. |
| 32 | 69.00442 SEC. |
| 33 | 73.13587 SEC. |
| 34 | 71.64404 SEC. |
| 35 | 69.54895 SEC. |
| 36 | 65.97479 SEC. |
| 37 | 72.07636 SEC. |
| 38 | 70.10084 SEC. |

| | |
|---|---|
| 39 | 71.77819 SEC. |
| 40 | 71.08071 SEC. |
| 41 | 69.21557 SEC. |
| 42 | 84.05148 SEC. |
| 43 | 77.36072 SEC. |
| 44 | 72.17180 SEC. |
| 45 | 82.77469 SEC. |
| 46 | 71.23881 SEC. |
| 47 | 83.72207 SEC. |
| 48 | 69.70365 SEC. |
| 49 | 65.33933 SEC. |
| 50 | 65.06395 SEC. |
| 51 | 76.01559 SEC. |
| 52 | 63.88510 SEC. |
| 53 | 73.66280 SEC. |
| 54 | 78.41831 SEC. |
| 55 | 68.66656 SEC. |
| 56 | 74.05673 SEC. |
| 57 | 76.42770 SEC. |
| 58 | 87.96331 SEC. |
| 59 | 73.54839 SEC. |
| 60 | 76.72771 SEC. |
| 61 | 78.96905 SEC. |
| 62 | 95.15236 SEC. |
| 63 | 84.89545 SEC. |
| 64 | 71.71534 SEC. |
| 65 | 74.69730 SEC. |
| 66 | 76.09610 SEC. |
| 67 | 66.09833 SEC. |
| 68 | 74.19460 SEC. |
| 69 | 67.55740 SEC. |
| 70 | 75.76001 SEC. |
| 71 | 77.21827 SEC. |
| 72 | 75.54616 SEC. |
| 73 | 71.41349 SEC. |
| 74 | 87.10790 SEC. |
| 75 | 83.99279 SEC. |
| 76 | 68.44539 SEC. |
| 77 | 68.17019 SEC. |
| 78 | 67.10315 SEC. |
| 79 | 69.95608 SEC. |
| 80 | 66.48021 SEC. |
| 81 | 82.38574 SEC. |
| 82 | 76.14987 SEC. |
| 83 | 74.11137 SEC. |
| 84 | 66.42470 SEC. |
| 85 | 76.56206 SEC. |
| 86 | 72.72628 SEC. |
| 87 | 75.24665 SEC. |
| 88 | 79.48398 SEC. |

