AD-A142 284   SCHEDULING OF MULTIPRODUCTS WITH LIMITED RESOURCES IN AN UPS (UNINTERRUPTIBLE POWER SUPPLY)(U) ARMY MILITARY PERSONNEL CENTER ALEXANDRIA VA   C J VENABLE 13 JUN 84   1/2

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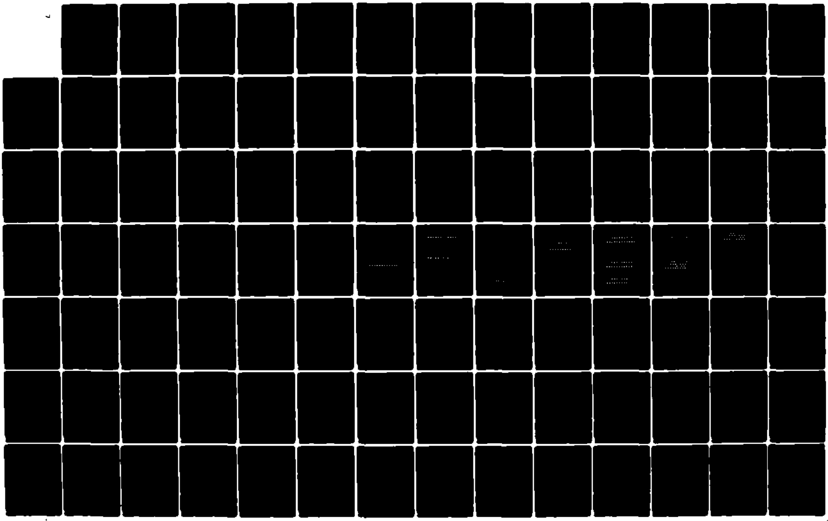

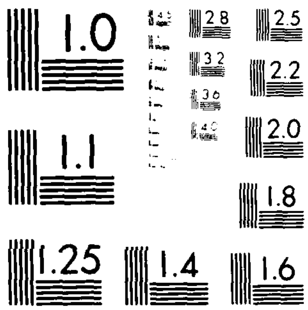

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AD-A142 284

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Scheduling of Multiproducts With Limited Resources in an UPS Testing Facility	5. TYPE OF REPORT & PERIOD COVERED Final Report 13 Jun 84
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Captain Charles J. Venable	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Student, HQDA, MILPERCEN (DAPC-OPA-E), 200 Stovall Street, Alexandria, VA 22332	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS HQDA, MILPERCEN, ATTN: DAPC-OPA-E, 200 Stovall Street, Alexandria, VA 22332	12. REPORT DATE 13 Jun 84
	13. NUMBER OF PAGES 155
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

JUN 2 2 1984

18. SUPPLEMENTARY NOTES

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science: Operations Research Program.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Scheduling
Capacity Loading
Simulation
Operations Research
Uninterruptible Power Supply

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Scheduling procedures in an Uninterruptible Power Supply (UPS) testing facility were investigated. It was determined that the facility was experiencing an inordinate number of missed product due dates. An analytical scheduling model was developed.

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However, due to a unique shift organization the computational complexity of the model overshadowed its usefulness and a reduced formulation was developed. The reduced scheduling formulation when used with an iterative approach, produced acceptable feasible solutions.

It was also determined that due to the multiproduct nature of the industry, test facility capacity was not considered for specific product mixes. An analytical capacity model was developed to be used in conjunction with a heuristic to estimate capacity. Again, the computational complexity of the model was large and the determination was made to use a simulation approach. An operational tool for the test facility manager was developed in the form of a sequential simulation as an aid in scheduling and determining capacity and resource restrictions. A simulation experiment was also conducted to determine the preferred queue discipline and second shift processing criterion. It was determined that neither had an effect on the number of late jobs or mean lateness, thereby, indicating that the source of the problem lies outside the test facility.

SCHEDULING OF MULTIPRODUCTS WITH LIMITED RESOURCES IN AN UPS TESTING FACILIY

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13 Jun 84

A thesis sumbitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

ABSTRACT

VENABLE, CHARLES J. Scheduling of Multiproducts with Limited Resources in an UPS Testing Facility. (Under the direction of DR. S. E. ELMAGHRABY.)

Scheduling procedures in an Uninterruptible Power Supply (UPS) testing facility were investigated. It was determined that the facility was experiencing an inordinate number of missed product due dates and it was the objective of this study to:

1. Develop a model to describe the assignment functions with regards to resource constraints.
2. Develop and implement an algorithm to determine the practicability of monthly test requirements.
3. Determine feasibility of a capacity loading model.
4. Determine feasibility of an optimum scheduling model.

An analytical scheduling model was developed. However, due to a unique shift organization the computational requirements of the model overshadowed its usefulness. In order to lessen the number of required constraints a reduced formulation was developed which considered only one shift. An algorithm was then presented which, when used with the reduced formulation, produced acceptable feasible scheduling solutions for both shifts.

It was also determined that due to the multiproduct nature of the industry, test facility capacity was not considered for specific product mixes. An analytical capacity

model was developed to be used in conjunction with a heuristic to estimate capacity prior to schedule development. Again, the computational requirements of the model proved too large, and the determination was made to use a simulation approach. An operational tool for the test facility manager was developed in the form of a sequential simulation, to be utilized as an aid in scheduling and determining capacity and resource restrictions.

Data was collected from the test facility in order to develop valid parameters to the simulation. Combining the input data with the sequential simulation model a valid randomized simulator for the test facility was constructed. A simulation experiment was conducted to determine the preferred queue discipline and second shift processing criterion. It was statistically determined that neither had an effect on the number of late jobs. However, it was shown that the dispatch rule of shortest processing time significantly increased the mean lateness, while the second shift processing criterion had no effect. The second shift processing criterion was also shown to have no effect on second shift testor utilization.

These results, thereby, indicated that the source of the inordinate number of late jobs lies outside the testing facility and that the second shift testor configuration may not meet the future needs of the system. This conclusion was verified by the sparsity of the second shift "qualification matrix", and a recommendation to management was made to this effect.

It was also recommended that the reduced scheduling model and the related algorithm be employed by the company both as a planning tool and an operational tool. As a planning tool it was recommended for use as a capacity model, with the assumption that products are immediately available, and as the first step in a backward planning process. As an operational tool it was recommended for use by the test facility manager on receipt of monthly test requirements. Additionally, it was recommended that the test facility manager employ the sequential simulator as a desk-side reference to provide immediate scheduling update as production information is received.

