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Computer Simulation in Design Applications

Edited by
Said Ashour, PhD
Marvin M. Johnson, PhD

JUNE 1973

COMPUTER SIMULATION IN DESIGN APPLICATIONS

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The ADAR Corporation

Marvin M. Johnson, PhD
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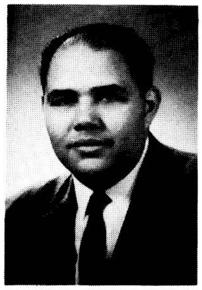
About the editors



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After earning a BSME degree with distinction from Purdue University in 1949, Professor Johnson spent fifteen years in the industrial world before continuing his education. From 1949 to 1952 he functioned as the supervisor of quality control for the Chicago Bumper Division of Houdaille-Hershey. In 1952 he joined Bell and Howell as an industrial engineer, and was instrumental in the design and implementation of the production planning and control system. For ten years he worked for the Pioneer-Central Division of Bendix Corporation in a variety of capacities, functioning at different times as reliability engineer, supervisor of systems and procedures, staff assistant to the director of manufacturing, and staff assistant to the assistant general manager. During the latter part of his employment with Bendix, he also served as lecturer in industrial engineering at the University of Iowa. He received an MSIE degree in 1966 and a PhD in industrial and management engineering in 1968, both from the University of Iowa. While a graduate student there he served as both instructor in industrial engineering and consultant to several industrial firms.

Professor Johnson is a registered professional engineer in Nebraska, Iowa, and Missouri. He is a member of Pi Tau Sigma, Tau Beta Pi, and Sigma Xi honorary societies, and of the AIEE, ASA, ASEE, ASME, ORSA, SCS, and Nebraska Academy of Science professional organizations. His contributions to the field of industrial engineering have been recognized by inclusion of his biography in more than ten different *Who's Who* publications.

TABLE OF CONTENTS

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Preface

This issue in the *Simulation Councils Proceedings* series is devoted to the utilization of computer simulation for the solution of design problems. These problems present special difficulties to the builder of models because either the system is only a concept in the mind of the designer or else he is contemplating major changes to an existing system. As a result, it is virtually impossible to validate and calibrate the model on a quantitative basis. Instead, qualitative, logical, step-by-step approaches frequently must be employed. The modeling procedure as shown graphically by Figure 1 emphasizes the relative importance of validation and calibration.

The second point emphasized in Figure 1 is that the modeler should make sure that experimentation with his model will yield usable results. The validation process is concerned with both the precision and the accuracy of the results. If the experimental results are erratic and exhibit a high degree of variability, the analyst must modify the model in order to obtain reliable results. When repeatability has been attained, calibration is needed to assure that experimental results obtained with the model can be usefully applied to the real system. While repeatability can be achieved and evaluated for design problems in existing systems (and even for new ones), calibration is much more difficult and may be impossible. An alternate approach is to perform a sensitivity analysis on the model and to compare the findings at least qualitatively with what appears to the modeler to be reasonable. As the reader studies the various articles included in this volume, he should consider how he would have attempted to validate and calibrate the model for each design problem and then compare his approach with that used by the authors.

A glance at the table of contents and the abstracts preceding each article will indicate the diversity of the design applications discussed in this volume. The major topics are (1) production and chemical processes, (2) dynamic equipment, (3) power generation and utilization, and (4) computer design and utilization. Obviously, these areas of application could be expanded to fill many volumes, and we hope that some of our readers will be motivated to treat more fully some of the areas we have touched, perhaps by offering their services as editors of future issues in this series.

The four areas of application mentioned above merely indicate the diversity which the reader will discover in this volume. The variables of concern may be continuous, discrete, or a mixture of the two. The computers utilized may be analog, digital, or hybrid. A digital computer may be used for continuous-variable problems, an analog computer may be used for discrete-variable problems, or any other combination may be encountered. The reader will find that a variety of simulation languages are used. The authors of the papers in this volume appear to have been strongly influenced in their choice of computer and simulation language by the options available to them. Secondary criteria were cost, potential returns, and desired accuracy.

