1969

As study in the design of an assembly line for reconditioning items

Thomas B. Long Jr.
Lehigh University

Recommended Citation

Long, Thomas B. Jr., "As study in the design of an assembly line for reconditioning items" (1969). *Theses and Dissertations*. 3786.
https://preserve.lehigh.edu/etd/3786

A STUDY IN THE DESIGN OF AN ASSEMBLY LINE FOR RECONDITIONING ITEMS

by

Peter J. Long

A THESIS
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science

Lehigh University
1969

CERTIFICATE OF APPROVAL

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

5/16/69
Date

John W. Adams
Professor in Charge

For
Chairman of the Department
of Industrial Engineering

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the people who made this study possible. Particular thanks are due to:

Professor John W. Adams of Lehigh University, my thesis advisor,

John W. O'Leary and Hazel C. Rogaczewski of the Western Electric Company for their helpful suggestions regarding the use of GPSS.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

LIST OF FIGURES

LIST OF FIGURES (cont'd)

LIST OF TABLES

ABSTRACT

The problem of balancing an assembly line has been facilitated by a number of analytic methods for which computer programs are available. The majority of such techniques accept only deterministic values as the element times of the operations. As such, the techniques ignore a very real condition existing in the industrial environment, namely, operation time variance. One technique is available which will include portions of the variance associated with the operation times in determining the assignment of operations to work stations.

The feasibility of using the variable element time balancing algorithm was investigated in reference to the task of setting up an assembly line type operation for the reconditioning of units which are disassembled, repaired, and returned to inventory and subsequent use. The variability of operation times is introduced through the tasks which comprise the operations. Many such tasks are executed only when a defect is discovered and must be repaired. Otherwise, the task is not performed and the job progresses to the next sequence of tasks. Two actual reconditioning processes were utilized during the course of the investigation.

The results of the investigation indicated that the technique which explicitly accounts for the variance of the operations during the balancing process provides a more efficient balance. However, the balance solution could not be implemented without first simulating the industrial process to determine whether the design production rate

is satisfied and the in-process queues are within tolerable limits imposed by the physical limitations of the production facility.

Therefore, the design process cannot use the balancing algorithm solution exclusively in setting up a line to recondition the items in question. The balance solution does not provide adequate information to evaluate whether the line network satisfies all design criteria and simulation must be attempted to furnish the necessary performance statistics.

I INTRODUCTION

Background

In assembly line manufacture, the total process is divided into two or more stages each consisting of a series of operations which consume approximately the same amount of time at each stage. The stages in the manufacturing process are referred to as work stations and the operations in each stage can be performed repetitively by the same operator. The units of product are moved from one station to the next through the complete sequence of work stations.

Assembly line techniques are often used for other processes which are not strictly classified as assembly manufacture. Such a process is the reconditioning of equipment which must be disassembled, repaired, and reassembled. The volume of such activity and the characteristics of the reconditioning process lend themselves to the assembly line layout of work stations.

Normally each operation is performed repetitively on each unit of product processed by an assembly line. However, the reconditioning and repair process does not include all operations on all units. This fact complicates the determination of the operations to be included at each work station.

The occurrence of a defect, which triggers the repair process, is a random occurrence which cannot be ascertained prior to disassembly and inspection of the item at the work station. The randomness precludes any attempts to sequence items processed by the line.

A literature search indicated that no research has been reported on this particular problem.

Objectives

The primary objective of this study will be to investigate the feasibility of using computerized line balancing algorithms to organize a line designed to recondition items. The problem under investigation differs from normal line balancing problems in the aspect that each defined work element is not performed 100% of the time. The characteristic difference of less than 100% execution of many of the work elements comprising the work content of a work station introduces a factor of variability which is normally not present in line balancing problems. Several methods of incorporating the variance element into the line balancing technique will be analyzed using two actual reconditioning applications. The inadequacies of present algorithms and heuristics in relation to the problem under discussion will be enumerated.

Associated objectives involve the establishment of guidelines to assist further attempts in the design of similar lines using line balancing techniques.

Summary of the Problem

Consider a reconditioning task comprising a maximum of k work elements. The i^{th} work element $(i = 1, k)$ requires an average time t_i for its execution. The work element times normally are subject to estimation errors although they will be considered as deterministic quantities during the study. Associated with each work element is a factor, f_i, called the mean frequency of defect occurrence. This factor differentiates the process from the assembly task to which line balancing techniques are generally applied. The frequency factor is the long run average of the occurrence of a particular defect and as such is subject to estimation errors. The work element required to rectify the defect may not be executed for each item processed by the line, thereby introducing a variability factor which could be more disruptive to the operation of the line than the variability of operator performance of the work elements.

Given a production requirement of P items per hour (or day), the problem would then be:

1. To determine N the minimum number of work stations.
2. Taking precedent restrictions into account, to distribute the K work elements among the N operators such that the operating cycle time is a minimum. Thus, the aim is to minimize both the number of work stations and the operating cycle time.
3. The main objective is that the actual rate P_A must be at least equal to P.

Sample Problems

Two actual repair lines will be utilized during the course of this study. One repair line consists of seventy-two tasks grouped together by logical and technological factors to form a set of thirty-one work elements to be distributed among the work stations. Of the seventy-two tasks involved, twenty-six have less than 100% frequency of occurrence.

The second example comprises one-hundred and ten tasks grouped to form a set of thirty-six work elements. Seventy-seven of the one-hundred and ten tasks have less than 100% frequency of occurrence.

II GENERAL LINE BALANCING PROBLEM

Related Definitions and Notation

Before embarking upon a general discussion of the line balancing problem, pertinent definitions and notation will be presented to facilitate the following discussions.

Definitions

Cycle Time - the amount of time a unit is available to an operator (the time between successive completions of units). In the case of constant work element times (the deterministic case) the cycle time is a constant. In the probabilistic case the cycle time may be a random variable as will be discussed later.

Work element - a minimum feasible subdivision of the work content of the total reconditioning process.

Work stations - a combination of work elements that must be performed serially forms a "work station".

Work station time - the sum of the times for the work elements that form the work station.

Blocking - a station is said to be blocked if work on the item is completed but the item cannot pass to the next station because the operator is busy and no available space for in-process inventory exists, or if the operator passes an item to the next station but cannot receive a piece since the preceding station is busy and no available inventory exists from which to draw an item.

Buffer inventory - items located between work stations to lessen the impact of blocking. Such buffers of inventory can exist between any or all stations.

Notation

$(i = 1, k)$ = means that i has values 1, 2, 3, ..., k.

d = the greatest integer equal to or less than d.

d^+ = the smallest integer equal to or greater than d.

k = the number of work elements in the reconditioning task.

t_i = the time of the i^{th} work element

t_{max} = the largest value of t_i, $(i = 1, k)$

T = the total work content in the reconditioning task (in this case it is a random variable).

N = the number of stations (hence the number of operators) in the reconditioning lines.

N_{max} = the maximum number of stations for the reconditioning task.

P = the production requirement.

P_A = the actual production output.

$(P_A)_{max}$ = the maximum production theoretically possible for a given number of stations.

$C(N)$ = the operating cycle time for N stations.

α = the cycle time safety factor.

$STN(n)$ = the cumulative time of work elements assigned to the n^{th} station.

S = the total slack; the excess work capacity available to the assembly.

$D(n)$ = the slack available at the n^{th} station.

f_i = mean frequency of occurrence of the defect requiring repair (percents).

V_i = variance associated with the i^{th} elemental time.

Considerable effort has been expended in deriving a solution to the assembly line balancing problem[15]. The bulk of the work has concentrated in solution techniques for the deterministic model, that is, the model in which thw work element times are considered constant. This model, while clearly defined, addresses only one part of the total line balancing problem that is faced by engineers in their attempts to design assembly lines.

Recently, effort has shifted to a new variation of the old problem. The revised model considers variable element times[27] and is referred to as the probabilistic model or the variable work element time line balancing problem.

Freeman and Jucker[4] present a minimum set of decisions which must be made for the design of any assembly line.

1. How are work elements to be assigned to work stations?
2. Should provision for inventory between work stations (buffer inventory) be allowed? If it should, how much?
3. Line Operation?
    a. An item is present at each work station for some fixed amount of time C (cycle time), (enforced cycle time).
    b. Line operated as a series queue. That is, work passes freely from work station to work station as long as no blocking occurs.
    c. Lines that combine elements of "a" and "b" such as a line with a constant speed conveyor where workers are free to move back and forth along some portion of the

line, thereby creating a variable station time with possible dependencies between stations and/or items (depending upon line design).

4. Parallel work station(s)? That is, it may be possible to increase output or reduce the number of work stations required on a line by paralleling (duplicating) certain work stations.
5. What cycle time should be employed?

The overall objective of line balancing is to effect a desired production rate at a minimum cost. Each of the above decisions has their affect upon the final design of the line and the models of the line balancing problem make some of them implicitly. A brief discussion of each model will follow.

Classical Deterministic Line Balancing Problem

Given:

1. Desired cycle time (output rate)
2. Work elements (constant times)
3. Precedence constraints.

Objective:

To find an assignment of work elements to work stations that minimizes idle time (minimizes the number of stations) subject to the following constraints:

1. Each work element is assigned to a single work station.
2. The precedence constraints are satisfied.
3. The desired cycle time is not exceeded.

The desired cycle time is required as input for the deterministic model and thus decision 5 is a constant for any execution of the balancing technique when, in fact, it should be a decision variable. All of the existing algorithms implicitly make decisions 2,3, and 4. It has been shown for the deterministic model that buffer inventory will not improve system performance. Decision 3 is reflected in the choice of cycle time c, that is, the line will cycle every c units of time. The majority of the algorithms do not allow for the possibility of parallel work stations, and thus decision 4 has also been made.

Balancing the line to cycle times in the neighborhood of the desired cycle time and examining the cost associated with each balance should help to decide what cycle time is desirable.

The preceding discussion illustrates two shortcomings of the deterministic techniques:

1. The model does not explicitly help the designer to determinate the minimum cost cycle time.
2. The existing algorithms for solving this problem do not allow for the possibility of paralleling work stations (One known exception exists. A private company has modified a published algorithm to permit paralleling[9]).

Probabilistic Line Balancing Problem

Given:

1. A desired cycle time (output rate)
2. Work element times that are random variables with known probability distributions.

3. Precedence constraints on the ordering of the work elements.

Objective:

To find an assignment of work elements to work stations that minimizes total cost per unit of product subject to at least the following constraints:

1. Each work element is assigned to at least one work station.
2. The precedence constraints are satisfied.
3. The average output rate attained is at least as great as the desired output rate.

The variable work element model represents a more general statemetn of the line balancing problem and therefore should reflect the real world more closely than the deterministic model.

Since the objective is to minimize total cost per unit, the total cost should at least consider the following:

1. Direct Labor Cost.
2. Inventory Charges.
3. Facilities Costs.
4. Breakdown Cost.

The variable work element time model requires a solution technique which is capable of simultaneously making all five of the design decisions (stated earlier) using at least the four cost considerations mentioned above. At present, no such solution technique exists and the likelihood of the development of such a technique appears remote due to the complexities of including all the decision variables into a feasible technique.

Should such a technique be formulated, it will probably consist of a combination of present day techniques such as (1) a line balancing algorithm using variable element times and permitting parallel stations and zoning restrictions, (2) a simulation module to determine the buffer inventory requirements and verify that the production requirements are met, and (3) a cost module to evaluate the various combinations generated by the previous modules.

Line balancing algorithms generate balances in a reasonable amount of time for small problems, however, the simulation runs necessary to investigate whether or not the inclusion of in-process inventory is beneficial would be large and time consuming using present simulation methods. Since the three modules would have to be executed in series for each possible alternative of cycle time, paralleling and buffer inventory, the technique would be extremely time consuming and too expensive at the present time.

Possible Contributions to Line Balancing Problem

As the previous section implies, the task of establishing an assembly line comprising work elements with variable times could be formidable since the present algorithms consider only a portion of the overall problem. Line balancing techniques and simulation procedures must now be used in an attempt to achieve a reasonable line design. Freeman and Jucker[4] indicate that real contributions toward the solution of this problem would be in the establishment of usable guidelines that would indicate:

1. A reasonable upper and lower bound on the value of c (cycle time) which must be considered.

2. When in-process (buffer) inventory would be beneficial and where it should be located.
3. When paralleling should be considered.

To the three research areas above may be added still another:

4. When line unbalancing should be considered and to what degree of imbalance.

The investigation to be reported here will consider a variation of the first area of research indicated above. The cycle time will be considered as an accumulation of the mean element times and various factors of the element time variance. The inclusion of several factors of the variance will be analyzed in an attempt to establish bounds on the variance.

III PROBLEM DEFINITION

The reconditioning process to be discussed and analyzed includes such operations as cleaning, inspection, repair, lubrication, buffing, testing, etc. Due to the volume of items requiring reconditioning, the bulk of the work is performed on lines patterned after assembly lines. The reconditioning process is divided into a number of small operations which in turn may consist of a grouping of tasks that are technologically related or would result in unreasonable loss of time if designated as a separate operation themselves.

Since the process under discussion is a reconditioning process, it is reasonable to expect that some of the tasks included in the operations are not performed on each item passing through the work stations. The tasks performed may be summarized as a sequence of disassemble, inspect, and repair procedures. If the particular function of the item being inspected does not require repair or replacement, the additional time required for the performance of such a repair is not expended and the next sequence of tasks is performed. This characteristic of all tasks not being performed upon each item as it passes through the line yields a unique factor of variability which is not experienced in the general assembly line operations after which the reconditioning process is patterned. True, there is a factor of variability present in both processes due to variation in worker performance, but the reconditioning process has the additional burden of overcoming the variation due to the inclusion or exclusion of a task or operation associated with the occurrence of a defect.

Therefore, with each task there is associated an element time t_i, as well as a factor, f_i, indicating the mean frequency of occurrence of the defect. If f_i is one hundred, the element time is consumed each time an item passes through the work station to which the operation is assigned. Any value less than one hundred means that the time is consumed only f_i per cent of the time. The expected value of the element time would therefore be

$$E(t_i) = f_i t_i \times 10^{-2}$$

The element times are actually random variables approximated by the normal distribution[11]. However, the element times will be assumed to be deterministic values since the objective is to analyze the variability due to the defect occurrence. The distribution of element times associated with the frequency dependent operations is not as clearly defined as that of the element times themselves. For example, one operation in the thirty-one element problem requires 6.84 time units. However, the associated defect occurs only 10 per cent of the time, yielding an expected value, or mean, of .68 time units. A graph of the time distribution appears in Figure 1. This example definitely is the extreme case, but it exemplifies the type of variability which can occur during the reconditioning. It is this type of variability which will be considered during the course of this discussion.

The precedence charts of the two sample reconditioning processes appear in Figures 2 and 3. Figure 2 represents a thirty-one operation

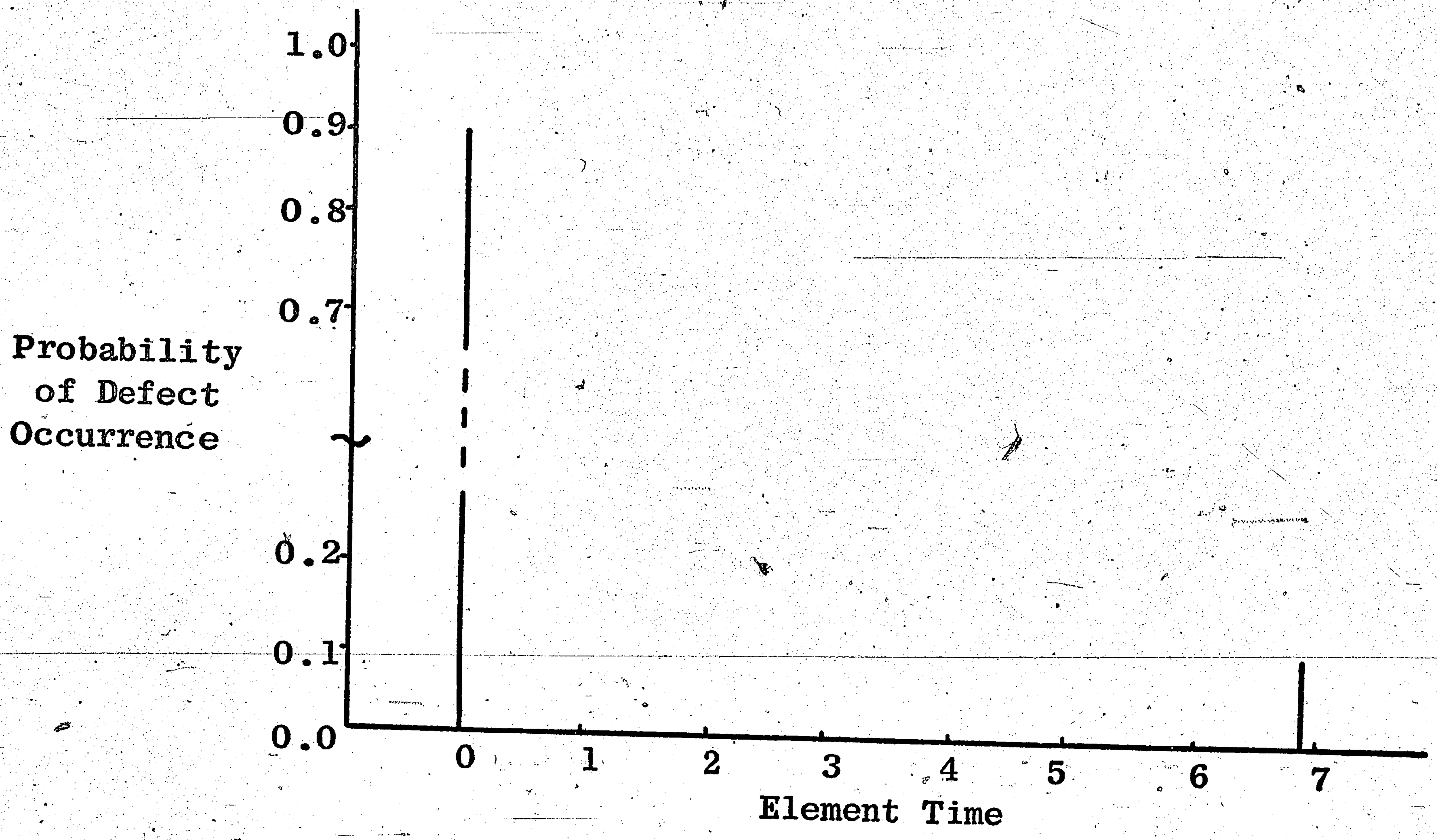


FIGURE 1. Sample Element Time Distribution

problem which is a composite of seventy-two tasks of which twenty-six have less than one hundred per cent frequency of occurrence. Figure 3 depicts thirty-six operations which are made up of one hundred and ten tasks of which seventy-seven are not executed on each item.

A more formal statement of the problem under discussion will now be presented.

Given that a specified production requirement of P items per designated time interval is to be maintained, the problem would then be:

1. To determine N, the minimum number of work stations.
2. Taking precedence restrictions into account, to distribute the K work elements among the N operators such that the operating cycle time is a minimum.