| | |
|---|---|
| 89 | 70.91445 SEC. |
| 90 | 76.01419 SEC. |
| 91 | 69.02749 SEC. |
| 92 | 76.93924 SEC. |
| 93 | 76.53288 SEC. |
| 94 | 72.18384 SEC. |
| 95 | 67.39852 SEC. |
| 96 | 71.42122 SEC. |
| 97 | 70.44922 SEC. |
| 98 | 69.65872 SEC. |
| 99 | 72.73301 SEC. |
| 100 | 70.10483 SEC. |
| 101 | 76.14395 SEC. |
| 102 | 73.43618 SEC. |
| 103 | 80.64569 SEC. |
| 104 | 71.33704 SEC. |
| 105 | 72.10846 SEC. |
| 106 | 71.41297 SEC. |
| 107 | 79.10289 SEC. |
| 108 | 78.90575 SEC. |
| 109 | 75.80734 SEC. |
| 110 | 88.38988 SEC. |
| 111 | 73.41337 SEC. |
| 112 | 71.63963 SEC. |
| 113 | 70.79370 SEC. |
| 114 | 73.37441 SEC. |
| 115 | 66.22880 SEC. |
| 116 | 74.66449 SEC. |
| 117 | 67.83224 SEC. |
| 118 | 78.89855 SEC. |
| 119 | 78.61346 SEC. |
| 120 | 75.24570 SEC. |
| 121 | 67.43550 SEC. |
| 122 | 63.94041 SEC. |
| 123 | 73.84318 SEC. |
| 124 | 79.94744 SEC. |
| 125 | 71.31519 SEC. |
| 126 | 71.31784 SEC. |
| 127 | 65.40425 SEC. |
| 128 | 71.06436 SEC. |
| 129 | 80.65763 SEC. |
| 130 | 69.24220 SEC. |
| 131 | 66.59240 SEC. |
| 132 | 61.74644 SEC. |
| 133 | 68.97951 SEC. |
| 134 | 74.37684 SEC. |
| 135 | 72.96582 SEC. |
| 136 | 80.04152 SEC. |
| 137 | 65.52615 SEC. |
| 138 | 65.12934 SEC. |

```
          139            74.05504 SEC.
          140            79.27575 SEC.
          141            61.46291 SEC.
          142            65.78081 SEC.
          143            69.48364 SEC.
          144            78.93760 SEC.
          145            78.27316 SEC.
          146            67.56056 SEC.
          147            77.08264 SEC.
          148            68.96101 SEC.
          149            79.23675 SEC.
          150            82.35668 SEC.
          151            85.20377 SEC.
          152            62.86726 SEC.
          153            59.69859 SEC.
          154            75.98246 SEC.
          155            76.40615 SEC.

NUMBER OF MACHINES =                                         3

TOTAL NUMBER OF OPERATOR SERVICE CYCLES =                  155

ELAPSED OPERATION TIME =                               4.33480  HR.

TOTAL NUMBER OF UNITS PRODUCED =                           465

AVERAGE CYCLE LENGTH =                               100.67916  SEC.

AVERAGE OPERATOR IDLE TIME/CYCLE =                     0.00000  SEC.

PERCENT AVERAGE OPERATOR IDLE TIME/CYCLE =                0.00

PERCENT OPERATOR IDLE TIME/RUN =                          0.00

MACHINE IDLE TIME/INDIVIDUAL MACHINE/CYCLE

                          SEC./CYCLE              PERCENT/CYCLE
      MACHINE NO.  1        73.64323                 73.15
      MACHINE NO.  2        73.64527                 73.15
      MACHINE NO.  3        73.84349                 73.35

PERCENT MACHINE IDLE TIME/INDIVIDUAL MACHINE/RUN

      MACHINE NO.  1        73.15
      MACHINE NO.  2        73.15
      MACHINE NO.  3        73.35

AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =             73.71066 SEC.

PERCENT AVERAGE MACHINE IDLE TIME/MACHINE/CYCLE =        73.21
```

# APPENDIX H

# ANALYSIS OF RESULTS

## Example of Calculations for Simulation Interference Variation

( 25% Level of Operation )

$\Sigma x = 100.72$

$\Sigma (x)^2 = 256.87$

$N = 155$

$$s = \sqrt{\frac{\Sigma (x)^2 - \frac{(\Sigma x)^2}{N}}{N}} = 1.11$$

Best Estimate of the Population Variance

$$\hat{\sigma}^2 = \left(\frac{N}{N-1}\right) s^2 = 1.2430$$

$\hat{\sigma} = 1.12$ seconds

$\hat{\sigma}$ Expressed as a Percentage of the Average Attention Time

$$\frac{\hat{\sigma}}{34.15 \text{ sec.}} \times 100 = \frac{1.12}{34.15} \times 100 = 3.28\%$$

| Level of Operation* (percent) | Average Interference Time / Cycle (seconds) | Variation (Std. Deviation) (seconds) | Average Interference Time / Cycle (% of attention time) | Variation (Std. Deviation) (% of attention time) |
|---|---|---|---|---|
| 10 | .25 | .65 | .73 | 1.90 |
| 25 | .65 | 1.12 | 1.90 | 3.28 |
| 35 | 5.71 | 4.22 | 16.72 | 12.35 |
| 50 | 32.71 | 6.34 | 95.78 | 18.57 |
| 75 | 54.71 | 6.01 | 160.20 | 17.60 |
| 100 | 66.71 | 6.02 | 195.34 | 17.63 |
| 125 | 73.71 | 6.02 | 215.84 | 17.63 |