SCHEDULING OF MULTIPRODUCTS

WITH LIMITED RESOURCES

IN AN UPS TESTING FACILITY

by

CHARLES J. VENABLE

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

OPERATIONS RESEARCH PROGRAM

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BIOGRAPHY

Charles Joseph Venable was born in Beckley, West Virginia on 7 October 1951. His father was in the United States Army and consequently he lived in a number of locations, both in the United States and overseas. He attended high school in North Carolina and graduated from Southern Wayne High School in Dudley, North Carolina in 1969. He received a Presidential Nomination to the United States Military Academy, West Point, New York, and was the recipient of a Bachelor of Science degree in June 1973. Subsequent to his graduation, he was commissioned as an Infantry officer in the United States Army.

As an Infantry officer he has served as a platoon leader, company executive officer and battalion staff officer. He has also commanded both an Infantry Headquarters Company and a Special Forces A-Detachment. His military education includes Infantry Officer's Basic Course, Infantry Officer's Advanced Course, Special Forces Officer's Course, the Basic Airborne Course, and the Defense Language Institute's Spanish Course. His assignments have been both in the United States and in the Republic of Panama.

His next assignment will be at the United States Military Academy, West Point, New York, as an instructor in the Department of Mathematics. He currently holds the rank of captain.

The author is married to the former Mikelle Louise Hatch and has one daughter, Dyonne Teresa. Mrs. Venable graduated from James Madison University in August 1977 with a Master of Science in Speech-Language Pathology.

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I. Introduction

With the growing reliance in business and government on computers and computer-based equipment a new problem has emerged - how to protect this equipment against power fluctuations and outages. There are several technologies available which offer varying degrees of power protection. The most complete solution, however, is an Uninterruptible Power Supply (UPS).

The UPS is composed of a static rectifier/charger which takes the incoming AC power and converts it to DC; a static inverter which converts DC back to clean, reliable AC power; and a bank of battery cells to supply full operating power, through the inverter, for a specified period of time during an extended power outage (Fig. 1.1, 1.2). Unlike other types of standby power sources which only take over during a utility failure, the UPS system actually becomes the principal source of power to the critical load, supplying smooth, regulated AC power regardless of the condition of incoming utility power.

The demand for UPS protection has increased dramatically as computer technology has evolved and will continue to accelerate in the coming years. In order to meet this demand UPS production firms are continuing to introduce new product lines, provide more custom engineering and increase production. However, sales continue to outpace production capacity causing strained customer relations, possible market loss, employee morale problems due to increased overtime

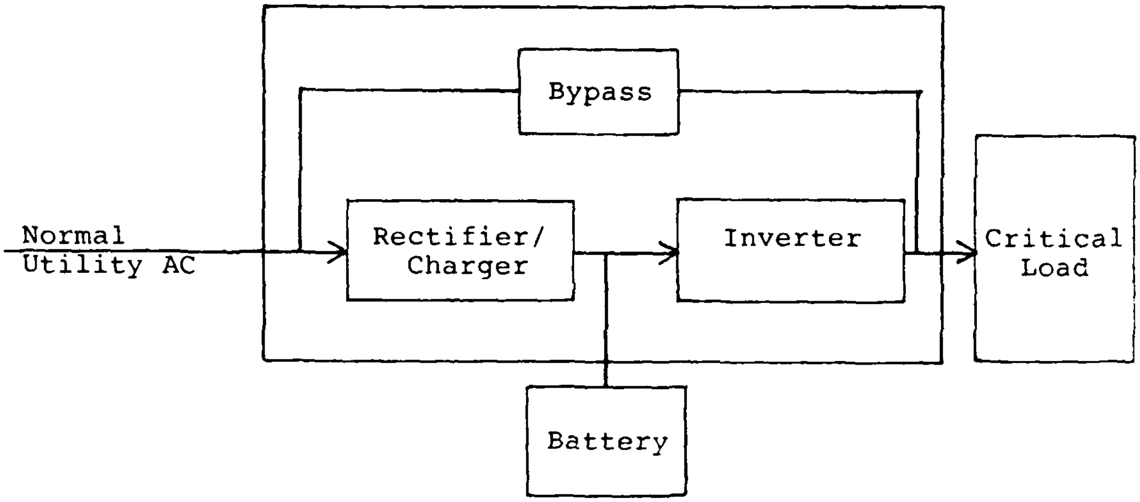


Fig. 1.1 System Operation During Available Utility Power

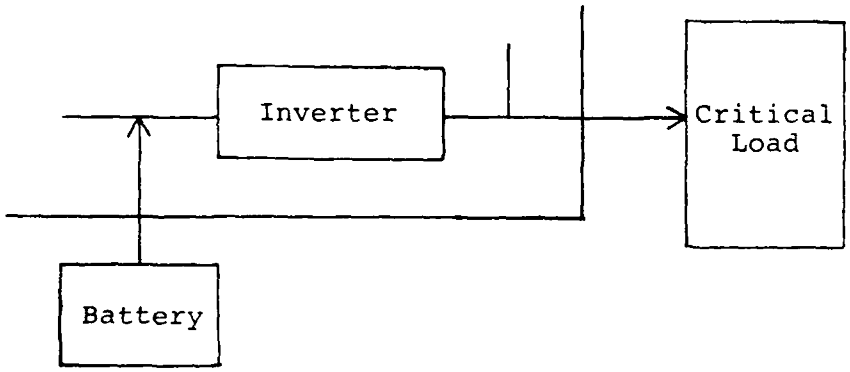


Fig. 1.2 System Operation During Power Outage

requirements and numerous other problems. In order to minimize these problems, UPS production firms are increasingly applying operations research methods to optimize production methods.

Common to all such firms is the requirement to fully test all UPS products, with a battery, following final assembly. This final testing provides a natural choke point in the production sequence. This area then becomes critical in any production optimization study. This study will, therefore, concentrate on the UPS system test phase.

In order to properly diagnose the problems associated with this phase of the production sequence a generalized discussion of the system test area and the resource allocation/planning systems in use will follow.

II. Problem Definition

The System Test Area

The system test area must be capable of fully testing all UPS Products, with a battery. this requires a tremendous power versatility. Products range in size from 15 kilowatts to 600 kilowatts. They are available in single or three-phase with input voltages ranging from 208 to 480 volts and output voltages ranging from 120 to 480 volts. Additionally, depending on product destination, it may be configured for 50, 60, or 415 Hz per second. Appendix A lists 72 product types and as mentioned previously, new UPS products are continuing to be introduced to the market.

Systems can also be obtained in both single module (non-redundant) configurations.

System test areas are divided into stations with all stations having four variables; maximum size unit, load size, available voltages, and a battery. These variables will dictate the product types that may be tested at that station. Appendix B details these variables for a given test facility and gives a matrix showing which of the 72 identified products can be tested at which stations.

This test facility will then provide a practical example for the discussion of the planning and resource allocation that follows.