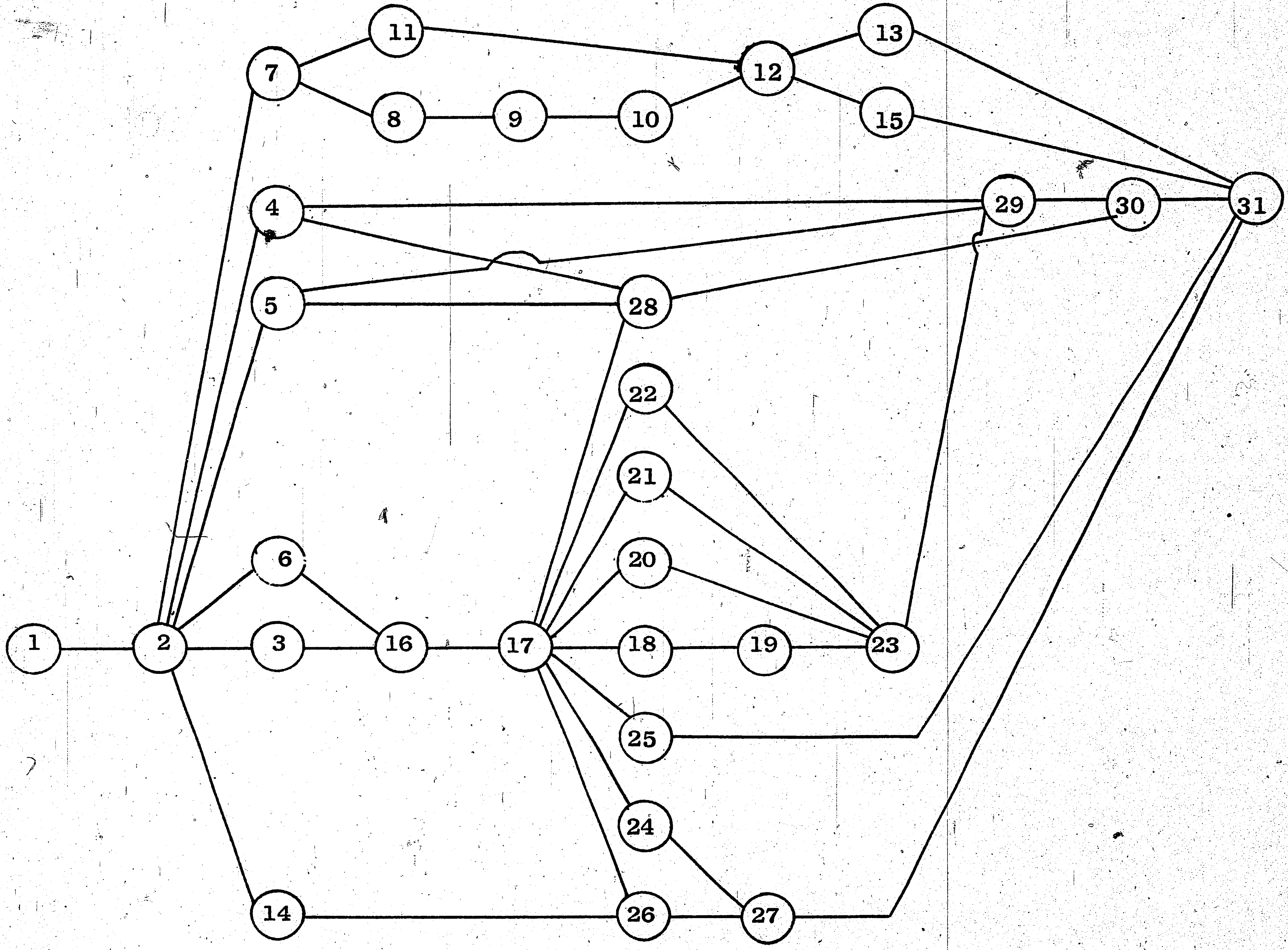


FIGURE 2. Precedence Diagram - 31 Elements

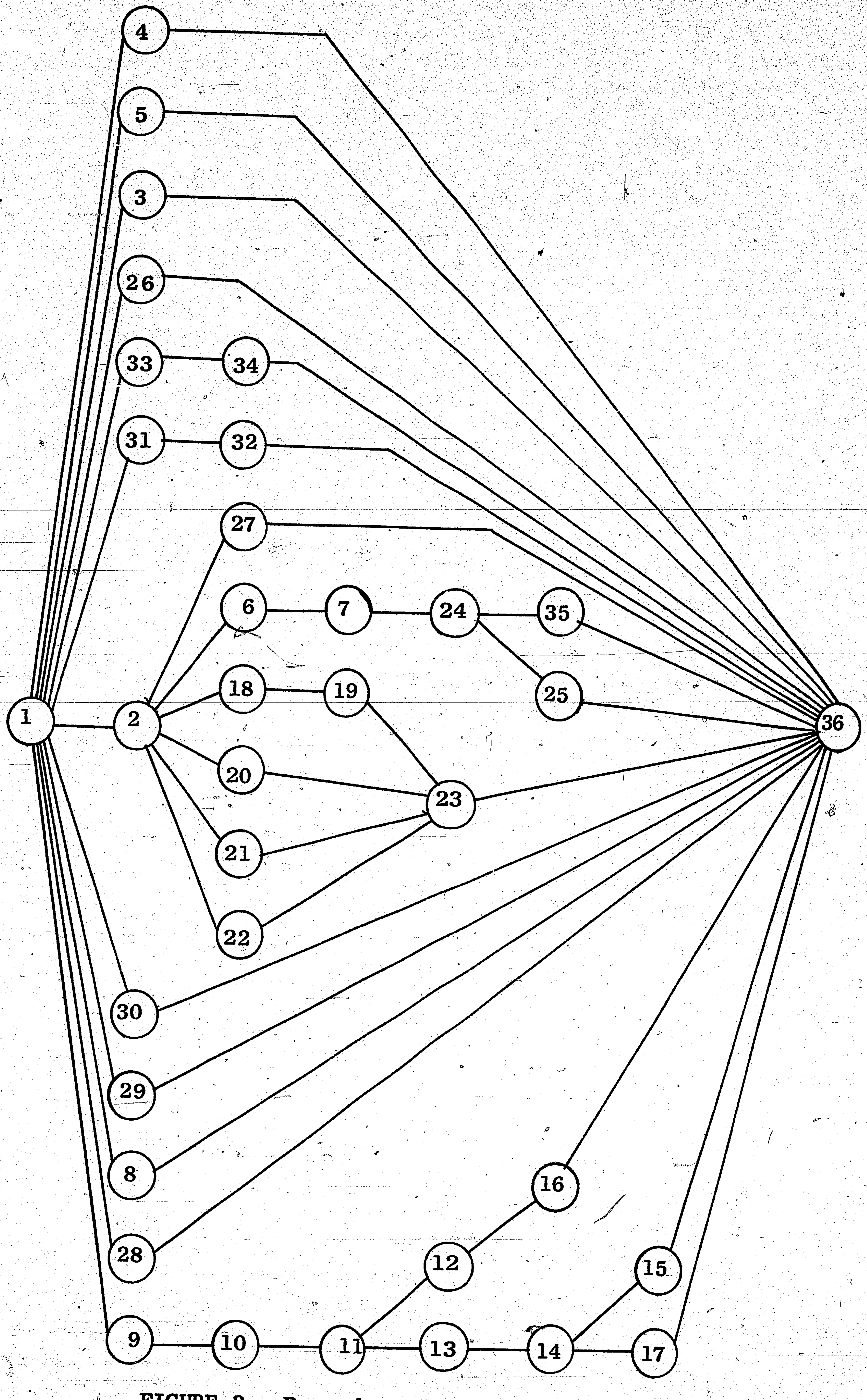


FIGURE 3. Precedence Diagram - 36 Elements

3. The primary objective being that the actual rate P_A must be at least equal to P.

The cycle time, C, can be determined from the expression

$$C = \frac{1}{P}$$

where P is the desired rate of production. The two sample problems will use three hundred units per day as the production rate. The above expression adjusted to the time units of the problem results in a theoretical cycle time of 267 time units.

A line balancing algorithm will be utilized to assign operations to work stations and simulation of the resultant balance will determine whether the objectives mentioned above have been fulfilled.

IV LITERATURE REVIEW

A literature search did not prove too fruitful an endeavor. Enumerable reports discuss assembly line balancing, mostly the deterministic model[6,7,8,13,16,18,36]. However, relatively few consider the probabilistic model[23,27] and none refer to a model defined as the present problem.

Mixed Model Systems

A model similar to the present problem was reported by Thomopoulos[34]. His model is classified as a mixed-model assembly problem which occurs when more than one model of the same general product are intermixed on one assembly line. The amount of work required to assemble units can vary from model to model, creating an uneven flow of work along the line. Consideration of an efficient mixed-model assembly line entails the solution to two separate but related problems: line balancing and model sequences. The method chosen by Thomopoulos is one that considers the total schedule for a whole shift and assigns work elements to work stations on a shift basis rather than a cycle-time basis. The element times considered in the balancing algorithm are adjusted by the number of each model which will be produced during the shift. For example, if an element time were designated as .32 minutes and a total of 20 units of the model are to be produced, the element time used in the assignment of operations to work stations would be 6.4 minutes, i.e., .32 x 20 = 6.4. The total of all such calculations, T, for the various operations yields the production time of the shift. This total divided by the time during the shift per operator which can be devoted to the production effort, T_p, yields the minimum number of operators required. The next integer larger than the quotient, $N = T/T_p$, will give the required number. The shift cycle time is obtained by dividing the total production time by the number of operators, that is, $C = T/N$.

Upon close examination, the method discussed above is actually a balance based upon the average time of all models expended at each operation. Consequently, if models were permitted to start at the first work station in a random manner, it would be expected that, on the average, fifty per cent of the items would not be finished within the cycle time, causing serious hold-ups of the line, especially if no buffer inventories were planned for the assembly line. The sequencing procedure was then developed to provide more efficient operation of the line. Sequencing proved beneficial and was applicable since the number of each model to be produced was known. The reconditioning process is similar to the mixed-model assembly problem in that the various combinations of defects could be enumerated and considered as separate models of the same general product. However, it is not possible to identify before the reconditioning process starts which items would fall into the model classifications enumerated. Therefore, it is not possible to sequence the items in such a way as to realize more efficient operation of the line, which would result if the work content of each item were known.

Variable Time Element Line Balancing Algorithm

Several sources make reference to line balancing involving variable element times[27,23,15,12]. Only Moodie[26] provides an actual line balancing algorithm which can be readily adapted to the reconditioning problem. The FORTRAN program listing of the balancing algorithm was included as an appendix in the above reference. The algorithm assumes that element times can be approximated by the normal distribution and the logic supporting the technique is derived from the property: if X and Y are both normal, the distributions of the sum X + Y is also normal. If an assumption of statistical independence between work elements is incorporated into the analysis, it is easy to include element variance in the line balancing procedure. Research by Walker[37] indicates that an assumption of independence is not without some foundation. Considering Figure 4, it can be seen that, if the line is balanced to the mean of the element times, the cycle time over the long run will be exceeded fifty per cent of the time.

When both elemental time averages and time variances are included in the balancing procedure, selected confidence levels can be established for the completion of assigned work at each work station. The allowance provided to the operator, that is, the difference between total assigned time and cycle time, is dependent upon the sum of the variances for the particular tasks assigned to an operator.

The criterion of optimization for an assumption of variable element times is

$$\text{Min} \sum_{K=1}^{N} \left[C - \sum_{i \in K} t_i - \alpha \sqrt{\sum_{k \in K} V_i} \right]$$

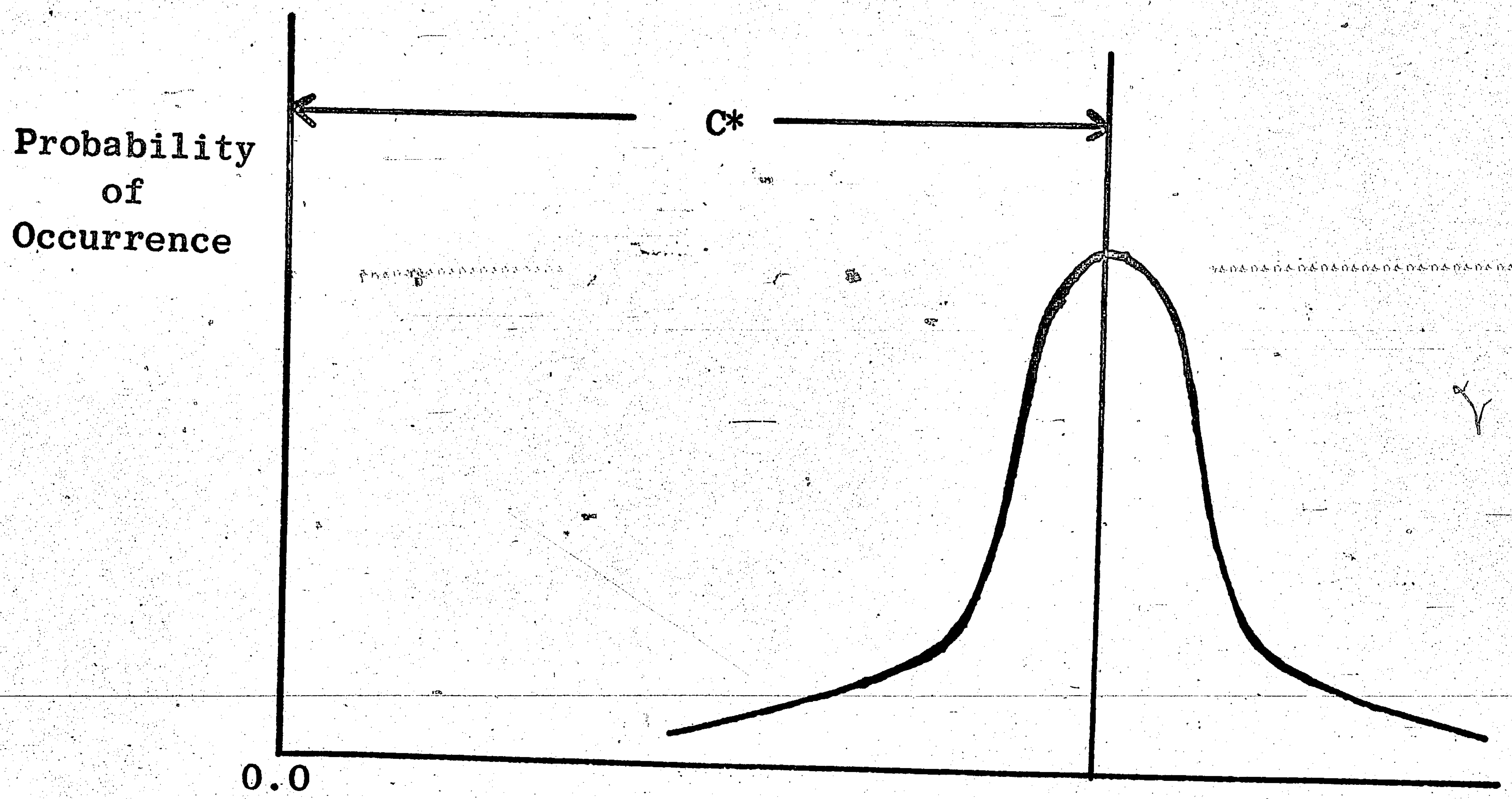


Figure 4. Balance to Mean Element Time

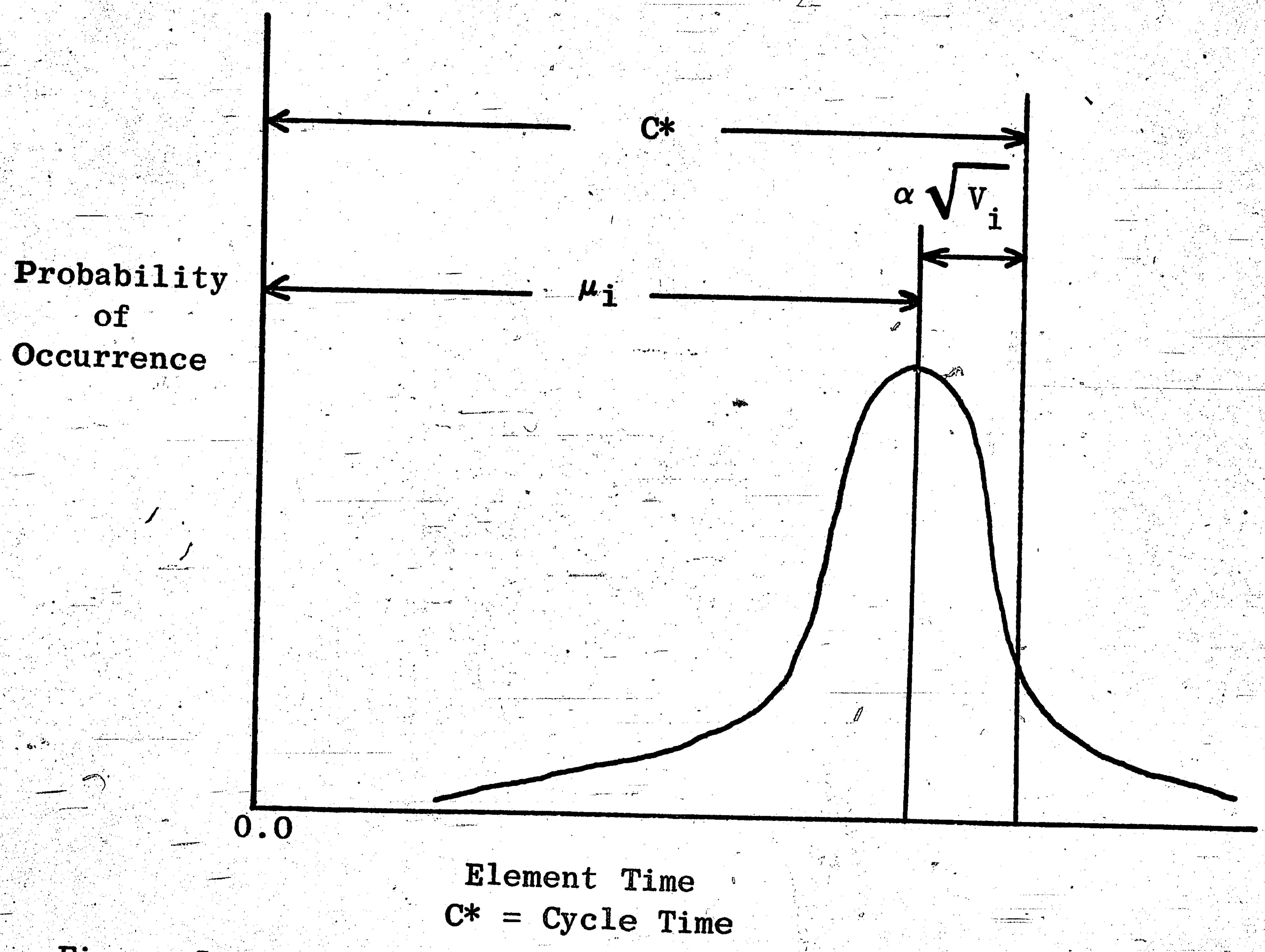


Figure 5. Balance Including Variance of Element Times

where N is the number of work stations, i is an element of station K, and is a constant multiplier to the standard deviation calculation $\sqrt{\sum V_i(K)}$. For the work station time, STN, to exceed C approximately fifteen per cent of the time, $\alpha = 1$. The value of α can be obtained from a table of areas under the normal curve. Thus we see that the work station time may be defined as follows:

$$\text{STN} = \sum_{i\ K} t_i + \alpha \sqrt{\sum_{i\ K} V_i(K)}$$

Hence, if the engineer wanted to assure with 97.5 per cent confidence that all work assigned to the work stations would be completed within the cycle time provided, α would equal two. Figure 5 shows the relationship between the cycle time C and the mean of the total station time μ_i. For some work stations on the line, the sum of the task variances would be large and for others the sum of the variances would be smaller. The line balancing technique attempts to smooth the imbalance of accumulated variances by trading off large and small variance tasks, so that both the average time summations and the variance summations are nearly as equal as possible for all work stations.