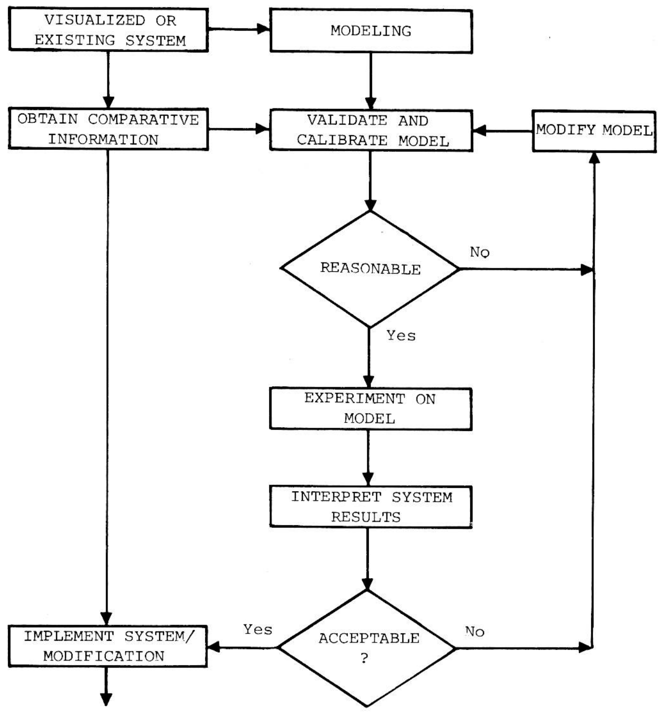


Figure 1 - Modeling procedure

In summary, the intent of this volume is to provide the practitioner with a variety of case studies which reveal the special difficulties encountered when design problems are investigated by simulation, and to portray some approaches which have been employed to overcome these difficulties. The volume can also be of help in the classroom, since it provides case studies for use by teachers.

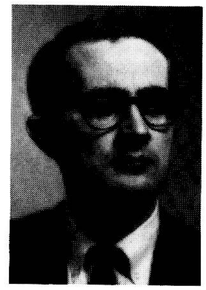
The editors wish to express their sincere appreciation to all contributing authors for their patience and cooperation. Without their efforts this volume on design applications would still be in the design stage.

Said Ashour
Marvin M. Johnson
Editors

I

Production and chemical processes

CHAPTER 1



by

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A utility program for assembly-line design

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ABSTRACT

This paper presents the results of an attempt to develop a general-purpose Monte Carlo simulation model for studying the system characteristics of a relatively small manual assembly line under various assembly-line alternatives. The simulation model was constructed using the IBM GPSS/360 simulation language.

INTRODUCTION

Monte Carlo simulation using digital computation has been in use for over a decade. During this period many simulation languages have been developed to aid the user. These simulation languages range from the general-purpose languages to the specialized application-oriented languages. However, during this same period very few models have been constructed which could be classified as general purpose. Instead, almost all models have been designed to solve one specific problem. The underlying thought behind the development of specialized models was that there was no need to make them general purpose since they would receive only limited use.

Because of this apparent dearth of general-purpose models, while studying the design of a small manual-assembly-line problem we decided to attempt to develop a single model which could, with modification, be used to study a number of related assembly-line problems. In attempting to derive the desirable attributes of a generalized assembly-line model, we concluded that the following were important:

1. A relatively simple and easy method for inputting data
2. A choice of several theoretical distributions for the service times
3. A relatively simple method of altering the number of facilities within the system
4. The ability to change the logic of the model during the simulation
5. The comparison of several alternatives within one simulation run.

The extent to which these characteristics were fulfilled is the subject of this paper.

DESCRIPTION OF THE PHYSICAL SYSTEM

The model presented in this paper simulates the physical system depicted in Figure 1. The assembly line consists of four subassembly stations and four final-assembly line stations.

The six operations performed on the assembly line are

1. Fabrication of the subassemblies from kits (at subassembly stations)
2. Inspection of the subassemblies (at subassembly stations)
3. Rework of the subassemblies (away from subassembly stations)
4. Assembly of the subassemblies into the final assembly (done in stages along a production line)
5. Inspection at each station of the production (final assembly) line
6. Rework of the final assembly (away from the production line).

In addition, incoming kits are stored in Store A from which they are distributed to the subassembly stations. Completed subassemblies are stored in Store B.

A maximum of four men can be assigned to each of the above functions. For example, man #1 may assemble the subassembly 1 kits, man #5 may inspect subassembly 1, and man #9 may rework subassembly 1. The parts associated with each of the 4 different subassemblies arrive in kit form and are stored in Store A. These kits are received in fixed-size lots, the arrival times of which follow a Poisson distribution.

The subassemblies are fabricated in fixed-size lots. For example, when subassembly 1 is completed, a fixed number N_1 (a "lot") of the subassemblies has been fabricated. After each subassembly is fabricated, it is inspected. Subassemblies failing the inspection are reworked before being placed in Store B. Collected data indicate that the times required to fabricate the subassemblies, to inspect them and to rework those that failed to pass inspection are either normally or exponentially distributed. Hence only these two types of distributions are included in the model.

The final assembly process is a sequence starting with a fixture and subassembly 1 and ending with subassembly 4, final inspection, and storing of the final product. During the production process, after each subassembly has been incorporated, the partially assembled product is inspected. If it passes inspection it continues down the production line. If it fails, it is removed from the assembly line, reworked, and then placed back on the assembly line. In the model the times required for the various production-line operations, including the inspection of the final assemblies and any necessary rework, may be either normally or exponentially distributed. After the last subassembly has been incorporated and passed inspection, the final assembly (product) is placed in Store C.