The System Test Forward Planning System

Upon sale of an UPS the firm gives their customer a promise date for delivery of the equipment. This promise date is arrived at by a mathematical equation that incorporates manufacturing lead times. Each product line has a standard amount of time, lead time, for production. These times were developed by the firm's Industrial Engineering Department for each phase of the production sequence, including Systems Test. These figures were then totaled with an additional "safety" factor to obtain the standard. Due dates are then published in a number of documents, chief of which is the Project Management System PM 21 report (Appendix C) which would be used by the manager of the Systems Test area to prepare his monthly plan for test

(Appendix H). The PM 21 report is by due date and in effect sets the priority for the equipment. In order to gain more information on the product, the manager would then cross-reference the equipment in priority with the Project Management System PM01 report (Appendix D). Of primary concern to the manager at this time is the date at which the item is scheduled to arrive at Systems Test (Reference #1, App. D), and the scheduled completion date for Systems Test (Reference #2, App. D). These dates give the manager the window within which the equipment must be tested. The next item of information from this report, of interest to the manager, is the type of equipment (Reference #3, App. D) which can also be obtained from the PM21 report, Appendix C. With this information he can schedule a test station compatible with this particular model. The manager must then determine the number of test hours required for the equipment.

Each product has a standard allotted test time. However, additional hours may be necessary. For example, the customer may wish to observe or personally verify testing. This is termed a "witness test." Or the customer may have ordered additional specifications to the product requiring custom engineering and, therefore, additional testing. Referring again to the PM01 report the manager determines if a witness test is required (Reference #4, App. D) and if its order type is custom or standard (Reference #5, App. D).

To gain more technical information about the piece of equipment, specifically if other tests are required which will add test time, the manager refers to the Special/Standard Order Data Sheet, SSPODS (Appendix E). Using the allotted test times (Appendix F) and the known test station constraints (Appendix B) the manager schedules the UPS for a particular date and station. Once the manager's test plan has been prepared the supervisor of Systems Test will schedule his personnel based on their productivity hours for the month and their skill qualifications.

As the UPS moves through the assembly process, updates will be made to the PM01 report on its progress. Of primary interest to the manager is the Current Scheduled Start (Reference #6, App. D) and the Current Scheduled Completion (Reference #7, App. D). These dates will advise the manager as to any changes in the availability window for Systems Test and allow him to revise his plan of tests accordingly. The PM01 report is run each week and, therefore, provides the manager with a weekly update. This section is summarized by Figure 2.1.

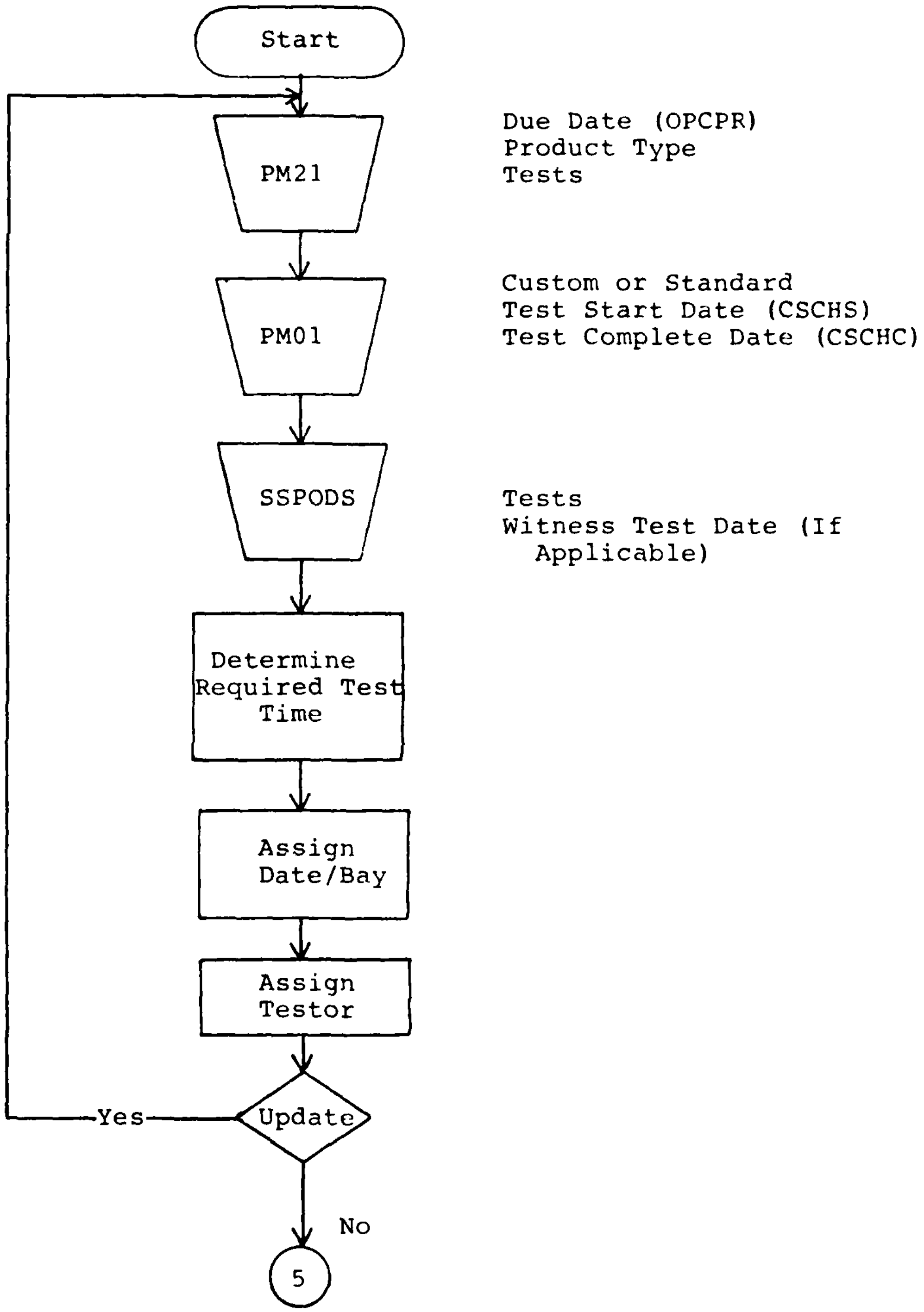


Figure 2.1 Systems Test Forward Planning System

The Working System

The manager of Systems Test currently uses the Monthly Sales Plan (Appendix G) as his priority document. From this document he is able to tell which week of the month the company expects the equipment to be delivered. The Monthly Sales Plan also allows the manager to identify sold, definite orders, versus pending, projected orders. The manager then cross-references the system number for the particular piece of equipment with the system number on the PM01 report (Appendix D) and determines the Operations Original Promise Date (Reference #8, App. D). This date will further set his priority for test as this is the last possible date for completion of production. Additionally, he is able to tell from both of these documents whether the UPS requires a witness test. He then refers to the SSPODS (Appendix E) to determine the date for the witness test, if required. This date then becomes critical in the test sequence, since a representative of the customer will be present on that date to verify testing. Additionally, the planning office gives a periodic priority update in informal conferences with the System Test Supervisor. In this conference information is collected as to the status and projected completion dates for priority products. These individuals also serve as troubleshooters if a problem, such as engineer support, stands in the way of test completion. A recent change in the working system that has taken place since the beginning of this study is the implementation of a thrice weekly conference on the current status of production. In attendance at this meeting are the major manufacturing managers, including the Systems Test manager. The result of the conference is an updated UPS Production Plan, Appendix I. This plan tracks the planned and actual completion dates at each stage of the manufacturing process for each scheduled product. This plan then serves to update the current planned arrival date of a product to Systems Test. This section is summarized by Figure 2.2.