Moodie's line balancing technique has been chosen as the algorithm to balance the sample problems mentioned earlier. By varying the α factor from 0 to 1 and 2 and finally 3, the line can be balanced from using strictly average elemental time values to the extreme case which considers almost the entire variance.

V THE MODELS STUDIED

The elemental time variability due to the defect occurrence rate is of prime concern in the design of the reconditioning line. This variability may be investigated from three viewpoints, namely, total job variance, individual work station variance, and operation variance.

Job Variance Model

This model and its various submodels will utilize only the mean element times in the balances. The total time to recondition an item is the accumulation of the elemental times consumed at the various work stations. Since all operations are not performed on each item, the total job time may be considered as a random variable with its associated mean completion time and variance. The job variance model will consider the job time mean and various factors of the job time variance. A random sample of ten thousand reconditioning jobs based upon the average frequency of defect occurrence resulted in the total job time histograms of Figures 6 and 7.

Model J1

The initial model will consider the mean job time with no variance. The chosen production rate of three hundred units yields a cycle time of 267. The quotient of total mean job time over cycle time (rounded to the next highest integer) will give the minimum number of work stations required for the desired cycle time. The balance generated by using the average job time should result in the work stations exceeding the cycle time 50 per cent of the time (mean

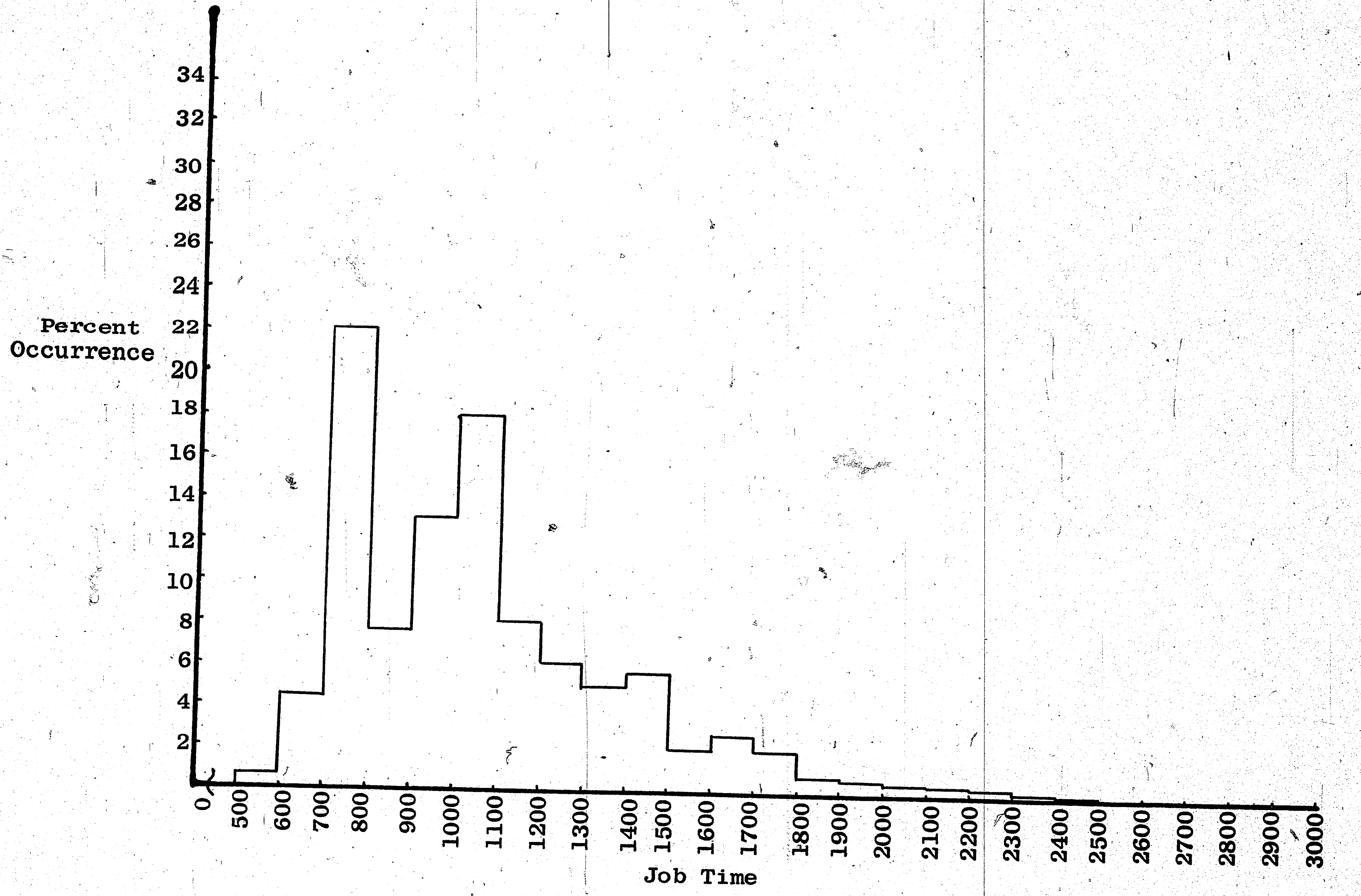


FIGURE 6. Histogram of Job Time Occurrence (31 Elements)

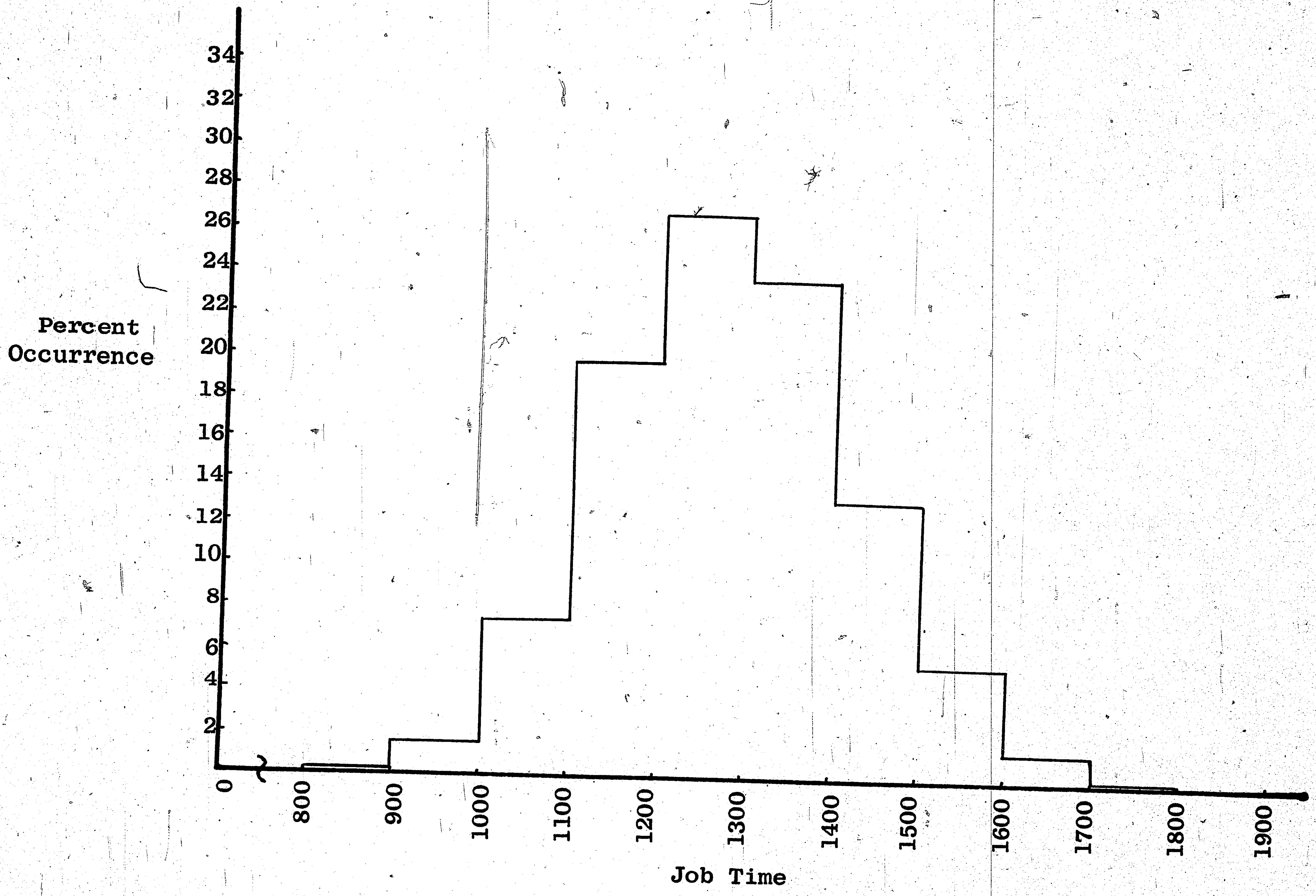


FIGURE 7. Histogram of Job Time Occurrence (36 Elements)

elemental times are used in the balance).

Model J2

The second model will include one standard deviation with the job mean, i.e., job time = $\mu + \sigma$. The sum of job mean time plus one standard deviation divided by the theoretical cycle time of 267 will provide the number of stations required to support the desired cycle time. This number divided into the mean job time provides the cycle time to which the mean element times must be balanced.

Model J3

The third model is the same as Model J2 in all respects except that a multiple of two is included for the variance factor, i.e., job time = $\mu + 2\sigma$. The desired cycle time is calculated as in Model J2.

Model J4

The final model follows directly from its predecessors, and a multiple of three is used for the accounting of the variance, i.e., job time = $\mu + 3\sigma$.

Each of the two sample problems will be balanced to the cycle time determined for each of the Models J1 through J4. The models take progressively larger account of the job time variance. The balances generated by each of these cycle times will subsequently be simulated using randomly generated reconditioning jobs. Figures 8 and 9 show the station and cycle time calculations for the two sample problems.

Work Station Variance Model

The time variance associated with the operations assigned to a

FIGURE 8. Job Variance Model Calculations
31 Element Problem

Theoretical Cycle Time = $C_T = 267$

Model J1: Job Time = average = μ

$$\text{Number of Stations} = N = \left[\frac{1067.93}{267}\right]^+ = 4$$

$$\text{Balance Cycle Time} = C = \left[\frac{1067.93}{4}\right]^+ \approx 268$$

Model J2: Job Time = $\mu + \sigma$

$$\text{Number of Stations} = N = \left[\frac{1067.93+313.51}{267}\right]^+ = [5.17]^+ = 6$$

$$\text{Balance Cycle Time} = C = \frac{1067.93}{6} \approx 178$$

Model J3: Job Time = $\mu + 2\sigma$

$$\text{Number of Stations} = N = \left[\frac{1067.93+627}{267}\right]^+ = [6.35]^+ = 7$$

$$\text{Balance Cycle Time} = C = \frac{1067.93}{7} \approx 153$$

Model J4: Job Time = $\mu + 3\sigma$

$$\text{Number of Stations} = N = \left[\frac{1067.93 + 940.5}{267}\right]^+ = [7.52]^+ = 8$$

$$\text{Balance Cycle Time} = C = \frac{1067.93}{8} \approx 134$$

FIGURE 9. Job Variance Model Calculations
36 Element Problem

Theoretical Cycle Time = $C_T = 267$

Model J1: Job Time = average = μ

Number of Stations = $N = \left[\frac{1285.17}{267}\right]^+ = [4.64]^+ = 5$

Balance Cycle Time = $C = \frac{1285.17}{5} \approx 258$

Model J2: Job Time = $\mu + \sigma$

Number of Stations = $N = \left[\frac{1285.17+144.22}{267}\right]^+ = [5.4]^+ = 6$

Balance Cycle Time = $C = \frac{1285.17}{6} \approx 215$

Model J3: Job Time = $\mu + 2\sigma$

Number of Stations = $N = \left[\frac{1285.17+288.44}{267}\right]^+ = [5.9]^+ = 6$

Balance Cycle Time = $C \approx 215$ as in Model J2.

Model J4: Job Time = $\mu + 3\sigma$

Number of Stations = $N = \left[\frac{1285.17+432.66}{267}\right]^+ = [6.44]^+ = 7$

Balance Cycle Time = $\frac{1285.17}{7} \approx 184$

particular work station may be accumulated to yield the variance of the work station time (assuming statistical independence between operations). Balances which result from using only the element mean times will therefore yield work stations with different ranges of variance. (See Figure 10.) The use of only mean times cannot effectively smooth the variance among the work stations. Even the inclusion of various α factors of the standard deviation will not normally result in an equitable distribution of the variances of the work stations. A portion of the variability will be taken into account but there is no guarantee that the variances of the work stations will be even closely aligned.

Hence the model which would consider only work station variance will be abandoned in favor of the operation time model which will accomplish the same objective of smoothing the variance over the various work stations.

Operation Time Model

The operation time model will consider the mean operation time and the operation variance, that is, both the mean and variance of the element times will be included in the attempts to balance the reconditioning process to the desired production rate.

Model OP1

This model will include one standard deviation plus the mean operation time, i.e., operation time = $\mu + \sigma$. The operations assigned to any work station will result in a balance where the accumulation of mean element times and one standard deviation of their

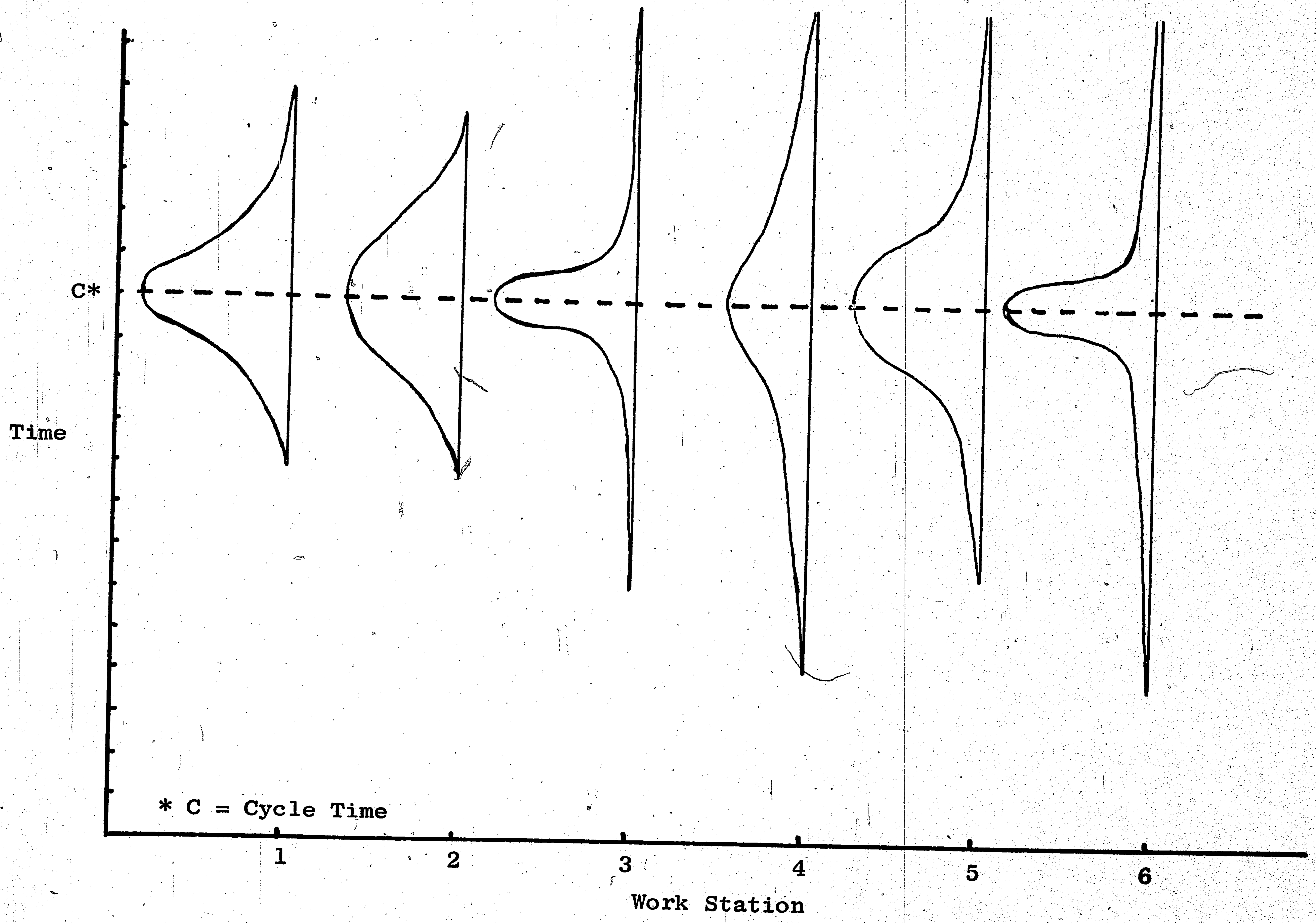


FIGURE 10. Distribution of Work Station Time

variance will be equal to or less than the theoretical cycle time.

Model OP2

This model is an extension of Model OP1 and will include two standard deviations of the elemental time variances of the operations. As was indicated earlier, more and more of the variance is being considered in the balance.

Model OP3

In this model, the variance factor will be three, i.e., operation time = $\mu + 3\sigma$. If the operation times were normally distributed random variables, the consideration of three standard deviations would include almost the entire variance and the probability of exceeding the balance cycle time would be less than .0014.

The line balancing program will attempt to smooth the work station time variation among the work stations. Phase one of the program will assign the operations to the work stations using the "largest candidate" rule and then phase two of the program will attempt to shift operations to achieve a better distribution of variance among the stations. Thus the objectives stated in the discarded work station variance model are inherent in the operation variance model given further credibility to the decision to ignore the work station model.

VI. DEVELOPMENT OF THE EXPERIMENTAL PROCEDURE

Determination of Total Job Time and Operation Time Variance

Since the variance of total job time and operation time have a vital role in the investigation being conducted, the variance for the respective elements had to be estimated. The distributions of the various task times are really discrete, in the sense that the value is a combination of the elemental time and the frequency factor. From a previous example, we saw that an operation required zero time or 6.84 time units depending upon whether the defect occurred or not. A combination of several tasks of this type plus the compulsory inspection tasks yield an operation time which could only be defined by complete enumeration of all possible discrete values of time that could be consumed. This would involve evaluating from one to one hundred and seventy-five combinations in the present problems.