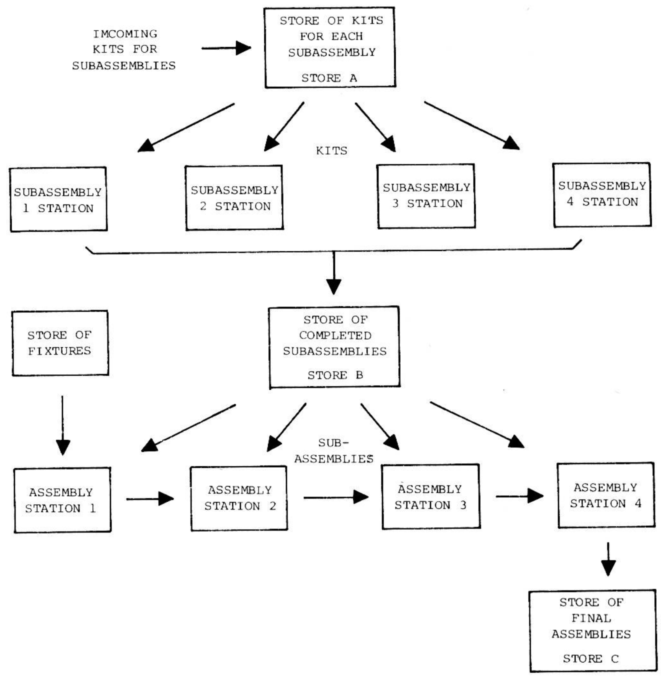

Figure 1 - Generalized description of assembly line

The problems to be studied involve the parameters of the assembly operations under various conditions. These conditions include (1) manpower allocations, (2) lot sizes of arriving subassembly kits, (3) the number of subassemblies in one lot, and (4) the required (minimum) inventory levels of kits before starting to make a subassembly. In addition to the above, the overall manufacturing operation can be studied using this model or modifications of it to reduce the number of subassembly stations, the number of stations on the final production line, etc.

DESCRIPTION OF THE MODEL

In describing the model the following areas are discussed: (a) assumptions, (b) programming simulation language and computer requirements, (c) inputs, (d) outputs, (e) execution, and (f) unique features.

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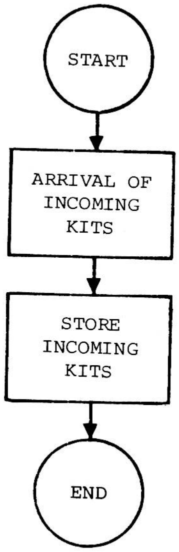

Figure 2 - Flow diagram of the arrival of incoming kits for the subassemblies

Assumptions

The following assumptions have been made in developing the assembly-line simulation model:

1. The time between arrivals of lots of subassembly kits of Store A is exponentially distributed.

2. All subassembly, assembly, inspection, and rework times are either normally or exponentially distributed.

3. Subassemblies are assembled in fixed lot sizes. Assembly does not start until enough kits for one entire lot are available.

4. An initial minimum inventory of subassembly kits and of assembled subassemblies is assumed. The reason for these assumptions will be discussed.

5. Minimum inventories are assumed for each subassembly in Store B. Once inventories drop below these minimums, additional subassemblies are assembled.

6. Each final assembly requires a fixture throughout its production.

7. Fixed percentages of rejects are assumed for each subassembly and for each station of the final assembly.

8. Each subassembly is inspected after it is completed. Necessary rework may begin immediately after rejection; it is done away from the subassembly station.

9. The final assembly (product) is inspected after completion. Rework is done off the production line.

10. Any number of men (not to exceed 24) can be assigned to the various assembly and inspection tasks. This assumption will be discussed in detail later.