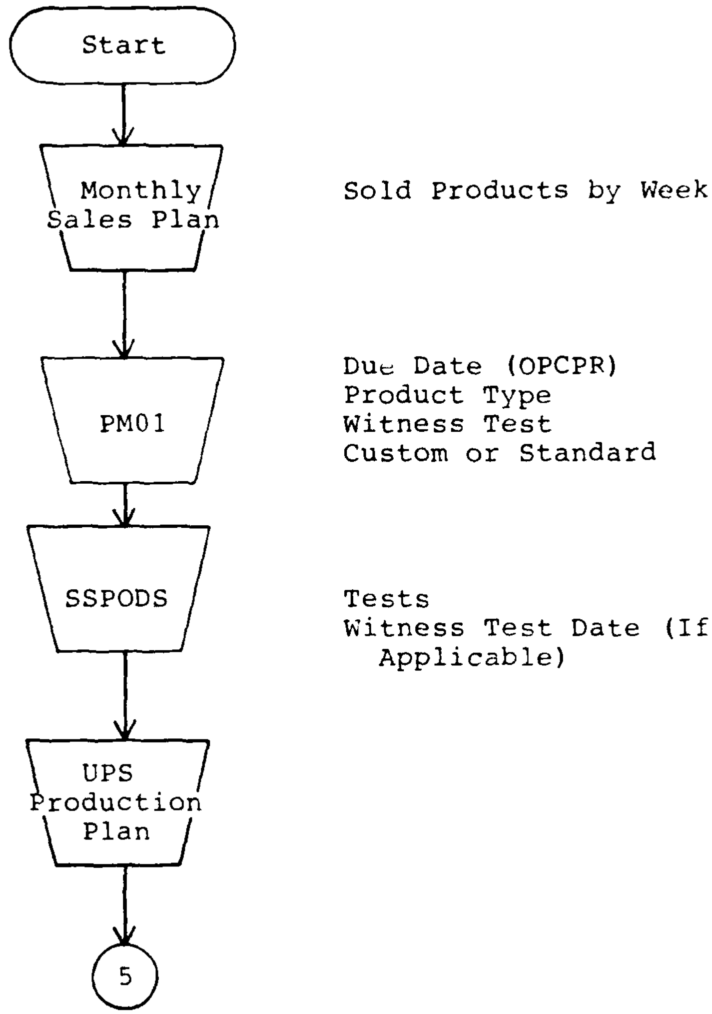


Figure 2.2 The Working System

The Test Sequence

Once an UPS is ready for Systems Test from the production line, the "lead hand" notifies the Systems Test Supervisor. The supervisor determines whether a station is available that will handle the specific model. If so it is moved to the station. Systems Test does not have a designated holding area. Therefore, if space is not available, it may sit at the end of the production line, be moved to a floor space in Systems Test, or if it is for stock, moved to the warehouse. The supervisor then determines whether he has a testor available to begin testing the equipment. Testors are only qualified to test certain product lines and are qualified to test all models within that product line. Additionally, the supervisor must determine whether to also assign the UPS to second shift based on its priority and projected system test time. This decision may be made anytime until the UPS is fully tested. However, once the decision has been made to test the product on second shift as well as first, it will continue to be tested by both shifts until completion. Similarly, the individual testors, once assigned to a specific UPS, will stay with that piece of equipment until completion. This section is summarized by Figure 2.3.

When a testor receives his assignment he reports to the quality control office. Here he is issued the test packet