* Average Attention Time as a Percent of the Total Cycle

Table 1. Summary of Simulation Interference Results

## Example of Interference Calculations Using Deterministic Models

( 25% Level of Operation )

### 1. Jones Algebraic Model

External Manual Time (WE) = 22.93 sec.
Automatic Machine Time (R) = 114.00 sec.
Operation Cycle Time (WE + R) = 22.93 + 114.00 = 136.93 sec.
Internal Manual Time (WI) = 11.22 sec.

Therefore $\Sigma$(WE + WI) = 3(22.93 + 11.22) = 102.45 sec.

The Battery Cycle Time is 136.93 sec.

The interference is determined by subtracting the operation cycle time (WE + R) from the battery cycle time.

Therefore, the interference = 136.93 - 136.93 = 0

### 2. Sandberg Algebraic Model

Operator Hand Service Time ($h_c$) = 22.93 sec.
Machine Run Time ($m_c$) = 114.00 sec.

In this case $p_d = 0$ $\qquad$ $h_c = 68.79$ sec.

$$h_{c1} + m_{c1} > \Sigma h_c + p_d$$

$$22.93 + 114.00 > 68.79$$

Therefore, $i_d = N( h_{c1} + m_{c1}) - \Sigma h_c - \Sigma m_c$

$$i_d = 3( 136.93 ) - 410.79 = \underline{0}$$

### 3. W. R. Wright Algebraic Model

( N is less than 6, therefore the empirical curves are used.)

Ratio of Machine Time to Attention Time = $\dfrac{75 \text{ sec.}}{34.15 \text{ sec.}} = 2.20$

From the chart of the empirical curves, N = 3, I (Interference in Percent of Attention Time) = 60%

Therefore, the interference = .60 x 34.15 = 22.88 sec.

## 4. W. G. Duvall Algebraic Model

$$I = 100\ (N-1)\ e^{-1.4N^{-0.946}R}$$

Where $N = 3$

$R$ = ratio $r/w$

$r$ = Machine Time = 114.00 sec.

$w$ = Total Attention Time = 34.15 sec.

$$R = \frac{114.00 \text{ sec.}}{34.15 \text{ sec.}} = 3.34$$

Therefore $I$ = 38.40 % of the Attention Time

Interference = .3840 x 34.15 = $\underline{13.11}$ sec.

|  | Method of Solution |  |  |  |  |
|---|---|---|---|---|---|
| Level of Operation* (Percent) | Jones | Sandberg | Wright | Duvall | Simulation |
| 10 | 0 | 0 | 3.59 | .68 | .25 |
| 25 | 0 | 0 | 11.61 | 13.11 | .65 |
| 35 | 4.52 | 4.52 | 20.49 | 22.88 | 5.71 |
| 50 | 34.52 | 34.52 | 44.40 | 35.52 | 32.71 |
| 75 | 56.52 | 56.52 | No | 48.83 | 54.71 |
| 100 | 68.52 | 68.52 | Evaluation | 58.06 | 66.71 |
| 125 | 75.52 | 75.52 | Possible | 64.54 | 73.71 |

*Attention time as a Percent of the Total Cycle.

Table 2. Summary of Interference Results
(Expressed in Seconds)

| Level of Operation* (Percent) | Method of Solution | | | | |
|---|---|---|---|---|---|
| | Jones | Sandberg | Wright | Duvall | Simulation |
| 10 | 0 | 0 | 10.51 | 1.99 | .73 |
| 25 | 0 | 0 | 34.00 | 38.39 | 1.90 |
| 35 | 13.24 | 13.24 | 60.00 | 67.00 | 16.72 |
| 50 | 101.08 | 101.08 | 130.01 | 104.01 | 95.78 |
| 75 | 165.51 | 165.51 | No | 142.99 | 160.21 |
| 100 | 200.64 | 200.64 | Evaluation | 170.01 | 195.34 |
| 125 | 221.14 | 221.14 | Possible | 188.99 | 215.84 |

*Attention time as a Percent of the Total Cycle.