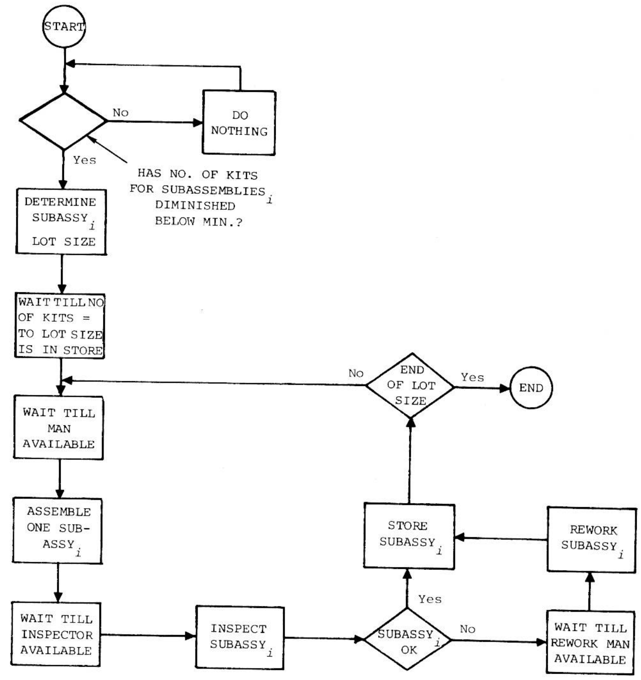

Figure 3 - Flow diagram of the assembly of subassembly *i*

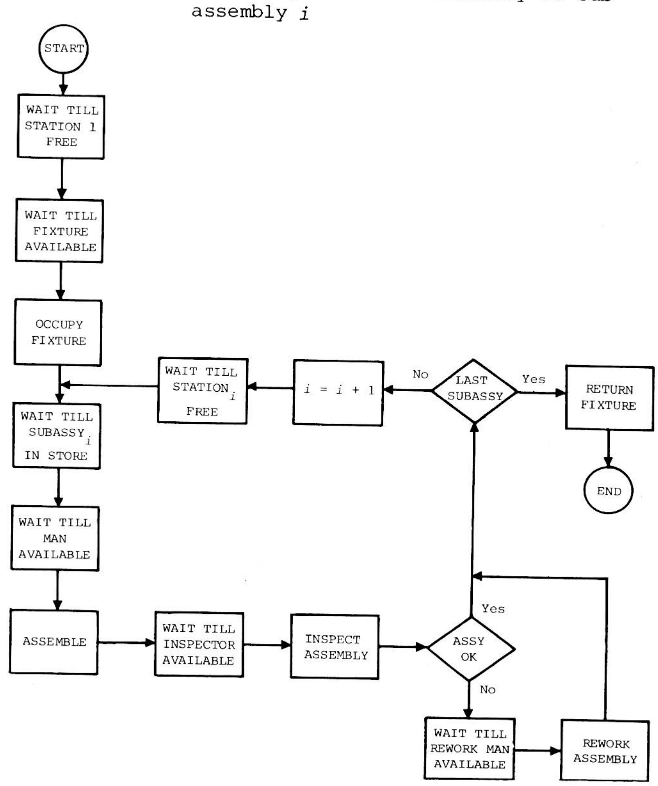

Figure 4 - Flow diagram of the production line (final assembly)

Programming language and computer requirements

A generalized flow-diagram of the model is presented in Figures 2, 3, and 4. Figure 2 presents the flow of incoming kits for each subassembly into Store A. Figure 3 presents the flow of the fabrication work on each subassembly. Figure 4 presents the flow of the production line (final assembly).

The model is written in the IBM GPSS/360 (General Purpose Simulation System) language. The model described here consists of six macros, four functions, 24 variables, and 10 tables. After expansion, these make up approximately 350 blocks in the model as it is programmed.

The program is set up to run in a 128K partition, and it takes an IBM 360/65 about 18 seconds to compile the program.

Inputs

To fulfill the objective of general usability, all input to the model is through the GPSS INITIAL and FUNCTION cards. The various types of input are presented in the following paragraphs.

The model is set up for a maximum of 24 men, and one man may be assigned to one or more operations. Manpower allocations are defined by the INITIAL cards. A typical allocation is

```
MANPOWER ALLOCATION

INITIAL   XH31,1    SUBASSY 1
INITIAL   XH32,2    SUBASSY 2
INITIAL   XH33,3    SUBASSY 3
INITIAL   XH34,4    SUBASSY 4
INITIAL   XH35,5    INSP SUBASSY 1
INITIAL   XH36,5    INSP SUBASSY 2
INITIAL   XH37,5    INSP SUBASSY 3
INITIAL   XH38,5    INSP SUBASSY 4
INITIAL   XH39,6    ASSY 1
INITIAL   XH4Ø,7    ASSY 2
INITIAL   XH41,8    ASSY 3
INITIAL   XH42,9    ASSY 4
INITIAL   XH43,1Ø   INSP ASSY 1
INITIAL   XH44,1Ø   INSP ASSY 2
INITIAL   XH45,11   INSP ASSY 3
INITIAL   XH46,11   INSP ASSY 4
INITIAL   XH47,12   REWORK ASSY 1
INITIAL   XH48,12   REWORK ASSY 2
INITIAL   XH49,13   REWORK ASSY 3
INITIAL   XH5Ø,13   REWORK ASSY 4
INITIAL   XH51,1    REWORK SUBASSY 1
INITIAL   XH52,2    REWORK SUBASSY 2
INITIAL   XH53,3    REWORK SUBASSY 3
INITIAL   XH54,4    REWORK SUBASSY 4
```

In the above allocation, 13 men have been allocated to the 24 functions. For example, man 1 makes up type 1 subassemblies and also does the necessary rework for this subassembly. Man 5 inspects all 4 types of subassemblies. Man 10 inspects the final assembly after subassembly 1 and subassembly 2 have been incorporated.

The standard normal distribution with mean zero and standard deviation one is defined via FUNCTION cards. From this standard normal distribution, any normal variate can be generated by knowing its mean and standard deviation. Therefore, only the means and standard deviations for the various normal distributions are required as input. Likewise, the negative exponential distribution with mean one is defined via the FUNCTION cards. Any exponential variate can be generated by knowing its mean.