A FORTRAN program was written to expedite the determination of the job and operation time variance. A listing of the program appears in Appendix A. The program utilizes a random number generator, provided as IBM Software, to sample the occurrence of defects in determining the variance. The random number routine generates a decimal number between 0.0 and 1.0. If the random number generated is less than or equal to the frequence of occurrence factor, the defect is considered as part of the sample. If the number is greater than the frequency factor, the elemental time associated with the repair of the defect is not included in the sample. Tables 1 and 2 list the operation means and variances for the individual operation times as

TABLE 1

31 Element Problem

Operation	Mean	Variance
1	20.3	1.8
2	0.04	0.2
3	3.95	17.2
4	1.7	26.5
5	0.5	4.7
6	25.25	2.3
7	18.0	0.0
8	28.0	0.0
9	23.0	0.0
10	19.0	0.0
11	16.2	45.4
12	38.0	0.0
13	18.0	0.0
14	3.0	0.0
15	22.0	0.0
16	27.3	7.2
17	30.0	0.1
18	16.0	0.0
19	68.4	40990.7
20	12.3	1304.1
21	111.6	18650.0
22	14.4	14.1
23	24.0	0.0
24	69.0	24314.6
25	4.0	0.0
26	18.8	2219.4
27	31.8	29.4
28	28.7	178.9
29	62.1	435.6
30	49.0	0.0
31	263.7	10738.3

Job Mean = 1067.9 Job Variance = 98288.4

TABLE 2

36 Element Problem

Operation	Mean	Variance
1	122.2	56.0
2	81.1	1546.2
3	0.9	14.0
4	8.0	0.0
5	11.0	0.0
6	38.2	136.2
7	17.0	0.0
8	53.3	1176.4
9	63.3	1083.4
10	31.7	833.1
11	43.9	165.5
12	20.3	192.3
13	18.8	22.4
14	77.9	4406.8
15	38.0	607.1
16	5.0	30.0
17	7.5	18.8
18	13.5	182.3
19	22.5	288.3
20	29.7	669.7
21	33.0	1089.1
22	18.6	614.1
23	48.0	1857.3
24	43.7	518.4
25	37.0	0.0
26	20.0	0.0
27	95.5	3472.5
28	17.0	0.0
29	8.0	0.0
30	3.0	0.0
31	21.0	0.0
32	97.4	876.7
33	2.5	57.3
34	2.1	25.3
35	5.0	0.0
36	129.8	737.6

Job Mean = 1285.2

Job Variance = 20798.6

well as the total job mean and variance. As can be noted, several of the variances are quite large due to the range of associated time values included in the operation.

Line Balance Technique

The line balance technique suggested by Moodie[26] will be used to derive the balances for the various cycle times calculated earlier. Moodie's technique was chosen since it provided the means whereby the variance of the operations could be introduced into the operation time models. The FORTRAN program was easily modified to enable it to run on an IBM/360 model 50.

The technique assigns operations to work stations using the "largest candidate" rule, that is, the operation possessing the largest element time is chosen first as the logical assignment to the particular work station (precedent constraints permitting). A new station is added if all the operations left to be assigned exceed the time remaining to be assigned at the work station under consideration. The procedure is repeated until all operations have been assigned to one of the work stations. The algorithm then attempts to shift operations among the work stations in an attempt to smooth the slack (delay) time present at the various stations. Delay time is the difference between the cycle time and the cumulative element times at any work station. The program terminates when the balance can no longer be improved by switching operation assignments. (See Appendix B for the program listing.)

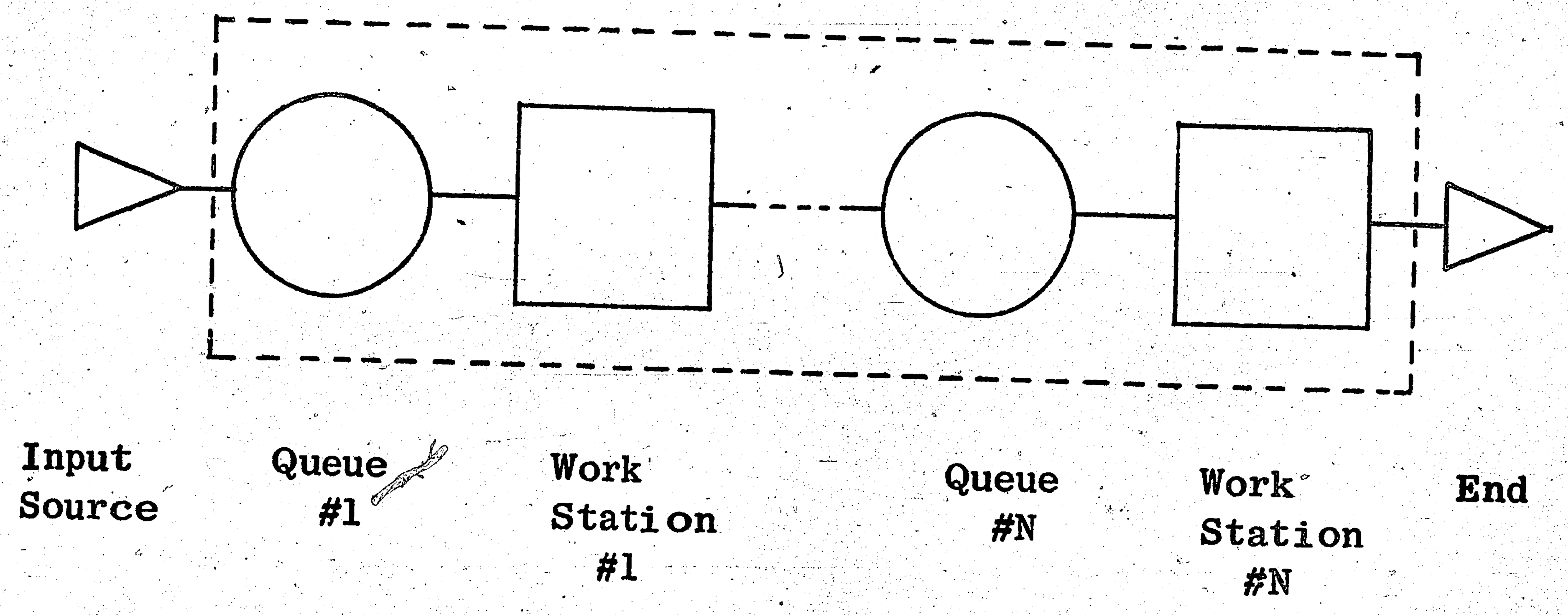
Initially, the two sample problems will be balanced to the number of stations suggested by the calculations appearing in Figures 8 and 9. This will give the balances for the job time models. Then the elements will be balanced anew by introducing the theoretical cycle time of .267 and various factors of the variance. This will give the balances for the operation time models.

Simulation Techniques

Due to the fact that the line balancing techniques are not capable of furnishing all the information necessary to evaluate the resulting line balances, simulation must be employed. There are several avenues which may be taken in this respect, namely, write a simulation program in a language such as FORTRAN or use a specially designed simulation language such as the "General Purpose Simulation System" (GPSS) provided by IBM. Since the model would require frequent changes due to the different balances that would be generated, GPSS was selected due to the ease in modifying and adding work stations with minimal programming effort required. In addition, GPSS either automatically or with little programming effort accumulates many of the statistics which are required for further analysis and comparison of balances. An example of a GPSS program appears in Appendix C.

As each new line setup is generated by the line balance program, a simulation is run using randomly generated reconditioning jobs. Even though the line balancing procedure generates what appears to be a reasonable balance, only actual simulation of the line structure will give an indication as to whether the production rate is actually achieved. It could be that the range of values about the mean of an operation is so large as to disrupt the line organization even with operation variance taken into account. Further statistics as to queue length and job transit time of each reconditioning job are also tabulated. Queue length provides an estimate of the storage that would be required in the case where cycle time was exceeded during any operation. Job transit time reflects the total time a job has been in the system. That is, transit time is an accumulation of the time spent in each queue, except the first, and the total repair time consumed at the various operations.

The simulation model is that of a series queueing situation where the work stations are arranged in a series and all reconditioning jobs progress from the first work station through all other stations in the same first-come-first served priority sequence (see Figure 11). The queue in front of the first work station is designed so that there is always work waiting to be processed, that is, the facility utilization of station one is defined to be one hundred percent. The queues of the subsequent stations have no restrictions since initially the criteria of meeting the required production rate is of prime consideration. If the required production rate is realized, then further investigation considers the maximum and average queue size experienced at each station. The estimated storage required to accommodate the jobs which must be deferred due to jobs which require time in excess of the planned cycle time may disqualify a particular balance even though the production rate criteria is satisfied. Thus, queue size is a



Series Queueing System

Figure 11

decision variable which is relative to the particular product and the cost of providing the off-line storage.

Simulation Input Generation

GPSS permits the use of almost any function desired to effect the generation of jobs to be processed and the distribution of service times. These functions are described in the form of a discrete cumulative distribution curve. Even with this flexibility, it was not deemed feasible to utilize this facet of GPSS, since the operations at each work station could change at each new balance generated. As the components of the stations changed, the cumulative distribution curve would have to be estimated anew and introduced into the simulator. Subsequently, a FORTRAN program was written to facilitate the generation of jobs for the simulator (see Appendix D for program listing).

Each operation with its associated tasks and frequence factors serve as constants in the program. The variables involve the number of work stations and their assigned operations. A sampling technique identical to the one described in first part of this section is used to generate reconditioning jobs for the simulator. This program considerably expedites the preparation of jobs to be simulated. Repeated simulations are realized with jobs generated with different seeds for the random number generator routine.

VII. RESULTS AND DISCUSSION OF THE INVESTIGATION

The discussion of the results will be separated into individual comments pertaining to each of the two sample problems analyzed. Further subdivision will include the line balances generated and the simulation results (Figures 12 through 26). Each of the models enumerated in the previous chapter will be discussed individually in the above format.

Thirty-one Element Problem

Job Variance Models
Model J1

The balance of this model which considers only the average operation times (Figure 12) yields a very close balance to the cycle time introduced into the balance program. No individual operation times exceed the desired cycle time and the precedent constraints permit an efficient assignment of operations to work stations.

The simulation outputs indicate that the utilization of the work stations is quite high ranging from 1.0 for the first station to 0.983 for station number four. Due to the fact that average time values were used to effect the balances, the high utilizations are to be expected. Also the queues in front of each work station tend to be quite large and are increasing. In fact, the system had not reached steady state conditions after processing the equivalent of fifteen working days of reconditioning jobs. The effect is the result of the type of distributions associated with the tasks making up the operations. The example given in Chapter 3 is typical of the repair element times

FIGURE 12. MODEL J1: BALANCE AND SIMULATION RESULTS
31 ELEMENTS

Model J1 - 4 Stations

Station	Operations Assigned	Avg. Station Time
1	1,2,3,6,7,8,9,10,11,12,14,16,17,22	266.4
2	13,14,18,19,20,21,26	267.1
3	4,5,23,24,27,28,29,30	266.8
4	25,31	267.7

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	32.4	83.7	2	.994
3	28.5	73.0	3	.983
4	20.5	56.0	4	.986

Average Production Rate = 36.7 units per hour
Standard Deviation = 2.57

Average Time In System = 22751
Standard Deviation = 7968

and shows that the range from the average time to the element time value needed to repair the job constitutes quite a disruptive effect when the defect is encountered. The balance using only average time values does not adequately solve the engineers line design problems concerning reconditioning jobs experiencing large operation time variance.

The desired production rate of 300 units per day or 37.5 units per hour is not satisfied by the balance of model J1. The average production rate of 36.7 units is calculated from the simulation results of the four station line. This failure to meet minimum production requirements plus the ever increasing queues preceding the work stations disqualify this model as a possible solution to the line balancing problem.

Model J2

This model which included one standard deviation of total job time into the determination of the number of stations desired for the line yielded the six station balance listed in Figure 13. A problem was encountered in attempting to balance the operations to the calculated cycle times. In fact the same problem plagued subsequent balances of both the job time variance and operation time variance models of sample problem number one. Operation thirty-one's average time exceeded the cycle time specified for the balance of all models except Model J1. In addition, the operation could not be partitioned to reduce the operation time within the desired cycle time limits. The operation was subsequently ignored in the remaining balances attempted and simply added as another station once the balances had been generated for the other operations of the problem.

The same operation subsequently introduced problems when it came time to simulate the performance of the line. If the operation was simply placed in the series as for the previous model, the station would cause a bottleneck and effectively blow up the simulation attempts due to a service rate far under the arrival rate of repair jobs. To alleviate this problem, the work station was defined as a parallel facility, that is, a work station manned by two operations performing the same task, hereafter referred to as a storage facility.

The inclusion of the storage as the last operation effectively resulted in one more work station than was indicated by the calculations in Figure 8. Therefore a balance for five stations was generated, Figure 13. The first four stations plus the two resulting from the storage assigned as the last station met the design requirements.

The simulation results indicated an average production rate of 47.3 units per hour with average facility utilization in excess of 0.98 for all work stations and 0.62 for the parallel facility. This model appears to satisfy the design criteria of production rate, however, the queues before each work station are quite large (see Figure 13). Such queue sizes normally could not be supported by assembly line manufacturing of the items in question and blocking would tend to lower the utilization of the work stations. The blocking effect would prevent an operator from passing a job to the next operator if the queue before the next operator's work position

FIGURE 13. MODEL J2: BALANCE AND SIMULATION RESULTS
31 ELEMENTS

Model J2 - 6 Stations

Station	Operations Assigned	Avg. Station Time
1	1,2,3,6,7,11,14,16,17,18,22,25,26	197.2
2	4,5,8,9,10,12,13,19	196.6
3	15,20,21,23,28	198.6
4	24,27,29,30	211.9
5,6	31	263.7

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	27.1	77.3	2	.983
3	46.6	93.0	3	.996
4	150.6	333.7	4	.997
5	0.15	4.3	5	.625

Average Production Rate = 47.3 units per hour
Standard Deviation = 4.92

Average Time in System = 45139
Standard Deviation = 19771

exceeded a specified number. The queue size is a design decision variable which is unique to the item being manufactured and is determined by the feasibility of providing the necessary storage to limit blocking. As such it is a question which must be considered once a balance has been generated which satisfies the design criteria and consequently exceeds the limits of the present research endeavor reported here.

Operation thirty-one further caused the balances of Models J3 and J4 to be modified from a strictly cycle time basis to a number of stations basis. Therefore, the remaining balances were performed with the intent of achieving a balance to a specific number of stations indicated by the same calculations used to determine cycle time (Figure 8).

Model J3

The seven station balance depicted in Figure 14 resulted in an average production rate of 60.5 units per hour and average queue sizes ranging from 0.19 to 48.4 units. The simulations indicate that the work station utilization is high with the lowest average value being 0.970 and 0.800 for the storage. As for the previous models discussed, the queues before each work station are above reasonable limits.

Model J4

As would be expected when more work stations are added to the line, the production rate has increased each time an additional station has been added to the line balance. The current model

FIGURE 14. MODEL J3: BALANCE AND SIMULATION RESULTS
31 ELEMENTS

Model J3 - 7 Stations

Station	Operations Assigned	Avg. Station Time
1	1,2,3,4,5,6,14,16,17,26,28	159.5
2	7,8,9,10,11,12,22,25	160.5
3	15,18,20,21	161.9
4	19,23,24	161.4
5	13,27,29,30	160.9
6,7	31	263.7

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	20.0	47.7	2	.998
3	48.4	95.0	3	.997
4	47.5	127.0	4	.970
5	34.2	96.0	5	.973
6	0.19	3.7	6	.800

Average Production Rate = 60.5 units per hour
Standard Deviation = 4.08

Average Time in System = 25116
Standard Deviation = 8176

(Figure 15) exhibits an average production rate of 72.2 units per hour which is slightly under double the design criteria. Work station utilization is quite good ranging from .955 to .999. As for previous models using average time values, the queue sizes are large and would be reduced by limiting the in-process storages with an accompanying reduction in work station utilization.

In general, the thirty-one element problem was difficult to analyze due to the restriction imposed by the operation whose execution time exceeded cycle time in all job time variance models except the initial average value model. The time variances of the operations possessing variability were quite large and tended to result in large queues building up in front of the operations. Time variance was not the only reason for such backlogs of work. The simulation model itself was a simplification of the actual real world situation. Normally, the repair jobs would not be available to the next operator in the sequence once the preceding operator had completed his assigned tasks. The repair job would either have to be transported manually or automatically by a conveyor to the next work station. Therefore, additional time would be consumed during the transportation phase which would probably result in a generally lower average facility utilization and queue lengths.

Since only average values were used during the determination of the line balances, no real provisions could be made for operation variance. The job time variance could be evaluated and taken into consideration in the determination of the number of stations (see

FIGURE 15. MODEL J4: BALANCE AND SIMULATION RESULTS
31 ELEMENTS

Model J4 - 8 Stations

Station	Operations Assigned	Avg. Station Time
1	1,2,3,4,6,7,14,16,17,25	133.5
2	5,8.9,10,11,18,20,26	133.7
3	12,19,28	135.1
4	15,21	133.6
5	13,22,24,27	133.2
6	23,29,30	135.1
7,8	31	263.7

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	29.9	52.3	2	.999
3	50.3	143.0	3	.983
4	47.5	106.7	4	.984
5	32.9	99.0	5	.960
6	22.5	68.3	6	.975
7	22.7	12.0	7	.955

Average Production Rate = 72.2 units per hour
Standard Deviation = 4.20

Average Time In System = 25881
Standard Deviation = 5877

Figure 8) but this did not relieve the congestion at the work station when the work content of any job exceeded the cycle time.

Operation Variance Models

Model OP05

This model included the cumulative operation times and one-half of the square root of the cumulative operation time variance in the determination of the station time. That is, one-half of the standard deviation plus the mean of the resultant operation assignments are considered in the balance of the repair line. In contrast to the job variance models, the individual variances are now taken into account during the line balance phase of the study.

The resultant balance consisted of five work stations, Figure 16. As can be noted from Figure 16, the work station utilization is less than that experience by the job variance models. However, the queues before each work station are considerably less and approach limits which would probably be tolerated on an actual repair line. The production rate is slightly above the design criteria of 37.5 units.

The last operation of the problem again is causing problems in both the balance and the simulation phases. The mean operation time is almost equal to the cycle time desired for the line. As for the previous models, the operation was ignored during the balance phase and simply added as an extra operation at the end of the line. As such, it proved to be a bottleneck operation which caused a large queue to build up and tended to suppress the production rate of the

FIGURE 16. MODEL OPO5: BALANCE AND SIMULATION RESULTS
31 ELEMENTS

Model OPO5 - 5 Stations

Station	Operations Assigned	Station Time
1	1,2,3,4,5,6,7,8,9,10,11,14,16,17,18,22,25	256.0
2	19,24	265.2
3	20,21,23,26	262.6
4	12,13,15,27,28,29,30	262.3
5	31	267.9

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	0.9	11	2	.555
3	1.2	11	3	.673
4	6.9	15	4	.995
5	155.4	297	5	1.000

Average Production Rate = 37.8 units per hour
Standard Deviation = 2.4

Average Time In System = 42241
Standard Deviation = 20373

balances. In reality, the operation would require either more than one operator to satisfactorily service the facility or the utilization of second shift operations to relieve the congestion at the last work station. Fortunately, the station involved is the last of the series queueing system which would make plausible the second alternative mentioned above.

Model OP1

The inclusion of one standard deviation of the operation times resulted in the seven station balance of Figure 17. The utilization of the facilities is not as uniform as for previous balances. Several operations are busy on the average of 32 percent of the time while others are busy 90 percent of the time. This is not desirable when the individuals work within proximity of each other and would be well aware of the uneven distribution of work load.

Of interest here is the fact that station time is highest for the operations which possess the lowest utilization. The inconsistency results from the distribution of the work content at these stations which are similar to the example of Figure 1. The range from the expected operation time to the actual time experienced is quite large and results in the operations being assigned to an individual work station which is not as busy as the engineer would like. The inclusion of the operation variance overestimates the work content at the station due to the large variance experienced.

As with the previous model, the production rate remains at 37.8 units due to the bottleneck operation at the end of the recondition-

FIGURE 17. MODEL OP1: BALANCE AND SIMULATION RESULTS
31 ELEMENTS

Model OP1 - 7 Stations

Station	Operations Assigned	Station Time
1	1,2,6,7,8,9,10,11,12,13,14	215.8
2	3,4,5,16,17,18,20,22,26,28	215.0
3	24	248.2
4	19	266.9
5	21	248.2
6	15,23,25,27,29,30	214.4
7	31	267.0

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	0.1	3	2	.737
3	0.3	6	3	.322
4	0.6	11	4	.324
5	1.0	11.3	5	.534
6	2.5	11.7	6	.923
7	741.8	1290	7	1.000

Average Production Rate = 37.8 units per hour
Standard Deviation = 2.38

Average Time In System = 158728
Standard Deviation = 80384

ing line.