Table 3. Summary of Interference Results
(Expressed in Percent of Attention Time)

## Example of Significance Test

## ( 25% Level of Operation )

Symbols to be used:

$m$ = average of the simulation results (unknown)

$m_o$ = average of the deterministic model results

$\overline{x}$ = average of the sample of n cycle results provided by the simulator

$s$ = standard deviation estimate computed from n cycle results provided by the simulator

$\sigma$ = the known standard deviation of the simulation results

The significance level of the test $(\alpha) = .05$

From the table of the Cumulative Normal Distribution $z_{.975} = 1.960$

$\overline{x} = .65$ ( see table 1. )

$\sigma = 1.12$

$$u = z \frac{\sigma}{\sqrt{n}} = \frac{1.960\ (1.12)}{12.4} = .177$$

Significance Test - if $|\overline{x} - m_o| > u$ decide that the average of the simulation results differs from that of the deterministic model; otherwise, that there is no reason to believe that they differ.

Note that the interval $\overline{x} \pm u$ is a $100\ (1-\alpha)\%$ confidence interval estimate of the true average m of the simulation results.

1. Test of Jones Model

$|\overline{x} - m_o| = |.25 - 0| = .25 > u$, therefore the average of the simulation differs from that of the model.

2. <u>Test of Sandberg Model</u>

"Same" as Jones Model

3. <u>Test of Wright Model</u>

$|\bar{x} - m_o| = |.65 - 11.61| = 10.96 > u$, therefore the average of the simulation differs from that of the model.

4. <u>Test of Duvall Model</u>

$|\bar{x} - m_o| = |.65 - 13.11| = 12.46 > u$, therefore the average of the simulation differs from that of the model.