The means and standard deviations are assigned via INITIAL cards to X50-X73 and X90-X113. If the exponential distribution is used, the mean times are specified via X50-X73. A typical set of mean times is

```
*
*
*  MEAN TIMES
*
   INITIAL   X5Ø,22    SUBASSY 1
   INITIAL   X51,3Ø    SUBASSY 2
   INITIAL   X52,8     SUBASSY 3
   INITIAL   X53,14    SUBASSY 4
   INITIAL   X54,11    REWORK SUBASSY 1
   INITIAL   X55,15    REWORK SUBASSY 2
   INITIAL   X56,4     REWORK SUBASSY 3
   INITIAL   X57,7     REWORK SUBASSY 4
   INITIAL   X58,7Ø    ASSY 1
   INITIAL   X59,95    ASSY 2
   INITIAL   X6Ø,5Ø    ASSY 3
   INITIAL   X61,8Ø    ASSY 4
   INITIAL   X62,14    REWORK ASSY 1
   INITIAL   X63,17    REWORK ASSY 2
   INITIAL   X64,1Ø    REWORK ASSY 3
   INITIAL   X65,13    REWORK ASSY 4
   INITIAL   X66,8     INSPECTION SUBASSY 1
   INITIAL   X67,12    INSPECTION SUBASSY 2
   INITIAL   X68,5     INSPECTION SUBASSY 3
   INITIAL   X69,7     INSPECTION SUBASSY 4
   INITIAL   X7Ø,2Ø    INSPECTION ASSY 1
   INITIAL   X71,14    INSPECTION ASSY 2
   INITIAL   X72,6     INSPECTION ASSY 3
   INITIAL   X73,23    INSPECTION ASSY 4
```

The arrival of incoming lots of subassembly kits follows a Poisson distribution. Therefore, the time between arrivals follows a negative exponential distribution. The mean times are specified via INITIAL cards. A typical set of input data is

```
MEAN TIMES BETWEEN ARRIVALS OF KITS FOR SUBASSYS

INITIAL   X11,24Ø   SUBASSY 1
INITIAL   X12,24Ø   SUBASSY 2
INITIAL   X13,48Ø   SUBASSY 3
INITIAL   X14,48Ø   SUBASSY 4
```

The lot sizes of the incoming subassembly kits are fixed and are specified for the model using INITIAL cards. A typical set of input data is

```
INCOMING LOT SIZE OF KITS FOR SUBASSYS

INITIAL   XH1Ø,1Ø   FOR SUBASSY 1
INITIAL   XH11,1Ø   FOR SUBASSY 2
INITIAL   XH12,15   FOR SUBASSY 3
INITIAL   XH13,15   FOR SUBASSY 4
```

Subassemblies are fabricated in fixed lot sizes. The number of kits assembled per lot is specified using INITIAL cards. A typical set of input data is

```
SUBASSY LOT SIZE

INITIAL   XH2Ø,2    FOR SUBASSY 1
INITIAL   XH21,2    FOR SUBASSY 2
INITIAL   XH22,2    FOR SUBASSY 3
INITIAL   XH23.2    FOR SUBASSY 4
```

When the inventory of the fabricated subassemblies drops below a defined minimum, additional subassemblies are made. These minimum inventory levels are also specified via INITIAL cards. A typical set of data is

MINIMUM INVENTORY LEVEL FOR SUBASSYS

```
INITIAL   X31,2   SUBASSY 1
INITIAL   X32,3   SUBASSY 2
INITIAL   X33,2   SUBASSY 3
INITIAL   X34,2   SUBASSY 4
```

The production line has a maximum of eight inspectors and eight rework stations. Each inspection station has a percentage of rejects. These percentages are defined using INITIAL cards. A typical set of data is

PERCENTAGE REJECTS

```
INITIAL   XH1,5Ø   SUBASSY 1
INITIAL   XH2,5Ø   SUBASSY 2
INITIAL   XH3,5Ø   SUBASSY 3
INITIAL   XH4,5Ø   SUBASSY 4
INITIAL   XH5,5Ø   ASSY 1
INITIAL   XH6,5Ø   ASSY 2
INITIAL   XH7,5Ø   ASSY 3
INITIAL   XH8,5Ø   ASSY 4
```

The 50's represent a five-percent rejection rate, though each station could have its own unique rate.

The model is also structured to permit the inputting of initial inventories for the subassembly kits and for the fabricated subassemblies. These initial inventories are specified using INITIAL cards. A typical set of data is

INITIAL INVENTORY OF KITS FOR SUBASSY

```
INITIAL   X25,5   SUBASSY 1
INITIAL   X26,5   SUBASSY 2
INITIAL   X27,5   SUBASSY 3
INITIAL   X28,5   SUBASSY 4
```

INITIAL INVENTORY OF SUBASSY

```
INITIAL   X41,2   SUBASSY 1
INITIAL   X42,2   SUBASSY 2
INITIAL   X43,3   SUBASSY 3
INITIAL   X44,2   SUBASSY 4
```

Outputs

The output from the simulation program consists of the following:

1. Utilization of the men

2. Queue statistics relating to the delays resulting from the men's being unavailable for particular tasks. These statistics include delays in the availability of subassembly kits, subassemblies, production-line fixtures, production-line stations, inspections, and rework stations

3. Inventory levels of subassembly kits and fabricated subassemblies

4. Distributions of times to assemble final assemblies.

Figures 5 through 10 depict some of the simulation displays generated from the standard GPSS output. These figures compare the consequences of manpower assignments A, B, and C. The assignments are