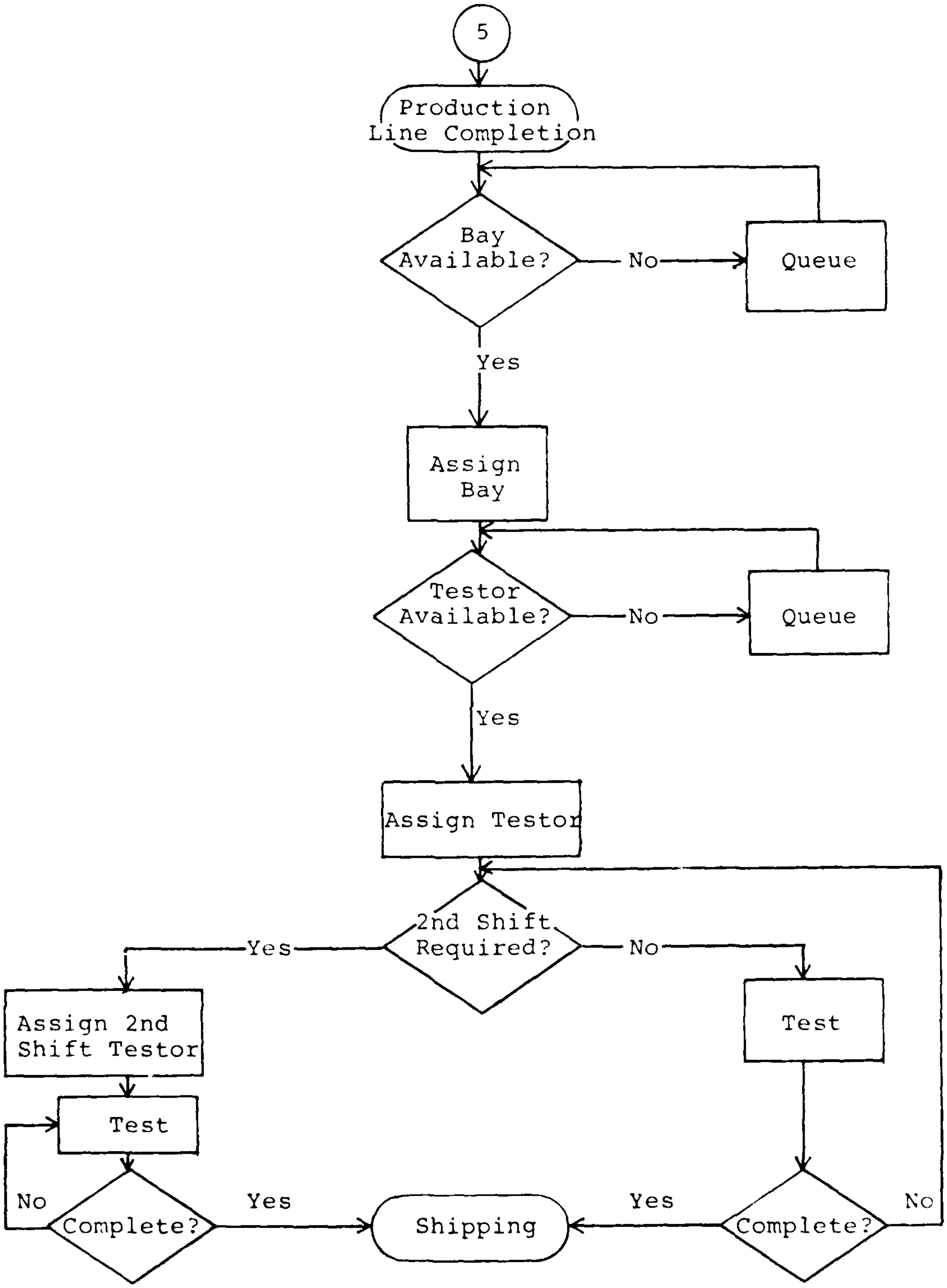


Figure 2.3 Assignment Sequence

for the particular UPS and the Test Data Sheets. The data sheets provide the testor with the test sequence and serve as a final record of testing when completed. As the testor moves through the test sequence he completes the Unit Status Report. This report is a record of his progress and serves as an inter-shift report if the UPS is assigned to second shift or if for some unforeseen reason the testor is not able to complete the sequence. Additionally, the testor records all problems/faults that he encounters in the test sequence on a Test Failure Report. This is a quality control form and gives a description of the failure, analysis of the cause, and the action taken.

Each day the supervisor prepares a status report. This report is compiled based on the Unit Status Reports and gives a percentage of completion, the current procedure being tested, any any major problems. This report is forwarded to the Quality Assurance Manager. Once an UPS has completed test the Shipping Department is informed and the UPS is moved.

Existing System Problems

The manager of Systems Test does not have confidence in the outlined forward planning system. This is due primarily to the failure of the update procedure. In the formal system without the update information, initial data becomes meaningless and the manager is unable to form a complete plan for test. This situation has been recognized and an attempt to rectify the problem has been made by the implementation of the thrice weekly conference on the status of production. Through this conference the manager is kept abreast of production dates and specifically, scheduled dates for arrival at Systems Test. However, delays that occur in the production system, although now accounted for by the UPS Production Plan (Appendix I), are not reflected in the original and current dates of the PM01 report. Since Systems Test is the last in the production sequence, the manager finds the ideal lead times drastically cut forcing him to make up production lost time to meet the promise date.

Monthly planning is based primarily on sales projections, and even though standard production lead times are used in determining due dates, consideration is not given to whether the specific monthly product mix will be able to be processed by Systems Test and still fall within the designated lead times, meeting the due date. As a result, Systems Test finds itself overcommitted. This problem is then amplified by the carryover from the previous month of the products which were not tested. This forces a severe backlog to occur at the end of the month as the manager attempts to meet the monthly projection figures necessitating numerous overtime hours.

III. Project Objectives

It has become apparent during the Problem Definition phase of this study that two major problems exist. The first is the lack of update in the firm's reporting procedures. As mentioned previously, the weekly manager's conferences on the status of production is an attempt to address the problem, however, the results must be integrated into the existing formal planning framework to gain maximum benefit. The second is the fact that Systems Test area constraints are not considered during the firm's planning phase. This is a result of a failure to accurately determine the Systems Test area capacity. This capacity, however, varies with product mix and, therefore, may not be able to be explicitly determined. It is the second problem on which the remainder of this study will focus.

It is the objective of this study to:

1. Develop a model to describe the System Test assignment functions with regard to resource constraints.
2. Develop and implement an algorithm which will allow the manager of a Systems Test facility to determine whether he will be able to meet monthly test requirements as delineated in the firm's monthly plan/forecast.
3. Determine feasibility of a capacity loading model for Systems Test.
4. Determine feasibility of an optimum scheduling model for Systems Test.

IV. Model Formulation

Prior to the statement of the model, the following aspects of the real system, developed during the problem definition phase, are recalled:

Each product is assigned to a test station and testor(s). It remains at that location, with that testor or testors, until processing is complete. However, due to the limited number of second shift testors, processing on second shift is reserved for products which would otherwise be completed late or within a certain factor of the due date if processed completely on first shift. Each test station is not compatible with every product and each operator is not qualified to test every unit. There are also various "pairwise" station constraints that may exist, where assignments in one station affect the product compatibility in another station due to limited resources shared between the stations. Additionally, operator productivity varies with individual experience levels. Another aspect which must be considered is that parallel systems must have their components tested separately prior to system testing. The final key consideration is the fact that each product has an assigned due date.

Therefore, for a complete scheduling model, equations must be developed to ensure that a schedule meets the following constraints:

1. Limited resources;
2. Precedence relations between jobs;

3. Product due dates;

4. Limited use of second shift; and

5. Product assignment.

During the problem definition phase it was noted that there were difficulties in both scheduling within Systems Test and capacity planning. Models for both scheduling and capacity will, therefore, be presented.

Scheduling Model

Definitions

i = product number, $i = 1, \ldots, I$; I = number of systems to be tested in planning horizon.

j = test station number, $j = 1, \ldots, J$; J = number of test stations.

k = first shift testor number, $k = 1, \ldots, K$; K = number of first shift testors.

m = second shift testor number, $m = K+1, \ldots, M$; M = total number of testors.

t = time period, $t = 1, \ldots, T$; T = last time period of planning horizon.

$e_{i(jk)}$ = efficiency index for product i tested on test station j with first shift testor k. 0 e_{ijk} 1.

$e_{i(jm)}$ = efficiency index for product i tested on test station j with second shift testor m. 0 e_{ijm} 1.

$x_{i(jk)t}$ = a variable which is 1 in period t if product i is scheduled to start testing on test station j with first shift testor k at time t; 0 otherwise. $x_{i(jk)t}$ need not be treated as a variable in all periods, since it equals 0 for t a_i.

a_i = arrival period of product i.

FSP_i = first shift processing time = number of periods required to test product i entirely on first shift.

DT_i = due period of product i.

u_i, v_i 0 and integer.

$_i$ = a variable which is 1 if a product would be late if processed entirely on first shift and 0 otherwise.

$R_{i(jk)t}$ = a variable which is 1 in period t if product i is being processed in station j by first shift testor k at time t, 0 otherwise. Defined only for products not requiring second shift testing.