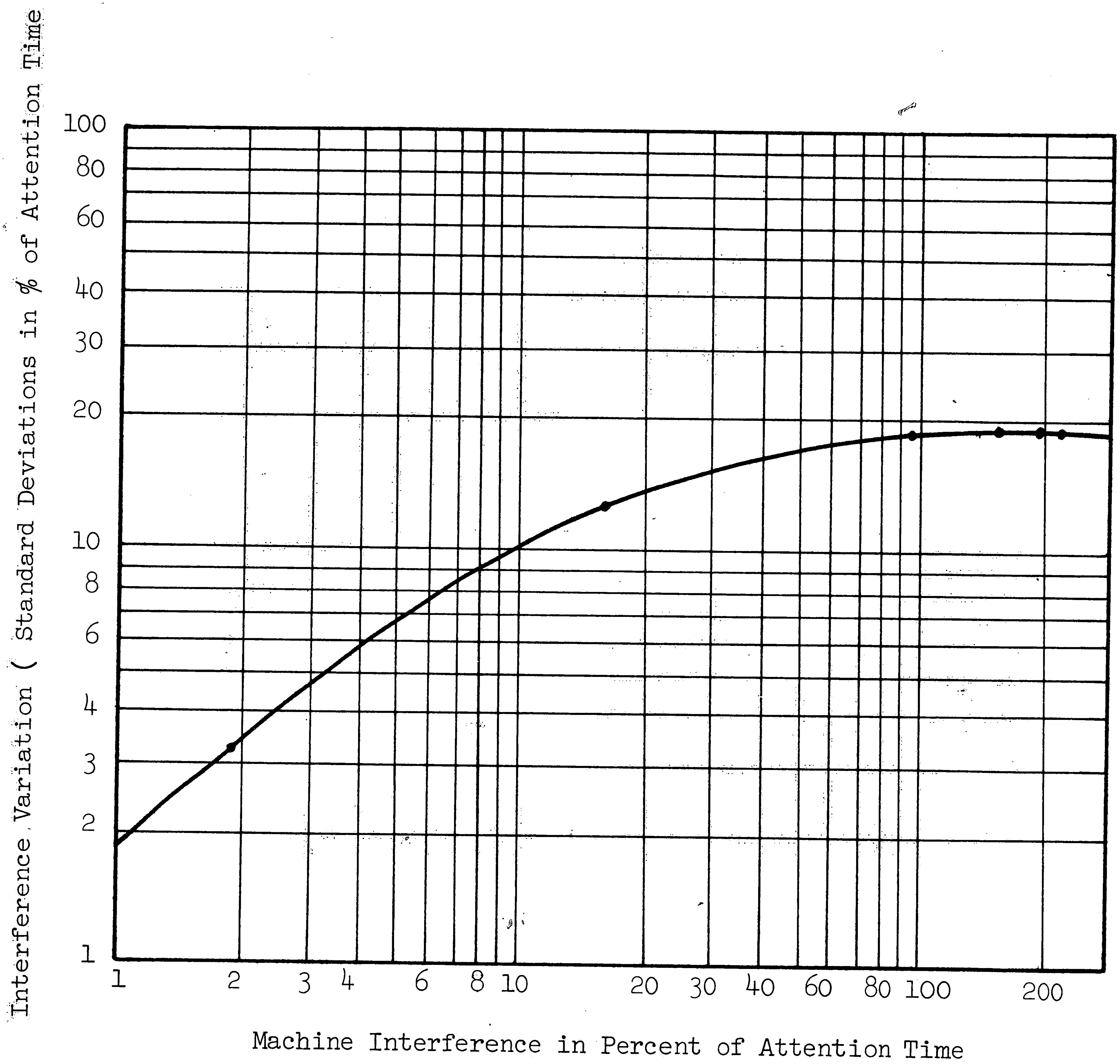
Confidence Interval Estimate

$$\bar{x} \pm u = .65 \pm .103$$

| Level of Operation | Method of Solution<br>Jones | Sandburg | Wright | Duvall | Simulation | Simulation Confidence Limits (sec.) |
|---|---|---|---|---|---|---|
| | Values of $|\bar{x}-mo|$ | | | | | |
| 10% | .25 | .25 | 3.34 | .43 | .103 | .25 ± .103 |
| 25% | .65 | .65 | 10.96 | 12.46 | .177 | .65 ± .177 |
| 35% | 1.19 | 1.19 | 14.78 | 17.17 | .665 | 5.71 ± .665 |
| 50% | 1.81 | 1.81 | 11.69 | 2.81 | 1.002 | 32.71 ± 1.002 |
| 75% | 1.81 | 1.81 | No Evaluation Possible | 5.88 | .953 | 54.71 ± .953 |
| 100% | 1.81 | 1.81 | | 8.65 | .953 | 66.71 ± .953 |
| 125% | 1.81 | 1.81 | | 9.17 | .953 | 73.71 ± .953 |

Table 4. Summary of Statistical Tests

## INTERFERENCE VARIATION ON MULTIPLE-UNIT MACHINES



( Showing values of expected variation in percent of attention time )

# BIBLIOGRAPHY

1. Allderige, J. M., and Lomicka, R. F., "Mathematical Man-Machine Analysis," The Journal of Industrial Engineering, Vol. 8, No. 3, (May-June 1957), pp. 157-164.

2. Boston, O. W., Metal Processing, John Wiley and Sons, Inc., New York, 1956, p. 410.

3. Carson, G. B., Production Handbook, The Roland Press Company, New York, 1959, pp. 12.85-12.87.

4. Davies, O. L., Design and Analysis of Industrial Experiments, Hafner Publishing Company, New York, 1960, pp. 12-56.

5. Dixon, W. J., and Massey, F. J., Jr., Introduction to Statistical Analysis, Mc Graw-Hill Book Company, Inc., New York, 1957, pp. 112-130.