Description	A	B	C
Subassy 1	1	1	1
Subassy 2	2	2	1
Subassy 3	3	3	2
Subassy 4	4	4	2
Insp subassy 1	5	5	5
Insp subassy 2	5	5	5
Insp subassy 3	5	5	5
Insp subassy 4	5	5	5
Rework subassy 1	1	12	1
Rework subassy 2	2	12	1
Rework subassy 3	3	12	2
Rework subassy 4	4	12	2
Assy 1	6	6	6
Assy 2	7	7	7
Assy 3	8	8	8
Assy 4	9	9	9
Insp assy 1	10	10	10
Insp assy 2	10	10	10
Insp assy 3	11	11	11
Insp assy 4	11	11	11
Rework assy 1	12	12	12
Rework assy 2	12	12	12
Rework assy 3	13	12	12
Rework assy 4	13	12	12
Total manpower	13	12	12

Figure 5 presents the mean number of units assembled per eight-hour day. Figure 6 shows the mean number of final-assembly fixtures used in the 3 cases. Figure 7 shows the mean inventory levels of fabricated subassemblies. Figure 8 presents the mean utilization per man, while Figure 9 presents the actual percent utilization of each man. Figure 10 indicates the extent of the queing between the final assembly stations.

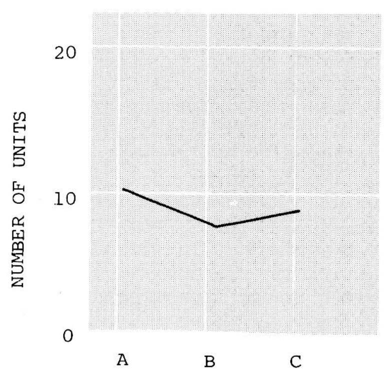

Figure 5 - Units assembled per day

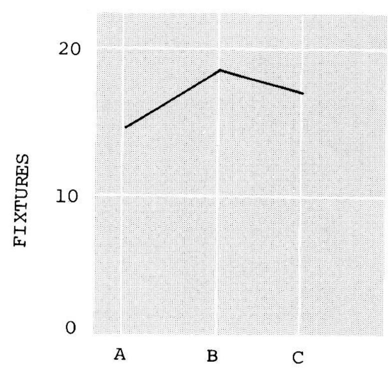

Figure 6 - Mean number of fixtures in use

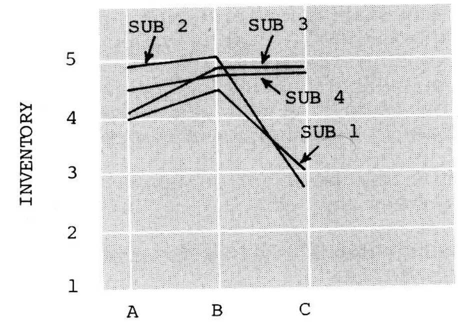

Figure 7 - Mean inventory of subassemblies

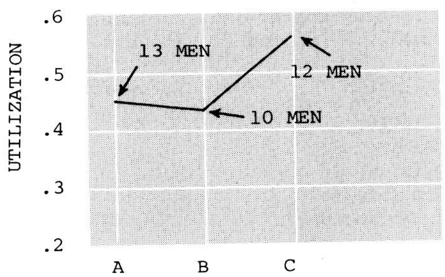

Figure 8 - Mean utilization of manpower

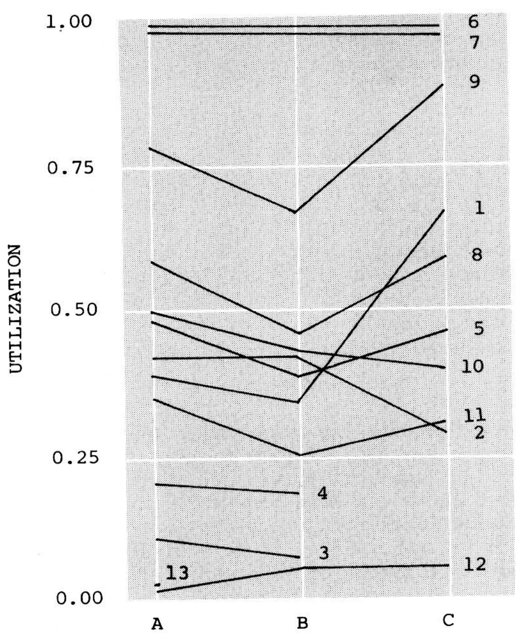

Figure 9 - Mean utilization of each man

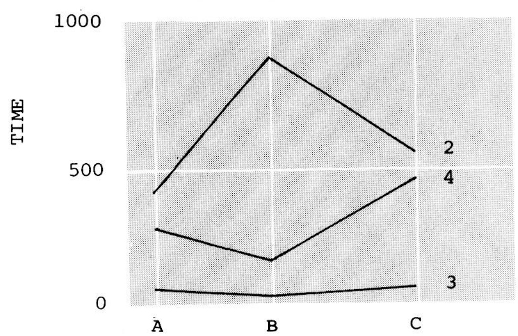

Figure 10 - Mean delay at stations 2, 3, and 4 of the production (final assembly) line

Execution

Four often-ignored problem areas that are generally implicit in most Monte Carlo simulations are:

(1) *When should measurements be collected from a simulation (i.e., how long does it take for equilibrium to be closely approached)?*

(2) *What should initial starting conditions of the simulation reflect?*

(3) *When has a model run long enough to give valid results?*

(4) *What should the sample size be.*

Equilibrium. Equilibrium is a limiting condition which is approached but never actually attained in a Monte Carlo simulation. This means that there is no single point in the simulation beyond which the system is in equilibrium. The difference between the present distribution of any variable in the simulation and its limiting distribution decreases with number of "transactions" or Monte Carlo simulation "runs" that have been made for a given set of initial conditions and parameters, but with different random numbers. Therefore, the user (since he cannot afford an infinite number of runs or "iterations") tries to find that point beyond which he is willing to neglect the error that is made by considering the system to have reached equilibrium.