Model OP2

Figure 18 represents the results of including two standard deviations of the operation variance. The balance consists of seven stations as for the previous model, however, the operations are shifted to satisfy the balance criteria of mean time plus two standard deviations. In general, the work station utilization is lower than for previous two operation models. Lower utilization factors are to be expected since more and more slack is being included into the balance to reduce the possibility of a reconditioning job exceeding the operation cycle time. Likewise the average queue sizes are smaller in relation to those experienced in models OP05 and OP1.

Model OP3

This last model included three standard deviations of the operation time variance and resulted in the eight station balance of Figure 19. The work station utilization is again lower than what would normally be tolerated in an industrial environment. The same inconsistency of high station time and low facility utilization is shown by the simulation results. The reason for the phenomena is expressed in the discussion of Model OP1.

Thirty-six Element Problem

The second sample problem proved to be easier to manipulate throughout the analysis due to the sizes of the operation times in relation to the cycle times attempted. In addition, the time variances were not as extreme (See Tables I and II) as those

FIGURE 18. MODEL OP2: BALANCE AND SIMULATION RESULTS
31 ELEMENTS

Model OP2 - 7 Stations

Station	Operations Assigned	Station Time
1	1,2,3,5,6,7,8,9,10,14,16,17,18,22,25	246.5
2	4,11,12,13,15,20,26	246.9
3	24	267.0
4	21	266.8
5	19	267.0
6	23,27,28,29,30	246.3
7	31	266.9

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	0.03	2	2	0.548
3	0.20	5	3	0.296
4	0.37	6	4	0.471
5	0.49	8.3	5	0.291
6	1.79	9	6	0.841
7	394.1	745.0	7	1.000

Average Production Rate = 37.8 units per hour
Standard Deviation = 2.41

Average Time In System = 93311
Standard Deviation = 46789

FIGURE 19. MODEL OP3: BALANCE AND SIMULATION RESULTS
31 ELEMENTS

Model OP3 - 8 Stations

Station	Operations Assigned	Station Time
1	1,2,5,6,7,8,9,10,11,12	210.4
2	3,4,13,15,16,17,18,22,25,28	212.9
3	24	267.0
4	19	267.0
5	14,20,26	212.2
6	21	267.0
7	23,27,29,30	231.0
8	31	267.0

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	0.003	1	2	.881
3	0.4	8.3	3	.384
4	0.8	11	4	.357
5	0.2	9.3	5	.179
6	1.4	10.7	6	.602
7	2.2	11.3	7	.886
8	737.1	1256	8	1.000

Average Production Rate = 37.8 units per hour
Standard Deviation = 2.35

Average Time In System = 171869
Standard Deviation = 79888

encountered in the first problem and more operations possessed the characteristic of variability than in the previous problem.

Job Time Variance Models

Model J1

The use of strictly average values resulted in the five station balance of Figure 20. The station times are very well distributed with average utilization above 0.990 for all work stations. The average production rate of 38.6 is slightly above the 37.5 units per hour set as a design objective. As in the first sample problem, the system has not reached steady state and the queues are gradually increasing. Most likely the work station utilization will decrease once in-process inventory restrictions are imposed before the decision to accept the line balance is realized.

Models J2 and J3

The two models which take into account the standard deviation of total job time and a multiple of two standard deviations resulted in a balance consisting of six stations, Figure 21. Each station had an average utilization greater than 0.980 and on the average had more in-process inventory (queues) scattered throughout the system than for the previous model J1 (See Figure 20). The average production rate was slightly above 46 units per hour as contrasted to the desired rate of at least 37.5 units.

Model J4

This model includes three standard deviations of the total job time standard deviation as well as the mean job time and call for a

FIGURE 20. MODEL J1: BALANCE AND SIMULATION RESULTS
36 ELEMENTS

Model J1 - 5 Stations

Station	Operations Assigned	Avg. Station Time
1	1,2,6,18,33	257.5
2	3,9,10,11,12,13,14	256.8
3	4,5,7,16,20,21,22,24,25,28,29,30,31,35	257.0
4	8,15,19,23,27	257.2
5	17,26,32,34,36	256.8

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	5.4	20.0	2	.993
3	11.1	29.6	3	.996
4	10.5	28.0	4	.997
5	5.1	17.2	5	.993

Average Production Rate = 38.6 units per hour
Standard Deviation = 1.26

Average Time In System = 9659
Standard Deviation = 2463

FIGURE 21. MODEL J2 & J3: BALANCE AND SIMULATION RESULTS
36 ELEMENTS

Model J2 & J3 - 6 Stations

Station	Operations Assigned	Avg. Station Time
1	1,2,3,30,33,34	211.8
2	6,7,9,10,11,12	214.4
3	4,13,14,16,18,22,24,28,29,35	215.5
4	15,17,19,20,21,23,25	215.7
5	27,31,32	213.8
6	5,8,26,36	214.1

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	42.2	77.0	2	1.000
3	20.1	54.7	3	.997
4	19.8	37.3	4	.998
5	5.7	20.3	5	.984
6	5.2	22.7	6	.987

Average Production Rate = 46.0 units per hour
Standard Deviation = 1.69

Average Time In System = 20952
Standard Deviation = 7888

balance of operations among seven work stations (Figure 22). The station times are evenly distributed with no obvious bottlenecks due to an inability to arrive at an efficient balance. Efficiency pert ains to the balance delay inherent in the particular balance solution in relation to the cycle time of the problem. Facility utilization is consistently high, greater than 0.98, as has been the experience with the other job time models considered. The queue build-ups are still present before each station. It should be reiterated that the queue length tolerated by a system is a variable which will change depending upon the problem under consideration. Certainly an average queue of fourteen refrigerators cause more concern by the design engineer than fourteen subminiature solid state electronic modules which require very little in the way of storage facilities. Therefore, the queue length was not introduced as a parameter to be investigated in this study.

The average production rate of 53.6 units satisfies the design criteria established by management. It should be noted that the production rate has a distribution with its associated mean and variance. Although the average production criteria of 37.5 units per hour was established as a design criteria, there is no reason why confidence limits could not be established for the rate. The criteria would then include a statement to the effect that the actual production rate should exceed the design criteria a set percentage of the time.

FIGURE 22. MODEL J4: BALANCE AND SIMULATION RESULTS
36 ELEMENTS

Model J4 - 7 Stations

Station	Operations Assigned	Station Time
1	1,9	185.5
2	2,10,11,31,33,34	182.3
3	4,6,7,12,13,16,18,22,26,28,29	184.4
4	3,8,19,20,21,24	183.0
5	5,14,27	184.4
6	15,17,25,30,32	182.9
7	23,35,36	182.8

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	3.6	15.3	2	.985
3	12.4	31.0	3	.998
4	3.8	16.0	4	.986
5	18.9	43.3	5	.996
6	6.0	24.3	6	.981
7	3.6	13.7	7	.980

Average Production Rate = 53.7 units per hour
Standard Deviation = 2.30

Average Time In System = 10220
Standard Deviation = 2487

Operation Variance Models

Model OP05

The six station balance generated as a result of including one-half of the operation time standard deviation is displayed in Figure 23. The balance station time appears to be uniform over the six stations. Average utilization of the work stations is consistently above .90 and the majority of the queues are within reasonable limits. However, the queue in front of the second work station is quite large since the average station time of the station is greater than that of its predecessor. Therefore, on the average the station is receiving jobs faster than it is servicing them. The average production rate of 44.4 units satisfies the design criteria.

Model OP1

Inclusion of one standard deviation of operation variance increases the line balance by one station over the balance of Model OP05, Figure 24. The seven station balance appears to be reasonably smooth when the station times are compared. The simulation indicates that the average utilization is uniformly above .80 with an overall average of .958. Station three appears to be forming a bottleneck since a large queue is building up at the station. Should a limit be placed upon in-process inventory, the stations preceding station three would experience a decrease in average utilization. The average production rate of 49.7 units per hour is well above the criteria of 37.5 units.

FIGURE 23. MODEL OPO5: BALANCE AND SIMULATION RESULTS
36 ELEMENTS

Model OPO5 - 6 Stations

Stations	Operations Assigned	Station Time
1	1,2,4	243.3
2	6,7,9,24,25,28,30,33	242.9
3	10,11,13,14,17,22,34	243.2
4	3,5,12,15,16,18,19,20,21,26,31	242.5
5	8,23,29,32,35	242.9
6	27,36	257.7

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	149.3	279.7	2	1.000
3	0.6	5.6	3	.901
4	1.6	7.7	4	.968
5	1.3	9.7	5	.953
6	45.9	90.3	6	1.000

Average Production Rate = 44.41 units per hour
Standard Deviation = 2.0

Average Time In System = 43205
Standard Deviation = 20603

FIGURE 24. MODEL OP1: BALANCE AND SIMULATION RESULTS
36 ELEMENTS

Model OP1 - 7 Stations

Stations	Operations Assigned	Station Time
1	1,4,9	239.22
2	2,3,6,10,18,26	237.4
3	5,11,12,30,31,32,33,34	237.5
4	7,13,16,20,21,24,25,35	237.42
5	8,14,17,19	238.3
6	15,22,27,28	239.0
7	23,29,36	236.7

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	1.1	8.3	2	.960
3	130.8	240.0	3	1.000
4	0.6	5.0	4	.941
5	0.3	4.3	5	.802
6	0.5	5.3	6	.837
7	0.9	6.0	7	.922

Average Production Rate = 49.7
Standard Deviation = 1.88

Average Time In System = 27137
Standard Deviation = 12400

Model OP2

The balance, when two standard deviations are considered, consists of nine work stations, Figure 25. This is a jump of two additional work stations over the previous model. The simulations indicate that none of the stations are experiencing any abnormal build-up of queues which require modifying the performance of preceding work stations. The average utilization ranges from .46 to .97 with an overall average of .82. The average production rate of 57.1 units per hour more than adequately satisfies the design criteria.

Model OP3

When three standard deviations of the operation variance are taken into account, the ten station balance displayed in Figure 26 was generated by the balance technique. The maximum time difference between the stations is approximately twenty time units which is not unusual since it is rarely possible to arrive at a perfect balance when considering practical applications. The station utilization ranges from .82 to .37, excluding the first station which was designed to have full utilization. The overall average of .606 is further realized in a decreased production rate of 47.2 units as compared to the previous nine station balance and its 57.1 unit production rate. The average sizes of the queues preceding each work station indicate that the queues were empty a considerable protion of the time. The balanced station time overcompensated for the operation variance so that in-process inventory was reduced to a minimum. In fact, the maximum queue size did not exceed four units at any point

FIGURE 25. MODEL OP2: BALANCE AND SIMULATION RESULTS
36 ELEMENTS

Model OP2 - 9 Stations

Station	Stations Assigned	Station Time
1	1,8	245.7
2	2,18,20,26	243.2
3	5,6,7,9,28,30,31	240.3
4	3,10,11,24,25,35	240.5
5	13,19,22,32	242.2
6	21,23	249.9
7	12,14,33,34	241.4
8	4,16,17,27,29	242.6
9	15,36	241.1

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	0.2	2.7	2	.822
3	1.4	8.0	3	.973
4	0.5	5.0	4	.926
5	0.4	4.7	5	.895
6	0.02	1	6	.460
7	0.2	3	7	.583
8	0.3	4	8	.705
9	1.5	8	9	.959

Average Production Rate = 57.1 units per hour
Standard Deviation = 1.84

Average Time In System = 2052
Standard Deviation = 316

FIGURE 26. MODEL OP3: BALANCE AND SIMULATION RESULTS
36 ELEMENTS

Model OP3 - 10 Stations

Station	Operations Assigned	Station Time
1	1,4,5,26,28,29,31,33,34	247.12
2	2,3,6,30	246.71
3	7,9,24,35	249.06
4	10,11,12,18,19	254.22
5	13,20,21,22	258.54
6	8,23	266.49
7	14	266.73
8	15,16,32	257.03
9	27	266.74
10	17,25,36	256.81

Queue	Avg. Size	Avg. Max. Size	Facility	Avg. Utilization
1	∞	∞	1	1.000
2	0.0	1	2	.582
3	0.02	1	3	.607
4	0.04	2	4	.621
5	0.02	1.7	5	.473
6	0.05	2	6	.478
7	0.05	3	7	.369
8	0.2	3	8	.662
9	0.04	2	9	.448
10	0.3	3.3	10	.824

Average Production Rate = 47.2 units per hour
Standard Deviation = 0.9

Average Time In System = 1433
Standard Deviation = 105

during the simulation.

Factors Affecting Results

Several factors which contribute to the overall problem of designing a production facility for the reconditioning task will be briefly discussed in the light of the balance and simulation results.

Precedence Constraints

The physical ordering of the various operations to be performed impose the most stringent limits upon the final balance generated for an assembly line. Due to the restrictions as to which operations must be performed before others, the number of feasible solutions of the balance problem is considerably reduced. Often a smooth balance of work among the work stations is not possible due to these precedent constraints. This is not to imply that the solution cannot represent the optimal solution for the particular balance problem.

The line balances generated for the job variance models of both sample problems do not appear to have been adversely affected by the precedent constraints imposed upon either of the problems. The average element times, except notably for the single operation of the first sample problem, coupled with the constraints resulted in reasonably smooth balances for the various models. In general, the line balances of the operation variance models faired as well except for model OP1 which had a difference of fifty time units between some work stations.

Operation Variance

The variance associated with the various operations was estimated by means of Monte Carlo simulation and are listed in Tables 1 and 2. The variances are quite large as compared to the element time averages, especially for several operations of the 31 element problem. The magnitude of such variances is due to the distribution of task times which constitute the various operations. The operation time can be characterized by a discrete distribution made up of the possible combinations of tasks which can occur at the stations. The estimated variance therefore does not permit the statement of confidence limits on operation time as could be stated for a continuous normally distributed random variable. The inclusion of various factors of the standard deviation of operation time does not have the same meaning as for the continuous distribution mentioned. Therefore, the inclusion of three standard deviations into the operation time evaluation does not imply that 99.87 percent of the reconditioning jobs will fall within the stated time over the long run. This fact introduces a degree of inexactness whose influence cannot be adequately evaluated as to its effect upon the balances of the operation variance models. The additional fact that the mean times and the associated variances were determined from combining the two values of recondition task time and frequence of such task performance, lends an air of fluidity which makes one reluctant to make probability statements without first simulating the balance and analyzing the results.

Line Balance Technique

The line balance technique utilized throughout this study was the only one available which permitted the inclusion of operation time variance into the final balance. The technique employs the "largest candidate" rule for the initial assignment of operations to work stations. The cycle time is a constant introduced into the technique and additional work stations are added to the balance as the cycle time is exceeded when attempting to assign available operations to the work station currently being loaded. Once the initial assignment has been completed, the technique attempts to interchange or remove operations from the work stations in order to arrive at a more efficient balance.

During several balance attempts, the technique generated one additional work station than was ultimately needed for the solution. This resulted in a cycling of the program which would not terminate the process unless cancelled by a time limit on the length of the computer run attempted. To overcome such an occurrence, the balance had to be attempted with cycle times neighboring on the desired cycle time and selecting the most efficient balance from those generated.

In addition, it would appear that the final balance is quite dependent upon the initial assignment of operations to the work stations. This condition was brought to light during the attempts to overcome the cycling problem mentioned above. The cycle times neighboring upon the theoretical time resulted in different balances for the same number of stations. This, in itself, is not an unusual aspect of the balance problem, since there are often more than one optimal solution to such problems. However, since the technique does not guarantee optimal solutions, it was necessary to simulate the balances to effectively determine which would perform most efficiently.

If deterministic times were used, the balance solution could provide sufficient information to gauge the more reasonable of two or more solutions for the same basic problem. This did not prove to be the case when dealing with the time variance problems discussed here. The most efficient solution based upon minimum unused time in respect to the cycle time did not automatically give the best operation results. Therefore, simulation proved to be the only effective tool for evaluating the balance solutions.

VIII. SUMMARY AND CONCLUSIONS

The primary objective of this study was to investigate the employment of a computerized line balance technique to set up a reconditioning process line patterned after an assembly line operation. The two approaches studied, namely the job time variance model and the operation time variance model, were analyzed not only from the viewpoint of the balances generated by the computerized technique but also from the line performance as estimated by the simulation of reconditioning jobs serviced by the work stations defined. A summary of the simulation results appears in Figures 27 and 28. As seen from these summarized results as well as the more detailed discussion of the previous chapter, the operation variance model yields a more efficient balance from the standpoint of realizing the established production requirements with tolerable in-process queues before the work stations.

The operation variance model explicitly accounts for variance in work content from job to job, whereas, the job variance model attempts to compensate for this variability by adding additional work stations to the balance in an implied attempt to smooth the variance among the work stations.

The job variance models uniformly experienced high station queues which would not be desirable from a manufacturing standpoint. The summarized figures of average queue size would seem to indicate that the same is also true for the operation variance models. However, a closer inspection of the detailed results of the last

FIGURE 27: SUMMARY OF RESULTS - 31 ELEMENTS

	# Stations	Avg. Util.	Hi Util.	Lo Util.	Avg. Queue	Hi Avg. Queue	Lo. Avg. Queue	Avg. Max. Queue	Avg. Prod. Rate	Std. Dev.
Model J1	4	.988	.994	.983	27.12	32.4	20.5	70.9	36.74	2.57
Model J2	4-2	.900	.997	.625	56.12	150.6	0.15	127.1	47.3	4.91
Model J3	5-2	.948	.998	.800	30.07	48.4	0.19	73.9	60.5	4.07
Model J4	6-2	.976	.999	.955	34.31	50.3	22.5	80.2	72.2	4.20
Model OP 5	5	.806	1.000	.555	41.1	155.4	0.93	83.5	37.8	2.40
Model OP1	7	.640	1.000	.322	124.4	741.8	0.1	222.1	37.8	2.38
Model OP2	7	.589	1.000	.291	66.21	394.1	.03	129.7	37.8	2.41
Model OP3	8	.613	1.000	.179	106.0	737.1	.003	186.8	37.8	2.35

FIGURE 28: SUMMARY OF RESULTS 36 ELEMENTS

	# Stations	Avg. Util.	Hi Util.	Lo Util.	Avg. Queue	Hi Station Queue	Lo Station Queue	Avg. Max. Queue	Avg. Prod. Rate	Std. Dev.
Model J1	5	.995	.997	.993	8.03	11.1	5.1	23.7	38.64	1.26
Model J2 Model J3	6	.993	1.000	.984	18.60	42.2	5.2	42.2	46.04	1.69
Model J4	7	.988	.998	.980	8.05	13.9	3.6	23.9	53.66	2.30
Model OP	6	.964	1.000	.953	78.6	279.7	5.6	78.6	44.4	2.00
Model OP1	7	.958	1.000	.875	25.19	87.7	0.7	44.8	51.67	2.29
Model OP2	9	.817	.973	.460	.56	1.5	0.02	4.5	57.11	1.84
Model OP3	10	.606	.824	.369	.08	.32	0.01	2.1	47.24	.9

chapter would show that the high average is attributed to a single operation which in most instances can be adjusted without an adverse effect upon the remaining line components.

In the course of this investigation, it became apparent that the standard criteria for evaluating the optimality of a particular balance solution does not unequivocally result in the most efficient actual line performance when the variance is introduced into the problem. The operation variance inherent in the reconditioning process is often localized by the precedent constraints so that the variance cannot be effectively smoothed over the work stations of the balance. The mix of deterministic time inspection tasks and the variable time reconditioning tasks further complicate the assignment problem facing the balance technique. A simulation of the suggested work station-operation assignment must be executed in order to evaluate the balance in terms of the actual production rate realized and the in-process queues experienced during the operation of the line.