$R_{i(jk)}$ = a vector of dimension T of 0's and 1's, representing the first shift resource occupancy in the horizon by product i and pair (jk) when second shift is not used.

$Y_{i(jk)t}$ = a variable which is 1 in period t if product i is being processed in station j by first shift testor k at time t, 0 otherwise. Defined only for products requiring second shift testing.

$Y_{i(jk)}$ = a vector of dimension T of 0's and 1's, representing the first shift resource occupancy in the horizon by product i and pair (jk) when second shift is used.

$Z_{i(jm)t}$ = a variable which is 1 in period t if product i is being processed in station j by second shift testor m at time t, 0 otherwise. Defined only for products requiring second shift testing.

$Z_{i(jm)}$ = a vector of dimension T of 0's and 1's, representing the second shift occupancy in the horizon by product i and pair (jm).

$P_{i(jk)}$ = $\lceil FSP_i/2 \rceil$ = first shift processing time for products requiring second shift.

$P_{i(jm)2}$ = second shift processing time.

r_{ic} = amount of resource of type c required on product i.

$RS_{c(j1j2)}$ = amount of resource of type c available between the test stations j_1 and j_2.

Since each product must be assigned to a test station and a testor, this assignment will be treated as a pair, "station, operator", either on first shift or second shift. If an operator, or a test station, is not eligible to work on a product or class of products the productivity is zero for that product and "station, operator" pair. This information, along with the operator's efficiency rating is included in the efficiency indexes, e_{ijk} and e_{ijm}. In this way varying processing times is possible in that the standard allotted test time when divided by the efficiency index yields the processing time as a function of the "station, operator" pair, i.e., $FSP_i = FSP_i(jk)$.

Constraints

Product Assignment

Testing on each product must be started sometime within the planning horizon, [1, T], in a compatible test station with an eligible testor. The interval for start of test is further reduced for each product by its arrival time and $P_{i(jk)1}$, the processing time requirement on first shift for those products tested on second shift. It should also be noted that second shift testing on a product will not occur until a first shift testor has been assigned. An assignment constraint is required to ensure that a product is assigned to only one "pair" in the horizon.

$$\sum_{t=a_i}^{T-P_{i(jk)1}} X_{i(jk)t} = 1 \qquad (1)$$

, for each product i. It should also be noted that the "pair" (jk) will not be defined if either the product is not compatible with the test station or the operator is not qualified to test the product. In addition, the constraint automatically requires that a product is assigned to only one pair (jk) for all t. The constraint is actually a "multiple choice" constraint over all t and all pairs (jk).

Additionally, a product assignment or capacity constraint is required to ensure that test stations and testors are assigned at most one job at a time. Obviously, there are two ways in which to proceed. First is to bound the "station, operator" pairs, (j,k) and (j,m). The second is to bound the test station, first shift testors, and second shift testors individually. As stated previously, the "pair" model will be presented.

Let $y_{i(jk)}$, $z_{i(jm)}$, and $R_{i(jk)}$ be vectors of dimension T representing the resource occupancy in the horizon by product i and "pair" (jk) and (jm). Then,

$$\sum_i (y_{i(jk)} + R_{i(jk)}) \leq 1_T \qquad (2)$$

, for each "pair" (jk) (1st Shift) and

$$\sum_i z_{i(jm)} \leq 1_T \qquad (3)$$

m for each "pair" (jl) (2nd Shift). 1_T represents a vector of ones of dimension T. It should be noted that constraints (9), (10), (11), (12), (13), and (14) will further restrict the variables $R_{i(jk)}$, $Y_{i(jk)}$ and $Z_{i(jm)}$ so that if $R_{i(jk)}$ exists then $Y_{i(jk)}$ and $Z_{i(jm)}$ will not and if $Y_{i(jk)}$ exists then $Z_{i(jm)}$ will exist but not $R_{i(jk)}$.

Limited Resources

In some instances resources, such as batteries, power, or voltage set ups, may be shared between stations. A "pairwise" station constraint then exists when the availability of these resources is reduced or denied to one station when in use in another. This consequently reduces the compatibility of the station. These types of constraints take two forms.

First, the use of a specific resource in one station denies its use in another. For example, only one 50 Hz unit may be tested in stations j_1, and j_2 at any time.

$$\sum_i \sum_k (Y_{i(j_1k)} + Y_{i(j_2k)} + R_{i(j_1k)} + R_{i(j_2k)} \leq 1_T \quad (4)$$

This is to be written for every pair j_1 and j_2 thus specified where i ranges over those products requiring the specific resource.

Secondly, the use of a specific resource in one station reduces its use in another so that the total use may not exceed a certain value. For example, the maximum power requirement in test stations j_1 and j_2 is limited to $RS_{C(j1j2)}$.

$$\sum_i \sum_k [r_{ic}(Y_{i(j_1k)} + R_{i(j_1k)} + Y_{i(j_2k)} + R_{i(j_2k)})] \leq RS_{c(j_1j_2)} \quad (5)$$

Again, this is to be written for every pair j_1 and j_2, thus specified where i ranges over those products requiring the specific resource. Both of the forms of the resource constraint may be expanded to any subset of stations j_1, $j_2, \ldots J_n$ instead of a single pair j_1 and j_2.

Inclusion of the terms $Z_{i(j_1 m)}$ and $Z_{i(j_2 m)}$ are not necessary in constraints (4) and (5). This is due to the fact that products must be assigned on first shift prior to second and that the test station assignment remains constant throughout the processing period. Therefore, any conflicts would have been resolved prior to second shift processing.

Precedence Relations

Precedence relations exist for the processing of parallel systems. A parallel system is composed of a number of components offering redundancy of protection to the user. Therefore, each component of the system must be tested as a single unit prior to testing as a system. If the number of periods required to process a component n of Product i is designated by PP_{i_n}, then

$$PP_{i_n} = \sum_{t=a_{i_n}}^{T} (R_{i_n(jk)t} + Y_{i_n(jk)t} + Z_{i_n(jm)t})$$

and,

$$\sum_{t=a_{i_n}}^{T-P_{i_n(jk)}+1} tX_{i_n(jk)t} + PP_{i_n} - 1 \leq \sum_{t=a_i}^{T-P_{i(jk)}+1} tX_{i(jk)t} \qquad (6)$$

where n = 1, 2,...N; N = number of components in parallel product i. This would be written for each component of each parallel system scheduled to be tested in the horizon.