A technique used to determine what constitutes an acceptable approximation to equilibrium has appeared in several publications.[1] Before the model is run in a production environment, the model is set up to print statistics on a periodic basis. Using GPSS, statistics may be printed after, say, every 25 transactions in a Monte Carlo simulation run. To do this, a series of START and RESET cards are arranged in the following sequence:

```
START    25
RESET
START    25
RESET
START    25
RESET
  .
  .
  .
```

At the completion of the simulation, statistics are available for each sample of 25 transactions as a function of number of such samples in the simulation. The statistics can then be plotted to give an indication of the behavior of any selected variable as a function of time (see Figure 11). Using the plotted statistics, we can subjectively determine when the statistics represent sufficiently usable (dependable) measurements; thereafter we should start retaining measurements. The technique is to ignore every measurement which is a maximum or a minimum and to select the first of 3 or more points which is neither a maximum nor a minimum. This is illustrated in Figure 11 in which the third point is neither a maximum nor a minimum of the ignored set. Therefore, in this case the first 75 transactions are processed before the system reaches an acceptable state of equilibrium. To bypass the printing of the useless statistics generated during the first 75 transactions, the GPSS model is now set up as

```
START    75
RESET
START    n
RESET
  .
  .
  .
```

where n is size of samples for which statistics are collected.

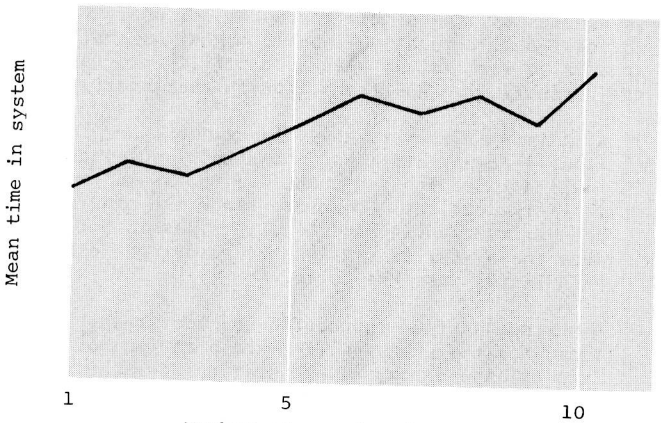

Figure 11 - Mean time in the system for each sample of 25 transactions

Starting conditions. The number of transactions which must be run before one can obtain statistics which are independent of the starting conditions is dependent on the starting conditions of the system. One of the most common ways of starting a Monte Carlo simulation is in the empty and idle state. That is, at the start of execution all queues are empty and all facilities are idle. Therefore it is obvious that if the model is started in a state other than zero, the time for the system to reach equilibrium should be reached.

In this model the starting conditions were defined such that all the manpower would be busy at the start of the simulation. To accomplish this initial inventories were assumed for the subassembly kits and for the assembled subassemblies. In addition, the initial inventory of the subassemblies was set to the minimum inventory level, which meant that it was immediately necessary to make up kits of parts for all subassemblies at the start of the simulation.

Stopping Conditions. A problem similar to that of determining equilibrium at the beginning of the run exists for determining when to stop a simulation run. Many times a simulation run is terminated by stopping the creation of new events for the system and then allowing the system to return to an empty and idle condition. But including the measurements collected after new events have ceased will introduce a bias which can be serious, especially if the total run is not long.

This problem can be avoided by terminating the simulation run after a given number of events have occurred. By using this approach, no limit is placed on the number of events entering the system. Instead, a limit is placed on the number of events exiting the system.

In GPSS this can be handled quite easily by not assigning an upper creation limit to the GENERATE block. The TERMINATE block is then used to count the number of transactions exiting the system.

How much is enough? The variability associated with the measurements of even the very simple simulation models is generally large. For this reason, large sample sizes are ordinarily required to provide an adequate test of the results of a simulation against established norms. Fortunately, a large portion of real-world problems require only a comparison between alternatives. This is one of the real benefits of simulation. The simulation model can be used much more efficiently to produce relative results than absolute results.

This unique capability for producing relative results comes from the ability of simulation to reproduce and reuse an identical sequence of events for different runs of the model. This is possible because the sequence of events is a function of a sequence of pseudo-random numbers. These pseudo-random numbers can be reproduced by starting the sequence with the identical seed (the starting number for a pseudo-random-number generator using a particular algorithm).

By reproducing the same sequence of random numbers for each alternative of the assembly line, it is possible to reproduce the identical sequence of events. This increases the contrast between alternatives by reducing the residual variation in the differences in the total performance of the assembly line; therefore, smaller samples are required to detect statistically significant differences.