In summary, this investigation has found that the variable element time line balance technique of Moodie[26] has produced a more efficient balance for the two sample problems under consideration when various factors of the operation time standard deviation are included in the work station assignment time. However, the balance solution cannot be implemented without first simulating actual line performance to prove that the balance will meet design criteria set for the line. The influences exerted by the precedent constraints, and the operation time variances cannot be fully appreciated without the inclusion of the simulation step in the design procedures associated with the set up of such a reconditioning process.

IX. AREAS OF FURTHER STUDY

Line Unbalance

Since performance times are variable except possibly in machine controlled operations, this variability has an effect on the lines operation. Any operator who consumes more time than is allotted to his assigned tasks affects the operators following him in the line. If he does not finish a workpiece, then no one after him can work on it. The relative position of the operator in respect to the other operators can have a varying affect upon line performance. If the operator is at the beginning of the line, the delay resulting from the operation time exceeding cycle time is felt by the entire line. Succeeding operators must work faster than usual to gain back the time. However, if an operator located near the end of the line is late, the consequences are less disturbing, since fewer operators follow him. Therefore, it may be desirable to deliverately unbalance the line in order to absorb the effects of variable performance times. A start on this problem has been made by Hillier and Boling.[12]

Unfortunately, the line balancing algorithms as the term implies, does not permit different cycle times for the various stations. From the results of Hillier and Boling,[12] it would appear that such a modification should be made to an existing algorithm and the deliberate unbalance of an actual assembly line be attempted to gain further insight into this area.

Parallel Facilities

During the course of the simulations it became necessary to assume that two operators were assigned to a particular work station since the operation time exceeded the cycle time desired. This arbitrary assignment does not result automatically in the best balance. There is slack time present at the multiple operator work station which should be considered along with the slack at all the other work stations. A balance utilizing this slack time effectively could result in fewer work stations per line.

The line balance program does not permit the assignment of multiple operators to work stations. The discussions of Freeman and Jucker[4] and Heskiaoff[9] indicate that the ability to include parallel facilities would be a reasonable extension of present line balancing techniques.

APPENDIX A

Appendix A contains the program listing of the FORTRAN program which was used to estimate the job time and operation time variance. The program was run on an IBM/360 model 50.

```
C ################################################################
C
C         PROGRAM TO DETERMINE MEAN AND SAMPLE VARIANCE OF OPERATION
C         TIMES OF THE ASSEMBLY PROCESS
C
C ################################################################
C
C ****************************************************************
C
C     VARIABLE DEFINITIONS
C
C         NTT = TOTAL NUMBER OF TASK OPERATIONS
C         NSAP = SAMPLE SIZE
C         IVAR = VARIANCE LOGIC
C              -0- MEANS THAT THE MEAN FREQUENCY OF DEFECT OCCURRENCE
C                  IS DETERMINISTIC -- CONSTANT --
C              -1- MEANS THAT FREQUENCY IS NORMALLY DISTRIBUTED
C         ITASK = AN ARRAY WHICH CONTAINS THE ELEMENT TIMES, MEAN
C                 FREQUENCY OF DEFECT OCCURRENCE AND THE VARIANCE
C                 OF THE FREQUENCY
C         ITER = THE NUMBER OF ITERATIONS OF THE SAMPLE ROUTINE
C         IX = SEED FOR RANDOM NUMBER GENERATOR -RANDU-
C         SUM = SUM OF SAMPLE VALUES GENERATED PER ITERATION FOR EACH
C               OPERATION (TASK)
C         SSQAR = SUM OF THE SQUARES OF THE VALUES FOR EACH OPERATION
C         TMEAN = SUM OVER ALL SAMPLE ITERATIONS
C         TSTD = SUM OF SQUARES OVER ALL SAMPLE ITERATIONS
C         TSUM = SUM OF VALUES FOR THE ENTIRE JOB ( SUM OF EACH
C                OPERATION COMPRIZING THE JOB)
C         TSSQAR = SUM OF SQUARES OF JOB VALUES
C
C ****************************************************************
C
      REAL*8 SUM,SSQAR,TSUM,TSSQAR
      DIMENSION SUM(50),SSQAR(50),ITASK(50,20,4),NST(50),TMEAN(50),TSTD(
```

```
      150)
       TJMEAN = 0.0
       TJSTD = 0.0
       DO 15 I =1,50
       DO 10 J=1,20
 10    ITASK(I,J,4) = 0
       TMEAN(I) = 0.0
 15    TSTD(I) = 0.0
 C
 C         READ CONTROL CARD
 C
       READ(1,100) NTT,IVAR,NSAP
 100   FORMAT(I3,I1,I5)
 C
 C         READ IN NUMBER OF SUBTASKS PER OPERATION
 C
       DO 30 K=1,NTT
       READ(1,110) NT,NST(NT)
 110   FORMAT(2I3)
       IF(NT-NTT) 20,20,220
 20    KST = NST(NT)
 C
 C         READ IN ELEMENT TIMES, FREQUENCY,VARIANCE
 C
       DO 30 KK = 1,KST
       READ(1,120) IT,IST,(ITASK(IT,IST,J),J=1,3)
 120   FORMAT(2I3,I5,I3,I5)
       IF(IT - NT) 240,30,240
 30    CONTINUE
 C
 C         READ IN NUMBER OF ITERATIONS TO PERFORM
 C
       READ(1,260) ITER
 260   FORMAT(I3)
       DO 86 JKL = 1,ITER
```

```
C
C          READ IN RANDU SEED
C          IX = SEED -- ODD POSITIVE INTEGER LESS THAN NINE DIGITS
C
      READ(1,270) IX
270   FORMAT(I8)
      TSUM = 0.0
      TSSQAR = 0.0
C
C          GENERATE RANDOM DATA FOR DISTRIBUTION SAMPLE
C          NSAP = NUMBER OF SAMPLES
C
      DO 35 I=1,NTT
      SUM(I) = 0.0
35    SSQAR(I) = 0.0
      DO 80 N = 1,NSAP
      TJOB = 0.0
      DO 70 I = 1,NTT
      LEND = NST(I)
      SET = 0.0
      DO 60 J = 1,LEND
      IF(ITASK(I,J,2) - 100) 40,50,50
40    IF(IVAR - 1) 42,90,200
42    IFREQ = ITASK(I,J,2)
44    FREQ = IFREQ
      CALL RANDU(IX,IY,YFL)
      IX = IY
      YFL = YFL*100.0
      IF( FREQ - YFL)60,50,50
50    SET = SET + ITASK(I,J,1)
      TJOB = TJOB + ITASK(I,J,1)
      ITASK(I,J,4) = ITASK(I,J,4) + 1
60    CONTINUE
      SUM(I) = SUM(I) + SET
      SSQAR(I) = SSQAR(I) + SET**2
```

```
   70 CONTINUE
      TSUM = TSUM + TJOB
      TSSQAR = TSSQAR + TJOB**2
   80 CONTINUE
C
C         THIS SECTION COMPUTES THE SAMPLE MEANS AND VARIANCES OF THE
C         ELEMENTS TIMES PER OPERATION
C
      WRITE(3,130)
      WRITE(3,135)
      DO 85 I = 1,NTT
      SMEAN = SUM(I)/NSAP
      STD = (NSAP*SSQAR(I) - (SUM(I))**2)/((NSAP)*(NSAP - 1))
      IF(STD)75,76,76
   75 STD = -STD
   76 WRITE(3,140) I,SMEAN,STD
      TMEAN(I) = TMEAN(I) + SMEAN
      TSTD(I) = TSTD(I) + STD
   85 CONTINUE
      SMEAN = TSUM/NSAP
      STD = (NSAP*TSSQAR - TSUM**2)/( NSAP*(NSAP-1))
      IF(STD)855,856,856
  855 STD = -STD
  856 WRITE(3,160) ITER,SMEAN,STD
  160 FORMAT(1H ,'ITERATION=',I3,5X,'JOB MEAN =',F10.4,5X,'JOB VARIANCE
     1=',F12.3)
      TJMEAN = TJMEAN + SMEAN
      TJSTD = TJSTD + STD
   86 CONTINUE
      WRITE(3,150)
      WRITE(3,170)
  170 FORMAT(1H1,'TASK  SUBTASK  E-TIME  FREQ  VARIANCE  COUNT  PERCENT'
     1)
      DO 750 I=1,NTT
      LEND = NST(I)
```

```
      DO 750 J=1,LEND
      A = ITASK(I,J,4)
      B = ITER*NSAP
      PER = (A/B)*100.0
      WRITE(3,180)I,J,(ITASK(I,J,K),K=1,4),PER
750   CONTINUE
180   FORMAT(1H ,I4,4X,I4,4X,I5,3X,I3,4X,I5,2X,I6,3X,F6.2)
      WRITE(3,190)
190   FORMAT(1H1,10X,'AVERAGE MEAN AND VARIANCE OF ALL SAMPLES')
      WRITE(3,135)
      DO 630 LL=1,NTT
      SMEAN = TMEAN(LL)/ITER
      STD = TSTD(LL)/ITER
      IF(STD)610,620,620
610   STD = -STD
620   WRITE(3,140) LL,SMEAN,STD
630   CONTINUE
      SMEAN = TJMEAN/ITER
      STD = TJSTD/ITER
      WRITE(3,160) ITER,SMEAN,STD
      WRITE(3,150)
      STOP
C
130   FORMAT(1H1,10X,'SAMPLE MEAN AND SAMPLE VARIANCE OF OPERATION TIMES
     1')
135   FORMAT(1HO)
140   FORMAT(1H ,'OPERATION =',I3,5X,'MEAN =',F10.4,5X,'VARIANCE =',F12.
     13)
150   FORMAT(1H1)
C
C        SAMPLE FREQUENCY FROM NORMAL DISTRIBUTION
C
90    YT = ITASK(I,J,3)
      IF(YT) 92,91,92
91    XS = 0.0
```

```
      GO TO 93
92    XS = SQRT(YT)
93    XAM = ITASK(I,J,2)
      CALL GAUSS(IX,XS,XAM,XV)
      IFREQ = XV
      IF(IFREQ) 60,60,95
95    IF(IFREQ - 100) 44,50,50
200   WRITE(3,210) IVAR
210   FORMAT(1H1,'VARIANCE LOGIC INCORRECT',5X,I5)
      STOP
C
220   WRITE(3,230) NT,NTT
230   FORMAT(1H1,'TASK # GREATER THAN TOTAL # OF TASKS',2I5)
      STOP
C
240   WRITE(3,250) IT,NT
250   FORMAT(1H1,'TASK # NOT EQUAL',2I3)
      STOP
      END
      SUBROUTINE RANDU(IX,IY,YFL)
C
C     GENERATES RANDOM NUMBERS FROM UNIFORM DISTRIBUTION
C
      IY=IX*65539
      IF(IY)5,6,6
5     IY=IY+2147483647+1
6     YFL=IY
      YFL=YFL*.4656613E-9
      RETURN
      END
```

```
      SUBROUTINE GAUSS(IX,S,AM,V)
C
C        SUBROUTINE TO GENERATE NORMALLY DISTRIBUTED NUMBERS
C
      A = 0.0
      DO 50 I=1,12
      CALL RANDU(IX,IY,Y)
      IX=IY
50    A = A+Y
      V = (A-6.0)*S+AM
      RETURN
      END
```