<u>Second Shift</u>

Second shift operation takes place only if time is not sufficient to complete the processing of the product by its due time or within a specified period of its due time on first shift only. A product that can be finished by the specified period of its due time is not permitted to have second shift testing and thus finish it even earlier.

$$\sum_{t=a_i}^{T-P_{i(jk)1}} tX_{i(jk)t} + 2(FSP_i - 1) - (DT_i + C) = u_i - v_i \qquad (7)$$

, for all i, where u_i, $v_i \geq 0$ and integer and C is the specified period of the due time before which products must be completed without requiring second shift.

$$u_i \leq \delta_i K$$
$$v_i \leq (1-\delta_i)K \qquad (8).$$

, where K is a large number greater than zero and each constraint is written for all i. This constraint with the proper valuation of u_i and v_i in the criterion function will result in:

1. If product i is late, completed after the specified period before the due time, when processed only on first shift, $u_i > 0, v_i = 0$, and $\delta_i = 1$.
2. If product i is early, completed prior to the specified period before the due time, when processed only on first shift, $u_i = 0$, $v_i > 0$, and $\delta_i = 0$.

From the assignment constraint, $x_{i(jk)t} = 1$, for some $t = t_o$, and $x_{i(jk)t} = 0$, for all $t \neq t_o$. Time must now be blocked to complete processing on first shift only if product i is "early", or on first and second shift if it is "late".

(i) Early: Let $R_{i(jk)t}$ = 0, 1 variable, representing "regular time" (first shift testing only) operation.

$$\sum_{(jk)} \sum_{t=a_1}^{T} R_{i(jk)t} \leq (1 - \delta_i) FSP_i + \qquad (9)$$

, for each i, and

$$\sum_{(jk)} \sum_{\tau=t}^{t+2(FSP_i-1)} R_{i(jk)\tau} \geq FSP_i \, X_{i(jk)t} - \delta_i K \qquad (10)$$

, for each i, t.

(ii) Late: Here there are two modes of operation to consider. The first is to split the job evenly between first shift and second shift. This results in an Integer Linear Programming model. The other is to do as much as possible, without exceeding the product due time, on first shift and assign the remainder to second shift. This results in a non-linear model. The ILP model will be presented.

Let $y_{i(jk)t}$ = 0, 1 variable representing first shift operation,

$P_{i(jk)1} = \lceil FSP_{(i(jk)}/2 \rceil$ and $P_{i(jm)2} = FSP_{i(jk)} - P_{i(jk)1}$, where $P_{i(jk)1}$ and $P_{i(jm)2}$ differ by at most one.

$$\sum_{t=a_i}^{T} Y_{i(jk)t} \leq \delta_i K \qquad (11)$$

, for all i and (jk) pairs.

$$\sum_{\tau=t}^{t+2(P_{i(jk)1}-1)} Y_{i(jk)\tau} \geq P_{i(jk)1} X_{i(jk)t} - (1-\delta_i)K \qquad (12)$$

, for all t and (jk) pairs.

$$\sum_{t=a_i}^{T} Y_{i(jk)t} \leq P_{i(jk)1}$$

, for all t and (jk) pairs. This pair of constraints forces a "window" of width exactly P_{ijk1} of $Y_{ijkt} = 1$, which starts at t_o and continues to period $t_o + P_{ijk1} - 1$. To accommodate the second shift operation, let $Z_{ijmt} = 0, 1$ a variable representing second shift operation. Proceeding in a like manner to first shift above,

$$\sum_{t=a_i}^{T} Z_{i(jm)t} \leq \delta_i K \qquad (13)$$

, for all i and (jm) pairs.

$$\sum_{\tau=t}^{t+2P_{i(jm)2}-1} Z_{i(jm)\tau} \geq P_{i(jm)2} X_{i(jk)t} - (1-\delta_i)K \qquad (14)$$

, for all t, (jm) pairs, and (jk) pairs.

$$\sum_{t=a_i}^{T} Z_{i(jm)t} \leq P_{i(jm)2}$$

, for all i and (jm) pairs. It should be noted that if $\delta_i=0$, constraint (11) and (13) force all $Y_{i(jk)t}$ and $Z_{i(jm)t}$ equal to zero. Then, the remaining sets of constraints, (12) and (14), are automatically satisfied.

However, if $\delta_i=1$ (late job), constraints (11) and (13) are automatically satisfied, but the remaining pairs are constrained only at t_o, for which

$$\sum_{\tau=t_o}^{t_o+2(P_{i(jk)1}-1)} Y_{i(jk)\tau} \geq P_{i(jk)1} \quad \text{and} \quad \sum_{\tau=t_o}^{t_o+2(P_{i(jk)1}-1)} Y_{i(jk)\tau} \leq P_{i(jk)1}$$

forcing
$$\sum_{\tau=t_o}^{t_o+2(P_{i(jk)1}-1)} Y_{i(jk)\tau} = P_{i(jk)1}$$

implying that $Y_{i(jk)\tau} = 1$ for every first shift period between $t_o \leq \tau \leq (t_o+2(P_{i(jk)1}-1))$.

Similarly,

$$\sum_{\tau=t_o}^{t_o+2P_{i(jm)2}-1} Z_{i(jm)\tau} \geq P_{i(jm)2} \quad \text{and} \quad \sum_{\tau=t_o}^{t_o+2P_{i(jm)2}-1} Z_{i(jm)\tau} \leq P_{i(jm)2}$$

forcing
$$\sum_{\tau=t_o}^{t_o+2P_{i(jm)2}-1} Z_{i(jm)\tau} = P_{i(jm)2}$$

implying that $Z_{i(jm)\tau} = 1$ for every second shift period in $t_o \leq \tau < (t_o+2P_{i(jm)2}-1)$.

Objectives

Determining when a product should be tested depends on the desired objective. As determined in the problem definition phase the immediate area of concern is lateness. Therefore, formulations for the following objectives are presented:

1. Minimize number of late jobs.
2. Minimize total lateness.
3. Minimize total cost of lateness.

Criterion 1 (Minimize number of late jobs):

A product is late if it is completed after its due date. Therefore, if at $t=DT_i + 1$, the period after the due date, $R_{i(jk)t} + Y_{i(jk)t} + Z_{i(jk)t} = 1$, the product is late because it is still occupying the resource. Let $\ _i$ = 0,1 variable, then,

$$\sum_{(jm)} \sum_{(jk)} \sum_{t=DT_i+1}^{T} (R_{i(jk)t} + Y_{i(jk)t} + Z_{i(jm)t}) \leq \alpha_i K$$

for all i, where K is a large number > 0.

If the left side of this inequality is greater than zero some processing must be taking place after the due time and α_i must = 1; otherwise $\alpha_i = 0$. Therefore, to minimize the number of late jobs

$$\text{Minimize} \sum_i \alpha_i$$

is the desired function.