The procedure used for comparing two alternatives of the assembly line is to compare the effects of the alternatives on the performance of the system when the performance resulted from same series of events using the same pseudo-random numbers. Since these pairs of performances are obtained under the same conditions, the differences between them become the relevant sample observation. This sample is used to test the hypothesis that the mean of these differences is zero and to obtain a confidence interval of the mean. This test indicates whether there is a significant difference between the means of the performance of the assembly line for the two alternatives.

To make such a statistical comparison for this model, the run, under each assembly-line alternative, was divided into equal portions of ten transactions each. The GPSS logic was

```
START    75
RESET
START    1Ø
RESET
START    1Ø
RESET
START    1Ø
RESET
START    1Ø
RESET
START    1Ø
  .
  .
  .
RMULT    31,33
CLEAR    XH1-XH54,X1-X73
INITIAL  XH31,1       SUBASSY 1
INITIAL  XH32,1       SUBASSY 2
```

```
INITIAL   XH33,2     SUBASSY 3
INITIAL   XH34,2     SUBASSY 4
INITIAL   XH51,1     REWORK SUBASSY 1
INITIAL   XH52,1     REWORK SUBASSY 2
INITIAL   XH53,2     REWORK SUBASSY 3
INITIAL   XH54,2     REWORK SUBASSY 4
INITIAL   XH47,12    REWORK ASSY 1
INITIAL   XH48,12    REWORK ASSY 2
INITIAL   XH49,12    REWORK ASSY 3
INITIAL   XH5Ø,12    REWORK ASSY 4
START     75
RESET
START     1Ø
RESET
  .
  .
  .
```

Therefore, for each alternative, 10 observations were collected: $s_1, s_2, \ldots, s_{10}$. By taking the difference for each of the 10 portions of the two alternatives, the average difference and the standard deviation of the difference were obtained. These equations are

$$d = \frac{1}{n} \sum_{i=1}^{n} (s_i\ alt1 - s_i\ alt2)$$

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} [(s_i\ alt1 - s_i\ alt2) - \bar{d}]^2}$$

The estimate of the standard deviation of the mean difference is $s/\sqrt{n}$. The corresponding t-statistic is $t = d/(s/\sqrt{n})$. The value of the t-distribution with $\alpha = 0.05$ and $(n-1) = 9$ degrees of freedom can be obtained from standard tables. If $t < t_\alpha = 0.05$, $(n-1) = 9$, the hypothesis is accepted that there is no significant difference in the mean differences for the two alternatives. Similar tests can be made for comparing remaining assembly-line alternatives.

Unique features. In developing this manual-assembly-line simulation model, it became apparent that the MACRO feature of GPSS offered great potential in devising a general-purpose model. The majority of the program logic was defined using MACRO's. As a result, the "main-line" consisted of a series of MACRO's. A portion of the main-line is

```
*       SUBASSY SIMULATION
*
*       SUBASSY 1
*
 SUBAS MACRO      3,PSS1,X25,XH2Ø,SSS1,XH31,1,X5Ø,25-
 SUBIN MACRO      ISS1,XH35,17,X66
 ASSXP MACRO      .XH1,RSS1,XH51,5,X54,X41,41+,X31,3
*
*       SUBASSY 2
 SUBAS MACRO      4,PSS2,X26,XH21,SSS2,XH32,2,X51,26-
 SUBIN MACRO      ISS2,XH36,18,X67
 ASSXF MACRO      .XH2,RSS2,XH52,6,X55,X42,42+,X32,4
*
```

Another feature is that all input to the model is through the use of INITIAL and FUNCTION cards. Logic has been built into the model for selecting either the normal or exponential distribution for the service times. This logic is controlled by an INITIAL card.

The model also uses the redefinition feature of GPSS. This feature permits the changing of manpower allocation and initial conditions without the necessity of manually changing these cards and resembling the program.

CONCLUSIONS

In conclusion, the simulation model for assisting in the design of a relatively small manual assembly line appears to work fairly well as a utility program when the assembly line has the following characteristics:

1 A maximum of four subassembly stations and four final assembly stations. No simple technique was devised to reduce the number of subassembly and assembly stations. However, since the program has been written using MACRO's, it is possible to reduce the number of stations by removing these MACRO cards from the logic.

2 A maximum of four inspection and four rework stations for the subassemblies and a maximum of four inspection and four rework stations for the final assembly. The number of these stations can be reduced through the manpower allocation INITIAL cards.

3 Subassembly parts are in kits and arrive following a Poisson distribution.

4 All service times are either normal or exponential.

This program has been successfully used to simulate an assembly line in the aerospace industry. The program should also be applicable to various types of relatively simple manual assembly lines possessing the above general characteristics.

This type of model has great potential as a teaching aid since the program has relatively simple input for data and provides for the simulation of a variety of assembly-line configurations merely by changing several data-input cards. The program introduces the student to a simulation language (GPSS) and to a computer. And—an aspect which is important in the real-world environment—it gives the student a chance to test his particular design against various alternatives.

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