APPENDIX B

Appendix B contains the program listing of the FORTRAN program used to balance the reconditioning lines. The program is primarily the same as Moodie's[26] program except that necessary changes were made to make it compatible with the IBM/360 FORTRAN level G. The program was also modified to handle a larger problem than originally planned. The program was run on an IBM/360 model 50.

```
C ################################################################
C          MOODIES LINE BALANCE ROUTINE FOR VARIABLE WORK ELEMENT TIMES
C
C ################################################################
C ****************************************************************
C
C          PARAMETER DEFINITIONS
C
C          E = MEAN ELEMENT TIME ARRAY
C          V = VARIANCE OF ASSOCIATED ELEMENT TIME ARRAY
C          PRE = PRECEEDING ELEMENT ARRAY
C          FOL = FOLLOWING ELEMENT ARRAY
C          CAND = CANDIDATE ARRAY OF ELEMENTS TO BE ASSIGNED
C                 TO WORK STATIONS
C          STAT = STATION ARRAY
C          BALDEL = BALANCE DELAY FOR EACH WORK STATION
C          TOTS = TOTAL TIME ALLOCATED TO EACH STATION, INCLUDES
C                 MEAN ELEMENT TIME PLUS STDF FACTOR OF ITS VARIANCE
C          PRECK = ARRAY INDICATING THE ORDER IN WHICH ELEMENTS
C                  MAY BE SELECTED FOR ASSIGNMENT.  VALUE EQUALS THE
C                  MAXIMUN NUMBER OF PRECEEDING ELEMENTS ALLOWED
C                  IN -PRE- MINUS THE NUMBER OF ELEMENTS IN THE
C                  ASSOCIATED PRECEEDING MATRIX ROW OF THE ELEMENT.
C          S = THE SUM OF THE MEAN ELEMENT TIMES PER STATION
C          VS = THE SUM OF THE VARIANCES PER STATION
C          BRYTON = ARRAY USED TO BALANCE WORK STATIONS DURING
C                   PHASE 2 OF THE TECHNIQUE
C ****************************************************************
C
C          VARIABLES
C
C          IPEND = MAXIMUM NUMBER OF ELEMENTS THAT MAY PRECEED
C                  ANY PARTICULAR ELEMENT
C          IFEND = MAXIMUM NUMBER OF ELEMENTS THAT MAY FOLLOW ANY
```

```
C                PARTICULAR ELEMENT
C        IET = MAXIMUM NUMBER OF ELEMENT TIMES PERMITTED
C        ICEND = NUMBER OF SPACES IN THE -CAND- ARRAY
C        ISTEND = MAXIMUM NUMBER OF STATIONS THE PROGRAM WILL HANDLE
C        LE = NUMBER OF ELEMENTS TO BE BALANCED DURING THIS RUN
C        C = CYCLE TIME OF THIS RUN
C        STDF = INCREMENT OF THE WORK ELEMENTS VARIANCE TO BE
C               INCLUDED IN THE BALANCE OF THIS RUN
C        NSTATS = THE NUMBER OF STATIONS DESIRED IN THE BALANCE
C        NBIND = INDICATES AS TO WHETHER THE NUMBER IN -NSTATS-
C                IS BINDING AND THE BALANCE WILL HAVE EXACTLY
C                (NSTATS) STATIONS
C                       0 = NOT BINDING
C                       1 = NUMBER OF STATIONS MUST EQUAL NSTATS
C
C *******************************************************************
      DIMENSION E(70),V(70),PRE(70,20),FOL(70,20),CAND(7,30),STAT(3,30,
     1  30),BALDEL(30),TOTS(30),PRECK(70),S(30),VS(30),BRYTON(2,30)
      ISTEND = 30
      ICEND = 30
      ICXEND = ICEND + 1
      ICCEND = ICEND - 1
      IPEND = 19
      IPPEND = 20
      IFEND = 20
      TTCAND = 500.0*ICEND
      IET = 70
      IOUCH = 0
      NBIND = 0
      ISTOP = 0
      DO 10 J=1,IET
      PRECK(J) = 0.0
      DO 10 I=1,IFEND
      FOL(J,I) = 0.0
   10 PRE(J,I) = 0.0
```

```
      DO 20 N=1,IET
      E(N) = 0.0
   20 V(N) = 0.0
C     DATA INPUT INSTRUCTIONS
      READ(1,30)LE
   30 FORMAT(I3)
      IF(IET - LE)40,60,60
   40 WRITE(3,50) IET,LE
   50 FORMAT(1H1,'PROGRAM LIMIT EXCEEDED. IET=',I4,'  LE =',I4)
      STOP
   60 READ(1,70) C
      CB = C
   70 FORMAT(F5.2)
      CNTB = 0.0
      BLST = 2000.0
      READ(1,70) STDF
      READ(1,80) NSTATS,NBIND
   80 FORMAT(I3,I1)
      DO 90 I=1,LE
   90 READ(1,100)E(I),V(I),(PRE(I,J),J=1,IPEND),PRECK(I)
  100 FORMAT(F5.2,F7.2,19F3.0,F2.0)
      DO 110 I=1,LE
  110 READ(1,120) (FOL(I,L),L=1,IFEND)
  120 FORMAT(20F3.0)
C
C          CHECK THAT NO ELEMENTS PLUS STDF(VARIANCE) EXCEEDS CYCLE TIME
C
      DO 150 I=1,LE
      IF(V(I)) 130,130,140
  130 V(I) = 0.0
  140 ARG = E(I) + STDF*SQRT(V(I))
      IF(ARG - C)150,150,170
  150 CONTINUE
      IF(IOUCH - 1)200,160,160
  160 STOP
```

```
  170 WRITE(3,180)
      WRITE(3,190) C,E(I),V(I),ARG
  180 FORMAT(1H0,'CYCLE TIME EXCEEDED BY MEAN TIME PLUS VARIANCE')
  190 FORMAT(1H0,'CYCLE TIME=',F7.2,' E TIME=',F9.2,' VAR=',F9.2,' ARG =
     1',F9.2)
      IOUCH = 1
      GO TO 150
C
C     INITIALIZATION
C
  200 CNT = 0.0
      NCOUNT=1
      NEXT=1
  210 DO 220 M = 1,ICEND
      CAND(1,M)=500.0
      CAND(3,M) = 0.0
      CAND(4,M) = 0.0
      CAND(5,M) = 0.0
      CAND(6,M) = 0.0
  220 CAND(2,M)=0.0
      DO 240 N=1,ISTEND
      DO 230 K = 1,ICEND
      STAT(1,K,N)=500.0
      STAT(2,K,N) = 0.0
  230 STAT(3,K,N)=99.0
  240 CONTINUE
      DO 250 I=1,ISTEND
      S(I)=0.0
      TOTS(I) = 0.0
      BALDEL(I) = 0.0
  250 VS(I)=0.0
      DO 260 N = 1,2
      DO 260 K=1,ISTEND
  260 BRYTON(N,K) = 0.0
      N=1
```

```
      DO 270 I=1,LE
  270 PRE(I,IPPEND) = PRECK(I)
      CUMBDL=0.0
C
C     PRECEDENCE CHECKING FOR NEW CANDIDATES
C
  280 DO 330 I=1,LE
      IF(PRE(I,IPPEND) - IPEND)330,290,330
  290 DO 320 M = 1,ICEND
      IF(CAND(1,M)-500.0)320,300,320
  300 CAND(1,M)=E(I)
      CAND(2,M)=V(I)
      AI=I
      CAND(3,M)=AI
      PRE(I,IPPEND) = IPPEND + 2
      CNT = CNT + 1.0
      IF (CNT - ICXEND)310,1770,1770
  310 GO TO 330
  320 CONTINUE
  330 CONTINUE
C
C     CANDIDATE SORT IN DECREASING ORDER
C
      DO 390 M = 1,ICCEND
      MP1=M+1
      DO 390 MM = MP1,ICEND
      IF(CAND(2,M))340,340,350
  340 CAND(2,M) = 0.0
  350 IF(CAND(2,MM))360,360,370
  360 CAND(2,MM) = 0.0
  370 IF (CAND(1,M) + STDF*SQRT(CAND(2,M)) - CAND(1,MM) - STDF*
     1  SQRT(CAND(2,MM))) 380,390,390
  380 TEMP=CAND(1,M)
      CAND(1,M)=CAND(1,MM)
      CAND(1,MM)=TEMP
```

```
      TEMP=CAND(2,M)
      CAND(2,M)=CAND(2,MM)
      CAND(2,MM)=TEMP
      TEMP=CAND(3,M)
      CAND(3,M)=CAND(3,MM)
      CAND(3,MM)=TEMP
  390 CONTINUE
C
C     ASSIGNMENT OF ELEMENTS TO STATIONS
C
  400 DO 520 M =1,ICEND
      IF(CAND(1,M) - 500.0)410,450,450
  410 IF(ISTOP - 1)420,550,550
  420 ARG = VS(N) + CAND(2,M)
      IF(ARG)430,430,440
  430 ARG = 0.0
  440 IF(CAND(1,M) + S(N) + STDF*SQRT(ARG) - C)550,550,450
  450 IF(M - ICEND) 520,460,460
  460 IF(VS(N)) 470,470,480
  470 VS(N) = 0.0
  480 BALDEL(N)=C-S(N)-STDF*SQRT(VS(N))
      TOTS(N)=S(N)+STDF*SQRT(VS(N))
      CUMBDL=CUMBDL+BALDEL(N)
      IF(CUMBDL-C)530,490,490
  490 IF(C - CB - 20)500,530,530
  500 C = C + 1.0
      WRITE(3,510) C
  510 FORMAT(1H ,'INCREMENTED CYCLE TIME =',F7.2)
      GO TO 210
  520 CONTINUE
      GO TO 400
  530 TCAND=0.0
      DO 540 M = 1,ICEND
  540 TCAND=TCAND+CAND(1,M)
      IF(TCAND - TTCAND) 610,670,670
```

```
  550 S(N)=CAND(1,M)+S(N)
      VS(N)=CAND(2,M)+VS(N)
      DO 570 K = 1,ICEND
      IF(STAT(1,K,N)-500.0)570,560,560
  560 STAT(1,K,N)=CAND(1,M)
      STAT(2,K,N)=CAND(2,M)
      STAT(3,K,N)=CAND(3,M)
      GO TO 580
  570 CONTINUE
C
C     PRECEDENCE UPDATING
C
  580 CAND(1,M)=500.0
      CNT = CNT - 1.0
      I=CAND(3,M)
      DO 600 L = 1,IFEND
      IF(FOL(I,L)-1.0)600,590,590
  590 I=FOL(I,L)
      PRE(I,IPPEND) = 1.0 + PRE(I,IPPEND)
      I=CAND(3,M)
  600 CONTINUE
      GO TO 280
  610 N=N+1
      IF(N - ISTEND - 1)620,650,650
  620 IF(NBIND - 1) 400,630,630
  630 IF(N - NSTATS) 400,640,640
  640 ISTOP = 1
      GO TO 400
  650 WRITE(3,660)N
  660 FORMAT(1H1,'NUMBER OF STATIONS CAPACITY EXCEEDED, N=',I3)
      STOP
C
C ***********************************************************************
C                PHASE 2
C ***********************************************************************
```

```
C
C
C         CHECK TO SEE IF BALANCE IS FOR NUMBER OF STATIONS DESIRED
C
  670 IF(NBIND - 1)700,680,680
  680 IF(N - NSTATS) 690,700,700
  690 NF = NSTATS
      GO TO 710
  700 NF = N
C
C         BALANCE AT END OF PHASE 1
C
  710 DO 730 N=1,NF
      WRITE(3,750)
      WRITE(3,750)
      DO 720 K=1,ICEND
      IF(STAT(3,K,N) - 99.0)720,730,720
  720 WRITE(3,740)N,STAT(3,K,N),STAT(1,K,N),STAT(2,K,N)
  730 WRITE(3,760) TOTS(N)
      WRITE(3,750)
      WRITE(3,770) C,CUMBDL
  740 FORMAT(I4,F8.0,F8.2,F8.2)
  750 FORMAT(1H0)
  760 FORMAT(1H0,F19.2)
  770 FORMAT(1H ,'CYCLE TIME = ',F10.2,5X,'CUM BALANCE DELAY =',F12.4)
C
      DO 780 M=1,ICEND
      CAND(4,M)=0.0
  780 CAND(7,M)=99.0
C
C     SORT STATION VALUES IN DECREASING ORDER
C
  790 DO 800 J=1,NF
      BRYTON(1,J)=TOTS(J)
  800 BRYTON(2,J)=J
```

```
      NF1=NF-1
      DO 820 J=1,NF1
      JP1=J+1
      DO 820 JJ=JP1,NF
      IF(BRYTON(1,J)-BRYTON(1,JJ))810,820,820
  810 TEMP=BRYTON(1,J)
      BRYTON(1,J)=BRYTON(1,JJ)
      BRYTON(1,JJ)=TEMP
      TEMP=BRYTON(2,J)
      BRYTON(2,J)=BRYTON(2,JJ)
      BRYTON(2,JJ)=TEMP
  820 CONTINUE
C
C     TRANSFER SINGLE ELEMENT FROM MAX TO MIN STATION
C
  830 NN=1
      MM=NF
  840 N1=BRYTON(2,NN)
  850 N2=BRYTON(2,MM)
      DO 1040 J=1,ICEND
      IF(STAT(3,J,N1)-99.0)860,1040,860
  860 GO TO (870,880),NEXT
  870 IF(TOTS(N1)-TOTS(N2)-STAT(1,J,N1))1040,1040,890
  880 IF(C-TOTS(N2)-STAT(1,J,N1))1040,890,890
  890 I=STAT(3,J,N1)
      IF(N1-N2)900,900,940
  900 N2M1=N2-1
      DO 930 N=N1,N2M1
      DO 930 K=1,ICEND
      DO 930 L=1,IFEND
  910 IF(FOL(I,L))930,930,920
  920 IF(FOL(I,L)-STAT(3,K,N))930,1040,930
  930 CONTINUE
      GO TO 980
  940 N2P1=N2+1
```

```
      DO 970 N=N2P1,N1
      DO 970 K=1,ICEND
      DO 970 M=1,IPEND
  950 IF(PRE(I,M))970,970,960
  960 IF(PRE(I,M)-STAT(3,K,N))970,1040,970
  970 CONTINUE
  980 ARG = VS(N2) + STAT(2,J,N1)
      IF(ARG) 981,981,982
  981 SQR1 = 0.0
      GO TO 983
  982 SQR1 = STDF*SQRT(ARG)
  983 GO TO (990,1000),NEXT
  990 IF(TOTS(N1)-S(N2)-STAT(1,J,N1)-SQR1) 1040,1040,1010
 1000 IF(C-S(N2)-STAT(1,J,N1)-SQR1) 1040,1010,1010
C
C     ASSIGNEMENT OF SINGLE TRANSFERS TO CANDIDATE MATRIX
C
 1010 DO 1030 M=1,ICEND
      IF(CAND(1,M)-500.0)1030,1020,1030
 1020 CAND(1,M)=STAT(1,J,N1)
      CAND(2,M)=STAT(2,J,N1)
      CAND(3,M)=STAT(3,J,N1)
      GO TO 1040
 1030 CONTINUE
 1040 CONTINUE
C
C     TRADE OF TWO ELEMENTS BETWEEN TWO STATIONS
C
 1050 DO 1390 JJ=1,ICEND
      DO 1380 J=1,ICEND
 1060 IF(STAT(3,J,N1)-99.0)1070,1380,1380
 1070 IF(STAT(1,J,N1)-STAT(1,JJ,N2))1380,1380,1080
 1080 GO TO (1090,1100),NEXT
 1090 IF(TOTS(N1)-S(N2)+STAT(1,JJ,N2)-STAT(1,J,N1))1380,1380,1110
 1100 IF(C-S(N2)+STAT(1,JJ,N2)-STAT(1,J,N1))1380,1380,1110
```

```
 1110 I=STAT(3,J,N1)
      IF(N1-N2)1120,1120,1210
 1120 N2M1=N2-1
      DO 1160 N=N1,N2M1
      DO 1160 K=1,ICEND
      DO 1160 L=1,IFEND
 1130 IF(FOL(I,L))1160,1160,1140
 1140 IF(FOL(I,L)-STAT(3,JJ,N2))1150,1380,1150
 1150 IF(FOL(I,L)-STAT(3,K,N))1160,1380,1160
 1160 CONTINUE
      I=STAT(3,JJ,N2)
      N1P1=N1+1
      DO 1200 N=N1P1,N2
      DO 1200 K=1,ICEND
      DO 1200 M=1,IPEND
 1170 IF(PRE(I,M))1200,1200,1180
 1180 IF(PRE(I,M)-STAT(3,J,N1))1190,1390,1190
 1190 IF(PRE(I,M)-STAT(3,K,N))1200,1390,1200
 1200 CONTINUE
      GO TO 1300
 1210 N2P1=N2+1
      I=STAT(3,J,N1)
      DO 1250 N=N2P1,N1
      DO 1250 K=1,ICEND
      DO 1250 M=1,IPEND
 1220 IF(PRE(I,M))1250,1250,1230
 1230 IF(PRE(I,M)-STAT(3,JJ,N2))1240,1380,1240
 1240 IF(PRE(I,M)-STAT(3,K,N))1250,1380,1250
 1250 CONTINUE
      I=STAT(3,JJ,N2)
      N1M1=N1-1
      DO 1290 N=N2,N1M1
      DO 1290 K=1,ICEND
      DO 1290 L=1,IFEND
 1260 IF(FOL(I,L))1290,1290,1270
```

```
 1270 IF(FOL(I,L)-STAT(3,J,N1))1280,1390,1280
 1280 IF(FOL(I,L) - STAT(3,K,N))1290,1390,1290
 1290 CONTINUE
 1300 ARG = VS(N2)-STAT(2,JJ,N2)+STAT(2,J,N1)
      ARG1 = VS(N1)-STAT(2,J,N1)+STAT(2,JJ,N2)
      IF(ARG) 1301,1301,1302
 1301 SQR1 = 0.0
      GO TO 1303
 1302 SQR1 = STDF*SQRT(ARG)
 1303 IF(ARG1) 1304,1304,1305
 1304 SQR2 = 0.0
      GO TO 1306
 1305 SQR2 = STDF*SQRT(ARG1)
 1306 GO TO (1310,1330),NEXT
 1310 IF(TOTS(N1)-S(N2)+STAT(1,JJ,N2)-STAT(1,J,N1)-SQR1) 1380,1380,1320
 1320 IF(TOTS(N1)-S(N1)-STAT(1,JJ,N2)+STAT(1,J,N1)-SQR2) 1380,1380,1350
 1330 IF(C-S(N2)-STAT(1,J,N1)+STAT(1,JJ,N2)-SQR1) 1380,1340,1340
 1340 IF(C-S(N1)-STAT(1,JJ,N2)+STAT(1,J,N1)-SQR2) 1380,1350,1350
 1350 NEXT=1
C
C     ASSIGNMENT OF TRADE CANDIDATES TO CANDIDATE MATRIX
C
      DO 1370 M=1,ICEND
      IF(CAND(1,M)-500.0)1370,1360,1370
 1360 CAND(1,M)=STAT(1,J,N1)
      CAND(2,M)=STAT(2,J,N1)
      CAND(3,M)=STAT(3,J,N1)
      CAND(4,M)=STAT(1,JJ,N2)
      CAND(5,M)=STAT(2,JJ,N2)
      CAND(6,M)=STAT(3,JJ,N2)
      GO TO 1380
 1370 CONTINUE
 1380 CONTINUE
 1390 CONTINUE
C
```

```
C      CHECK TO SEE IF CANDIDATES AVAILABLE
C
 1400 TCAND=0.0
      DO 1410 M=1,ICEND
 1410 TCAND=TCAND+CAND(1,M)
      IF(TCAND - TTCAND) 1530,1420,1420
 1420 MM=MM-1
      IF(MM-NN)1430,1430,850
 1430 MM=NF
      NN=NN+1
      IF(NN-MM)840,1440,1440
 1440 IF(NCOUNT-2)1450,1450,1470
 1450 NEXT=NEXT+1
      NCOUNT=NCOUNT+1
      IF(NCOUNT-1)830,830,1460
 1460 NN=1
      MM=NF
      GO TO 840
C
C      PRINTOUT OF FINAL LINE BALANCE
C
 1470 CUMBDL = 0.0
      DO 1490 N = 1,NF
      FCT = C - TOTS(N)
      IF(FCT)1490,1490,1480
 1480 CUMBDL = CUMBDL + FCT
 1490 CONTINUE
      DO 1510 N =1,NF
      WRITE(3,750)
      WRITE(3,750)
      DO 1500 K=1,ICEND
      IF(STAT(3,K,N)-99.0)1500,1510,1500
 1500 WRITE(3,740)N,STAT(3,K,N),STAT(1,K,N),STAT(2,K,N)
 1510 WRITE(3,760)TOTS(N)
      WRITE(3,750)
```

```
      WRITE(3,770) C,CUMBDL
 1520 STOP
C
C     COMPARE CANDIDATES WITH GOAL
C
 1530 DO 1570 M=1,ICEND
      IF(CAND(1,M)-500.0)1540,1570,1570
 1540 IF(CAND(4,M))1550,1550,1560
 1550 ARG = VS(N1) - CAND(2,M)
      ARG1 = VS(N2) + CAND(2,M)
      IF(ARG) 1551,1551,1552
 1551 SQR1 = 0.0
      GO TO 1553
 1552 SQR1 = STDF*SQRT(ARG)
 1553 SQR2 = STDF*SQRT(ARG1)
      VALUE=ABS(S(N1)-CAND(1,M)+SQR1-S(N2)-CAND(1,M)-SQR2)
      CAND(7,M)=VALUE
      GO TO 1570
 1560 ARG = VS(N1)-CAND(2,M)+CAND(5,M)
      ARG1 = VS(N2)-CAND(5,M)+CAND(2,M)
      IF(ARG) 1561,1561,1562
 1561 SQR1 = 0.0
      GO TO 1563
 1562 SQR1 = STDF*SQRT(ARG)
 1563 IF(ARG1) 1564,1564,1565
 1564 SQR2 = 0.0
      GO TO 1566
 1565 SQR2 = STDF*SQRT(ARG1)
 1566 VALUE=ABS(S(N1)-CAND(1,M)+CAND(4,M)+SQR1-S(N2)+CAND(4,M)-CAND(1,M)
     1  -SQR2)
      CAND(7,M)=VALUE
 1570 CONTINUE
C
C     CANDIDATE SORT IN ORDER OF CLOSENESS TO GOAL
C
```

```
      DO 1590 M=1,ICCEND
      MP1=M+1
      DO 1590 MM=MP1,ICEND
      IF(CAND(7,M)-CAND(7,MM))1590,1590,1580
 1580 TEMP=CAND(7,M)
      CAND(7,M)=CAND(7,MM)
      CAND(7,MM)=TEMP
      TEMP=CAND(6,M)
      CAND(6,M)=CAND(6,MM)
      CAND(6,MM)=TEMP
      TEMP=CAND(5,M)
      CAND(5,M)=CAND(5,MM)
      CAND(5,MM)=TEMP
      TEMP=CAND(4,M)
      CAND(4,M)=CAND(4,MM)
      CAND(4,MM)=TEMP
      TEMP=CAND(3,M)
      CAND(3,M)=CAND(3,MM)
      CAND(3,MM)=TEMP
      TEMP=CAND(2,M)
      CAND(2,M)=CAND(2,MM)
      CAND(2,MM)=TEMP
      TEMP=CAND(1,M)
      CAND(1,M)=CAND(1,MM)
      CAND(1,MM)=TEMP
 1590 CONTINUE
C
C      ASSIGNMENT OF BEST CANDIDATE
C
      IF(CAND(4,1))1660,1660,1600
 1600 DO 1620 K=1,ICEND
      IF(STAT(3,K,N2)-CAND(6,1))1620,1610,1620
C        DOUBLE EXCHANGE --- ELEMENT TIMES SWITCHED BETWEEN TWO STATIONS
 1610 STAT(1,K,N2)=CAND(1,1)
      STAT(2,K,N2)=CAND(2,1)
```

```
      STAT(3,K,N2)=CAND(3,1)
      S(N2)=S(N2)+CAND(1,1)-CAND(4,1)
      VS(N2)=VS(N2)+CAND(2,1)-CAND(5,1)
      IF(VS(N2)) 1615,1615,1616
 1615 VS(N2) = 0.0
 1616 TOTS(N2) = S(N2) + STDF*SQRT(VS(N2))
      GO TO 1630
 1620 CONTINUE
 1630 DO 1650 K=1,ICEND
      IF(STAT(3,K,N1)-CAND(3,1))1650,1640,1650
 1640 STAT(1,K,N1)=CAND(4,1)
      STAT(2,K,N1)=CAND(5,1)
      STAT(3,K,N1)=CAND(6,1)
      S(N1)=S(N1)+CAND(4,1)-CAND(1,1)
      VS(N1)=VS(N1)+CAND(5,1)-CAND(2,1)
      IF(VS(N1)) 1645,1645,1646
 1645 VS(N1) = 0.0
 1646 TOTS(V1) = S(N1) + STDF*SQRT(VS(N1))
      GO TO 1740
 1650 CONTINUE
C        SINGLE EXCHANGE OF ELEMENT TIME
 1660 DO 1670 K=1,ICEND
      IF(STAT(3,K,N1)-CAND(3,1))1670,1680,1670
 1670 CONTINUE
C        REMOVE ELEMENT TIME FROM HIGH STATION
 1680 STAT(1,K,N1)=500.0
      STAT(2,K,N1) = 0.0
      STAT(3,K,N1)=99.0
C        RESORT STATION ASSIGNMENTS AFTER ELEMENT TIME REMOVED
      DO 1700 K=1,ICCEND
      KP1=K+1
      DO 1700 KK=KP1,ICEND
      IF(STAT(3,K,N1)-STAT(3,KK,N1))1700,1700,1690
 1690 TEMP=STAT(3,K,N1)
      STAT(3,K,N1)=STAT(3,KK,N1)
```

```
      STAT(3,KK,N1)=TEMP
      TEMP=STAT(2,K,N1)
      STAT(2,K,N1)=STAT(2,KK,N1)
      STAT(2,KK,N1)=TEMP
      TEMP=STAT(1,K,N1)
      STAT(1,K,N1)=STAT(1,KK,N1)
      STAT(1,KK,N1)=TEMP
 1700 CONTINUE
C         PLACE ELEMENT TIME IN LOW STATION
 1710 DO 1730 K=1,ICEND
      IF(STAT(1,K,N2)-500.0)1730,1720,1730
 1720 STAT(1,K,N2)=CAND(1,1)
      STAT(2,K,N2)=CAND(2,1)
      STAT(3,K,N2)=CAND(3,1)
      S(N1)=S(N1)-CAND(1,1)
      VS(N1)=VS(N1)-CAND(2,1)
      S(N2)=S(N2)+CAND(1,1)
      VS(N2)=VS(N2)+CAND(2,1)
      IF(VS(N1)) 1722,1722,1723
 1722 VS(N1) = 0.0
 1723 IF(VS(N2)) 1724,1724,1725
 1724 VS(N2) = 0.0
 1725 TOTS(N1) = S(N1) + STDF*SQRT(VS(N1))
      TOTS(N2) = S(N2) + STDF*SQRT(VS(N2))
      GO TO 1740
 1730 CONTINUE
C
C     INITIALIZATION FOR NEXT BRYTON
C
 1740 DO 1750 M=1,ICEND
      CAND(1,M)=500.0
      CAND(2,M) = 0.0
      CAND(3,M) = 0.0
      CAND(5,M) = 0.0
      CAND(6,M) = 0.0
```

```
      CAND(4,M)=0.0
 1750 CAND(7,M)=99.0
      CNTB = CNTB + 1
      IF(CNTB - BLST)790,790,1470
 1770 WRITE(3,1780)
 1780 FORMAT(1H1,'CAND AREA EXCEEDED')
      STOP
      END
```