6. Elderton, W. P., Frequency Curves and Correlation, Harren Press, Washington, D. C., 1953.

7. Honeywell Electronic Data Processing, Automath 400 Reference Manual, Minneapolis-Honeywell Regulator Company, Wellesley Hills, Massachusetts, 1963.

8. Jones, D., "Work Measurement of Multimachine Assignments," Industrial Engineering Handbook, Mc-Graw-Hill Book Co., Inc., New York, 1963, 2nd edition, pp. 3.112-3.138.

9. Jones, W. D., "Mathematical and Experimental Calculation of Machine Interference Time," The Research Engineer, Georgia Institute of Technology, January 1949.

10. Kenney, J. F., and Keeping, E. S., Mathematics of Statistics (Part Two), D. Van Nostrand Company, Inc., Princeton, New Jersey, 1951, pp. 94-126.

11. Moroney, M. J., Facts from Figures, Penguin Books, Inc., Baltimore, Maryland, 1958, pp. 216-270.

12. Mundel, M. E., Motion and Time Study (Principles and Practice, Prentice-Hall, Inc., 1955, pp. 203, 357-366.

13. Naylor, T. H., Balintfy, J. L., Burdick, D. S., and Chu, Kong, Computer Simulation Techniques, John Wiley and Sons, Inc., New York, 1966.

14. Organick, E. I., A Fortran Primer, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1963.

15. Palm, D. C., "The Assignment of Workers in Servicing Automatic Machines," The Journal of Industrial Engineering, Vol. 9, No. 1, (Jan.-Feb. 1958), pp. 28-42.

16. Sandberg, Dr. K. O. W., "Measurement of Machine Interference," Industrial Engineering Handbook, Mc Graw-Hill Book Co., Inc., New York, 1956, 1st edition, pp. 3.77-3.107.

17. Sasieni, M., Yaspon, A. and Friedman, L., Operations Research-Methods and Problems, John Wiley and Sons, Inc., New York, 1965.

18. Smail, L. L., Calculus, Appleton-Century-Crofts, Inc., New York, 1949, pp. 328-330.

19. United States Department of Commerce, Experimental Statistics, National Bureau of Standards Handbook 91, United States Government Printing Office, 1963.

20. White, R. J., and Stephens, K. S., Evaluation of Fortran Pseudo-Random Number Generators, Western Electric Co., Inc. Tech. Report No. PRN-165, 1964.

21. Wright, W. R., and Duvall, W. G., "Machine Interference - Two Solutions of Problem Raised by Multiple Machine Units," Mechanical Engineering, (August 1936), pp. 510-514.

# VITA

## PERSONAL HISTORY

| | |
|---|---|
| Name: | Leonard Alfred Sonntag |
| Date of Birth: | November 2, 1936 |
| Place of Birth: | Easton, Pennsylvania |
| Parents: | Alfred E. and Elsie H. Sonntag |
| Wife: | Dawn Lois Sonntag |
| Children: | Todd Leonard and Drew Patrick Sonntag |

## EDUCATIONAL BACKGROUND

| | |
|---|---|
| Washington High School<br>Washington, New Jersey | 1950-54 |
| Lehigh University<br>Bachelor of Science Degree in Industrial Engineering | 1954-58 |
| Lehigh University<br>Candidate for Master of Science Degree in Industrial Engineering | 1967 |

## PROFESSIONAL EXPERIENCE

Tung-Sol Electric Co., Inc.
Washington, New Jersey and Weatherly, Pennsylvania
Industrial Engineer
June 1958 - August 1962

Western Electric Co., Inc.
Allentown, Pennsylvania
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## PROFESSIONAL REGISTRATION

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| Professional Engineer Registration<br>Commonwealth of Pennsylvania | 1965 |

## PROFESSIONAL ORGANIZATIONS

Senior Member, American Institute of Industrial Engineers