APPENDIX C

Appendix C contains a listing of a GPSS simulation written for one of the balances generated in the course of this study. Input to the simulator was generated by a FORTRAN program (see Appendix D) onto disk storage. The simulator, in turn, accessed the reconditioning jobs and compiled the statistics defined. The program was run on an IBM/360 model 50.

```
 SIMULATE
*
*    SIMULATION OF ITEM RECONDITIONING LINE -----
*         TRANSACTIONS ARE GENERATED BY A FORTRAN PROGRAM AND WRITTEN
*         UNTO A DISK STORAGE  TO BE USED BY GPSS/360
*
         JOBTAPE     JOBTA1,STRT
         STORAGE     S1,2
*
*          WORK STATION NUMBER 1
*
 STRT    QUEUE       10            JOIN QUEUE AT 1ST WORK STATION
         LINK        1,FIFO,ONE
 ONE     SEIZE       WSN1
         DEPART      10            LEAVE QUEUE
         MARK                      RESET TRANSIT TIME FOR TRANSACTION
         ADVANCE     P1
         RELEASE     WSN1
         UNLINK      1,ONE,1
*
*          WORK STATION NUMBER 2
*
         QUEUE       20            JOIN QUEUE AT 2ND WORK STATION
         SEIZE       WSN2
         DEPART      20
         ADVANCE     P2
         RELEASE     WSN2
*
*          WORK STATION NUMBER 3
*
         QUEUE       30            JOIN QUEUE FOR 3RD WORK STATION
         LINK        2,FIFO,THE
 THE     SEIZE       WSN3
         DEPART      30
         ADVANCE     P3
```

```
          RELEASE     WSN3
          UNLINK      2,THE,1
*
*           WORK STATION NUMBER 4
*
          QUEUE       40           JOIN QUEUE AT 4TH WORK STATION
          LINK        3,FIFO,FOR
 FOR      SEIZE       WSN4
          DEPART      40
          ADVANCE     P4
          RELEASE     WSN4
          UNLINK      3,FOR,1
*
*           WORK STATION NUMBER 5
*
          QUEUE       41           JOIN QUEUE AT 5TH WORK STATION
          LINK        4,FIFO,FIV
 FIV      SEIZE       WSN5
          DEPART      41
          ADVANCE     P5
          RELEASE     WSN5
          UNLINK      4,FIV,1
*
*           WORK STATION NUMBER 6
*
          QUEUE       42           JOIN QUEUE AT 6TH WORK STATION
          LINK        5,FIFO,SIX
 SIX      SEIZE       WSN6
          DEPART      42
          ADVANCE     P6
          RELEASE     WSN6
          UNLINK      5,SIX,1
*
*           WORK STATION NUMBER 7
*
```

```
          QUEUE       43         JOIN QUEUE AT 7TH WORK STATION
          ENTER       1
          DEPART      43
          ADVANCE     P7
          LEAVE       1
*
          TABULATE    100        TRANSIT TIME OF RECONDITIONED ITEMS
          TABULATE    15
          TERMINATE   1
100       TABLE       M1,5000,100,722      TOTAL TRANSIT TIME
15        TABLE       RT,0,1,352,10000
          START       300,NP
          RESET
          START       600
          START       4500
          END
```

APPENDIX D

Appendix D contains the program listing of the FORTRAN program which generated reconditioning jobs for use by the GPSS simulation model. The program was run on an IBM/360 model 50.

```
C ######################################################################
C
C   PROGRAM TO GENERATE TRANSACTIONS ON MAGNETIC DISK STORAGE TO
C   BE USED LATER BY THE GENERAL PURPOSE SYSTEM SIMULATOR/360 (GPSS)
C
C ######################################################################
C
C **********************************************************************
C
C   VARIABLE DEFINITIONS
C
C        IFUL IS USED TO STORE FULLWORD PARAMETERS
C        IHALF IS USED TO STORE HALFWORD PARAMETERS
C        NAME IS READ FROM A CARD IN WHICH -END OF FILE JOBT-
C             IS PUNCHED IN COLUMNS 1 THRU 16
C        ITASK = AN ARRAY WHICH CONTAINS THE ELEMENT TIMES, MEAN
C                FREQUENCY OF DEFECT OCCURRENCE AND VARIANCE OF
C                THE FREQUENCY
C        IWST = AN ARRAY CONTAINING THE OPERATIONS ASSIGNED TO THE
C               WORK STATIONS
C        P = PRIORITY -- INITIALIZED AT 0
C        IAT = INTERARRIVAL TIME OF TRANSACTIONS
C        NTT = TOTAL NUMBER OF TASKS
C        IX = SEED FOR RANDOM NUMBER GENERATOR -- RANDU--
C        IVAR = VARIANCE LOGIC
C             -0- INDICATES THAT FREQUENCY OF DEFECT OCCURRENCE IS
C                 DETERMINISTIC -- CONSTANT--
C             -1- FREQUENCY IS NORMALLY DISTRIBUTED
C        NT = TASK NUMBER
C        NST = NUMBER OF SUBTASKS PER TASK
C        BIT IS 0 OR 1 FOR HALF OR FULL WORD PARAMETERS
C        NUM IS THE NUMBER OF PARAMETERS PER TRANSACTION
C        NUMA IS THE NUMBER OF PARAMETERS WITH NON-ZERO VALUES
C        IF NUMA IS 0, NO PARAMETERS HAVE NON-ZERO STARTING VALUES
C
```

```
C           NUMA IS THE NUMBER OF WORK STATIONS IN THE SIMULATION FOR THIS
C           APPLICATION
C           NTRAN IS THE NUMBER OF TRANSACTIONS
C
C ***********************************************************************
C
        IMPLICIT INTEGER (A-H,O-W)
        INTEGER*2 IHALF
        DIMENSION IFUL(101),IHALF(202),NAME(16),ITASK(50,20,3),IWST(10,20)
       1,NST(50)
C
        TT = 0
        DO 1 J=1,101
        IHALF(J)=0
1       IFUL(J)=0
        DO 2 J=102,202
2       IHALF(J)=0
        DO 33 I=1,10
        DO 33 J=1,20
33      IWST(I,J)=0
C
C       READ CONTROL CARD
C
        READ(1,100)BIT,NUM,NUMA,NTRAN
C
C          READ IN TOTAL NUMBER OF TASKS, SEED, AND VARIANCE LOGIC
C
        READ(1,198)NTT,IX,IVAR,IAT
        DO 300 JJ=1,NTT
C
C          READ IN NUMBER OF SUBTASKS PER TASK
C
        READ(1,199) NT,NST(NT)
        IF(NT-NTT) 250,250,397
250     KST=NST(NT)
```

```
C
C        READ IN ELEMENT TIMES, FREQUENCY, VARIANCE
C
      DO 300 KK=1,KST
      READ (1,200) IT,IST,(ITASK(IT,IST,J),J=1,3)
      IF(IT-NT)398,300,398
300   CONTINUE
C
C        READ IN WORK STATION - TASK ASSIGNMENT .
C
      DO 310 KK=1,NUMA
      READ(1,210) IWS,IWSTN,(IWST(IWS,I),I=1,IWSTN)
      IF(IWSTN - 20) 310,310,399
310   CONTINUE
C
C        GENERATE RANDOM DATA FOR SIMULATION
C        NTRAN = NUMBER OF TRANSACTIONS
C
      P = 0
      IA = 0
312   DO 400 N=1,NTRAN
C
C             NUMA = NUMBER OF WORK STATIONS
C
      DO 380 I=1,NUMA
      IFUL(I) = 0
      IHALF(I)=0
      DO 370 J=1,20
      IF(IWST(I,J)) 380,380,315
315   L = IWST(I,J)
      LEND = NST(L)
      DO 360 K=1,LEND
      IF(ITASK(L,K,2)-100) 340,350,350
340   IF(IVAR-1) 342,390,396
342   IFREQ = ITASK(L,K,2)
```

```
343   XFREQ = IFREQ
      CALL RANDU(IX,IY,YFL)
      IX = IY
345   YFL = YFL*100.0
      IF(XFREQ - YFL)360,350,350
350   IF(BIT.EQ.0)IHALF(I) = IHALF(I) + ITASK(L,K,1)
      IF(BIT.EQ.1)IFUL(I) = IFUL(I) + ITASK(L,K,1)
360   CONTINUE
370   CONTINUE
380   CONTINUE
C
C        THIS SECTION GETS THE INFORMATION IN THE CORRECT BYTES OF THE
C                           THIRD WORD
C
      OP=P*65536
      OBIT=BIT*32768
      OK=OBIT+OP+NUM
      IF(BIT.EQ.0)WRITE(12,170)IA,TT,OK,(IHALF(L),L=1,202)
      IF(BIT.EQ.1)WRITE(12,175)IA,TT,OK,(IFUL(L),L=1,101)
      IA = IAT
      DO 3 II=1,NUMA
      IHALF(II)=0
3     IFUL(II)=0
400   CONTINUE
C
C        -1- REFERS TO CARD READER UNIT
C        -12- REFERS TO DISK STORAGE UNIT
C
      READ(1,130)(NAME(K),K=1,16)
7777  WRITE(12,195)(NAME(K),K=1,16),(IFUL(L),L=1,100)
      ENDFILE 12
      REWIND 12
      STOP
C
C        CONTROL CARD READ FORMAT
```

```
C
100   FORMAT(I1,1X,I3,1X,I3,1X,I5)
C         TRANSACTION CARD FORMAT
110   FORMAT(I6,1X,I10,1X,I3,1X,8(I6,1X)/,20(11(I6,1X)/))
C         WRITE FORMATS
170   FORMAT(3A4,202A2)
175   FORMAT(3A4,101A4)
195   FORMAT(16A1,100A4)
130   FORMAT(16A1)
C
C         SAMPLE FREQUENCY FROM NORMAL DISTRIBUTION
C
390   YT = ITASK(L,K,3)
      IF (YT) 392,391,392
391   XS = 0.0
      GO TO 393
392   XS = SQRT(YT)
393   XAM = ITASK(L,K,2)
      CALL GAUSS(IX,XS,XAM,XV)
      IFREQ = XV
      IF(IFREQ) 360,360,395
395   IF(IFREQ-100) 343,350,350
396   WRITE(3,180) IVAR
180   FORMAT(1H1,'VARIANCE LOGIC INCORRECT',5X,I5)
      STOP
C
397   WRITE(3,181) NT,NTT
181   FORMAT(1H1,'TASK # GREATER THAN # OF TASKS',I5,I5)
      STOP
C
398   WRITE(3,182) IT,NT
182   FORMAT(1H1,'TASK # GREATER THAN TOTAL # OF TASKS',I5,I5)
399   WRITE(3,183)IWSTN
183   FORMAT(1H1,'MORE THAN 20 SUBTASKS PER TASK',I5)
198   FORMAT(I3,I9,I1,I5)
```

```
199   FORMAT(I3,I3)
200   FORMAT(I3,I3,I5,I3,I5)
210   FORMAT(26I3,2X)
220   FORMAT(3A4,20A2)
      STOP
      END
      SUBROUTINE RANDU(IX,IY,YFL)
C
C        SUBROUTINE TO GENERATE UNIFORMLY DISTRIBUTED RANDOM NUMBERS
C
      IY = IX*65539
      IF(IY)5,6,6
5     IY = IY+2147483647+1
6     YFL = IY
      YFL = YFL*.4656613E-9
      RETURN
      END
      SUBROUTINE GAUSS(IX,S,AM,V)
C
C        SUBROUTINE TO GENERATE NORMALLY DISTRIBUTED NUMBERS
C
      A = 0.0
      DO 50 I=1,12
      CALL RANDU(IX,IY,Y)
      IX=IY
50    A = A+Y
      V = (A-6.0)*S+AM
      RETURN
      END
```

BIBLIOGRAPHY

1. Bartee, Edwin M., *Engineering Experimental Design Fundamentals*, (Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1968).

2. Barten, Kenneth, "A Queueing Simulator for Determining Optimum Inventory Levels in a Sequential Process," *The Journal of Industrial Engineering*, Vol. XIII, No. 4, (July - August, 1962), pp. 245 - 252.

3. Freeman, Michael C., "The Effects of Breakdowns and Interstage Storage on Production Line Capacity," *The Journal of Industrial Engineering*, Vol. XV, No. 4 (July - August, 1964) pp. 194 - 200.

4. Freeman, D. R., and J. V. Jucker, "The Line Balancing Problem," *The Journal of Industrial Engineering*, Vol. XVIII, No. 6 (June, 1967), pp. 361 - 364.

5. *General Purpose Simulation/360 User's Manual*, IBM publication: H20-0326-2, White Plains, New York, 1967.

6. Gutjahr, A. L., and G. L. Nemhauser, "An Algorithm for the Line Balancing Problem," *Management Science*, Vol. II, No. 2, (November, 1964), pp. 308 - 315.

7. Held, M., R. M. Karp, and R. Shareshian, "Assembly Line Balancing with Precedence Constraints," *Operations Research*, Vol. II, No. 3, (May - June, 1963), pp. 442 - 459.

8. Helgeson, W. B., and D. P. Birnie, "Assembly Line Balancing Using the Ranked Positional Weight Technique," *The Journal of Industrial Engineering*, Vol. 12, No. 6, (November - December, 1961), pp. 394 - 398.

9. Heskiaoff, Heskia, "An Heuristic Method for Balancing Assembly Lines," *The Western Electric Engineer*, Vol. XII, No. 3, (October, 1968), pp. 9 - 16.

10. Hicks, Charles R., *Fundamental Concepts in the Design of Experiments*, (New York: Holt, Rinehart, and Winston, 1964).

11. Hicks, C. R. and H. H. Young, "A Comparison of Several Methods for Determining the Number of Readings in a Time Study," *The Journal of Industrial Engineering*, Vol. 13, No. 2 (March - April, 1962), pp. 93 - 96.

12. Hillier, Frederick S., and Ronald W. Boling, "The Effect of Some Design Factors on the Efficiency of Production Lines with Variable Operation Times," The Journal of Industrial Engineering, Vol. XVII, No. 12 (December, 1966), pp. 651 - 658.

13. Hoffman, T., "Assembly Line Balancing with a Precedence Matrix," Management Science, Vol. 9, No. 4 (July, 1963), pp. 551 - 562.

14. Hunt, Gordon C., "Sequential Arrays of Waiting Lines," Operations Research, Vol. 4, No. 6 (December, 1956), pp. 674 - 683.

15. Ignall, Edward J., "A Review of Assembly Line Balancing," The Journal of Industrial Engineering, Vol. XVI, No. 4, (July - August, 1965), pp. 244 - 254.

16. Jackson, J. R., "A Computing Procedure for a Line Balancing Problem," Management Science, Vol. 2, No. 3, (April, 1956), pp. 261 - 271.

17. Kilbridge, M., and L. Wester, "The Balance Delay Problem," Management Science, Vol. 8, No. 1, (October, 1961), pp. 69 - 84.

18. Kilbridge, M., and L. Wester, "A Heuristic Method of Assembly Line Balancing," The Journal of Industrial Engineering, Vol. XII, No. 4 (July - August, 1961), pp. 292 - 298.

19. Kilbridge, M. D., and L. Wester, "A Review of Analytical Systems of Line Balancing," Operations Research, Vol. 10, No. 5 (September - October, 1962), pp. 626 - 638.

20. Kilbridge, M., and L. Wester, "The Assembly Line Problem," Paper presented at the Second International Conference on Operations Research, Aix-en-Provence, France, September, 1960.

21. Klein, Morton, "On Assembly Line Balancing," Operations Research, Vol. 11, No. 2 (March - April, 1963), pp. 274 - 281.

22. LeGrande, Earl, "The Development of a Factory Simulation System Using Actual Operating Data," Management Technology, Vol. 3, No. 1 (May, 1963), pp. 1 - 19.

23. Mansoor, E. M., "Assembly Line Balancing - A Heuristic Algorithm for Variable Operator Performance Levels," The Journal of Industrial Engineering, Vol. XIX, No. 12 (December, 1968), pp. 618 - 629.

24. Monsoor, E. M., "Assembly Line Balancing - An Improvement on the Ranked Positional Weight Technique," The Journal of Industrial Engineering, Vol. XV, No. 2 (March - April, 1964), pp. 73 - 77.

25. Mansoor, E. M., and S. Ben-Tuvia, "Optimizing Balanced Assembly Lines," The Journal of Industrial Engineering, Vol. XVII, No. 3, (March, 1966), pp. 126 - 132.

26. Moodie, C. L., "A Heuristic Method of Assembly Line Balancing for Assumptions of Constant or Variable Work Element Times," Unpublished Ph.D. Dissertation, Purdue University (January, 1964).

27. Moodie, C. L., and H. H. Young, "A Heuristic Method of Assembly Line Balancing for Assumptions of Constant or Variable Work Element Times," The Journal of Industrial Engineering, Vol. XVI, No. 1 (January - February, 1965), pp. 23 - 29.

28. Naylor, T., J. L. Balintfy, D. L. Burdick, and Kong Chu, Computer Simulation Techniques (New York: John Wiley and Sons, Inc., 1966).

29. Naylor, Thomas H., and J. M. Finger, "Verification of Computer Simulation Models," Management Science, Vol. 14, No. 2 (October, 1967), pp. B-92 - B-106.

30. Prenting, T. O., and R. M. Battaglin, "The Precedence Diagram: A Tool for Analysis in Line Balancing," The Journal of Industrial Engineering, Vol. XV, No. 4 (July - August, 1964), pp. 208 - 213.

31. Rowe, Alan J., "Computer Simulation - A Solution Technique for Management Problems," Proceedings of Fall Joint Computer Conference (1965), pp. 259 - 267.

32. Salveson, M. E., "The Assembly Line Balancing Problem," The Journal of Industrial Engineering, Vol. 6, No. 3 (May - June, 1955), pp. 18 - 25.

33. Salveson, M. E., "The Assembly Line Balancing Problem," Transactions of the ASME, Vol. 77, No. 6 (August, 1955), pp. 939 - 947.

34. Thomopoulos, Nick T., "Line Balancing-Sequencing for Mixed-Model Assembly," Management Science, Vol. 14, No. 2 (October, 1967), pp. B-59 - B-75.

35. Tonge, F. M., "Assembly Line Balancing Using Probabilistic Combinations of Heuristics," Management Science, Vol. 11, No. 7 (May, 1965), pp. 727 - 735.

36. Tonge, F. M., A Heuristic Program for Assembly Line Balancing, (Englewood Cliffs, New Jersey: Prentice-Hall, 1961).

37. Walker, J. R., A Study of Element Independence in Work Cycles, Unpublished M.S. Thesis, Georgia Institute of Technology (1959).

38. Wester, Leon, and Maurice D. Kilbridge, "Heuristic Line Balancing: A Case," The Journal of Industrial Engineering, Vol. XIII, No. 3, (May - June, 1962), pp. 139 - 149.

VITA

Personal History

Name	Peter Joseph Long
Date of Birth	April 26, 1938
Place of Birth	Topeka, Kansas
Parents	Peter J. and Rosalia C. Long
Wife	Jill Joanne Long
Children	Mark, Craig, Scott, Jennifer, and Todd

Educational Background

Institutions Attended
  Rockhurst College, Kansas City, Missouri
    Bachelor of Arts, Physics, 1960
  Lehigh University, Bethlehem, Pennsylvania
    Candidate forDegree of Master of Science - Industrial Engineering

Honors
  Alpha Phi Mu, Industrial Engineering Honor Society

Professional Experience

Western Electric Company, Inc.
  Kansas City Works - 1961 - 1967
Western Electric Company, Inc.
  Princeton, New Jersey - 1967 - 1969

Professional Organizations

The Institute of Management Science, Member