Criterion 2 (Minimize total lateness):

Again, a product is late if it is completed after its due period, DT_i. Therefore a product is late if $(R_{i(jk)t} + Y_{i(jk)t} + Z_{i(jm)t}) > 0$ in the periods after the due period, indicating that testing is not complete. If total lateness is to be minimized, then

$$\text{Minimize} \sum_{i} \sum_{(jk)} \sum_{(jm)} \sum_{t=DT_i+1}^{T} (R_{i(jk)t} + Y_{i(jk)t} + Z_{i(jm)t})$$

is the desired function, where lateness is defined as the number processing periods required after the due period.

<u>Criterion 3 (Minimize total cost of lateness)</u>:

If a penalty or cost of W_{it} is assessed when product i is not completed by period t, the total cost of lateness is minimized by the function

$$\text{Minimize} \sum_{i} \sum_{(jk)} \sum_{(jm)} \sum_{t=DT_i+1}^{T} W_{it}(R_{i(jk)t} + Y_{i(jk)t} + Z_{i(jm)t})$$

This expression reduces to total lateness, Criterion 2, if all $W_{it} = 1$.

To ensure that constraints (7) and (8) function as intended, the variables u_i and V_i must also be a part of the chosen objective function. This is accomplished by adding the following term to the chosen Criterion:

$$+ \sum_{i} M(u_i + v_i)$$

where M is a positive number sufficiently large to ensure that the contribution of the additional term is less than that of any $(R_{i(jk)t} + Y_{i(jk)t} + Z_{i(jm)t})$.

Computational Complexity

The computational complexity of this formulation is easily demonstrated by a realistic example. Using the data in Table 4.1 the necessary number of constraints for each constraint as presented in the formulation is tabulated in Table 4.2.

Table 4.1 Example Planning Data

	InPut 1		Input 2
Horizon	40	shifts	20
Number of products to be tested	55		22
Number of test stations	14		14
Number of first shift testors	13		13
Number of second shift testors	7		7
"Pairwise" stations	3		3
Number of parallel systems to be tested	4		2
Number of components in each parallel system	2		2

Table 4.2 Number of Scheduling Constraints

	Number Required	
Constraint Number	Data 1	Data 2
(1)	55	22
(2)	182	182
(3)	98	98
(4)	3	3
(5)	3	3
(6)	8	4
(7)	55	22
(8)	110	44
(9)	55	22
(10)	2,200	440
(11)	10,010	4,004
(12)	14,560	7,280
(13)	5,390	2,156
(14)	718,830	358,876
TOTAL	751,559	443,156

It is readily apparent by the total number of constraints required that, even though the scheduling model as presented in the formulation is an integer linear programming model, it is unsolvable and, therefore, another approach must be used. However, the first objective of this study: Develop a model to describe the System Test assignment functions with regard to resource constraints has been met.

Scheduling Alternative

Returning to the scheduling model and Table 4.2 it is obvious that the number of required constraints balloon after constraint (10). The remaining constraints all deal with second shift operation. If these constraints were eliminated and the assumption made that all processing occurs on first shift the scheduling constraints would reduce to the following:

Product Assignment

(1) $$\sum_{t=a_i}^{T-FSP_i} \sum_{(jk)} X_{i(jk)t} = 1$$

, for each product i.

(2) $$\sum_{i} R_{i(jk)} \leq 1_T$$

, for each pair (jk).

Limited Resources

(4) $$\sum_{i} \sum_{k} (R_{i(j_1k)} + R_{i(j_2k)}) \leq 1_T$$

, for each pair j_1 and j_2 "pairwise" constrained and where i ranges over the products requiring the specific resource.

(5) $\sum_{i} \sum_{k} r_{ic}(R_{i(j_1k)} + R_{i(j_2k)}) \leq RS_{c(j_1j_2)T}$

, for each pair J_1 and j_2 "pairwise" constrained and where i ranges over the products requiring the specific resource.

Precedence Relation

(6) $\sum_{t=a_{i_n}}^{T-FSP_{i_n}} tX_{i_n(jk)t} + \sum_{t=a_{i_n}}^{T} R_{i_n(jk)t} - 1 \leq \sum_{t=a_i}^{T-FSP_i} tX_{i(jk)t}$

, for each component of each parallel system.

(9) $\sum_{(jk)} \sum_{t=a_i}^{T} R_{i(jk)t} = FSP_i$

, for all i

(10) $\sum_{(jk)} \sum_{\tau=t}^{t+2(FSP_i-1)} R_{i(jk)\tau} \geq FSP_i \; X_{i(jk)t}$

, for each i, t

Again using the data of Table 4.1 the computational complexity of the reduced formulation is represented in Table 4.3 by the number of required constraints.

Table 4.3 Number of Reduced Scheduling Constraints

Constraint Number		Number Required	
		Data 1	Data 2
(1)		55	22
(2)		182	182
(4)		3	3
(5)		3	3
(6)		8	4
(9)		55	22
	TOTAL	306	236

The totals are now well within the bounds of a mixed integer programming package.

Continuing the reduction to the objectives of the scheduling model, the reduced formulation yields:

Criterion 1 (Minimize number of late jobs):

$$\sum_{(jk)} \sum_{t=DT_i+1}^{T} R_{i(jk)t} \leq \alpha_i K$$

, for all i, where α_i = 0, 1 variable and K is a large positive number. The desired criterion function remains

$$\text{Minimize} \sum_i \alpha_i$$

Criterion 2 (Minimize total lateness):

$$\text{Minimize} \sum_i \sum_{(jk)} \sum_{t=DT_i+1}^{T} R_{i(jk)t}$$

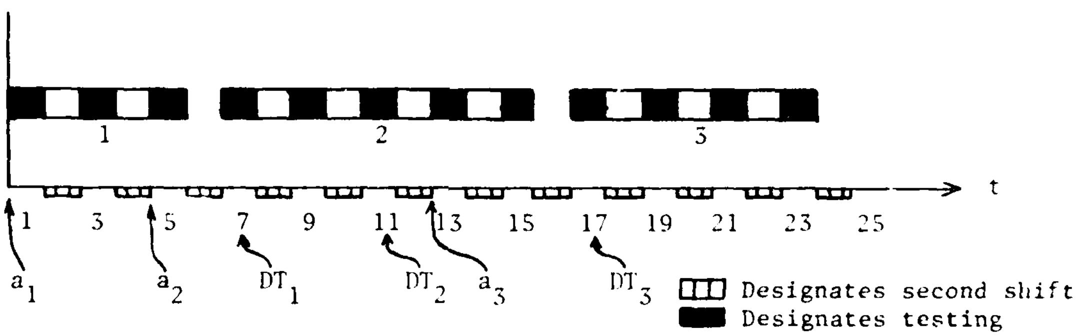
<u>Criterion 3 (Minimize Total cost of lateness):</u>

$$\text{Minimize} \sum_{i} \sum_{(jk)} \sum_{t=DT_i+1}^{T} W_{it} \, R_{i(jk)t}$$

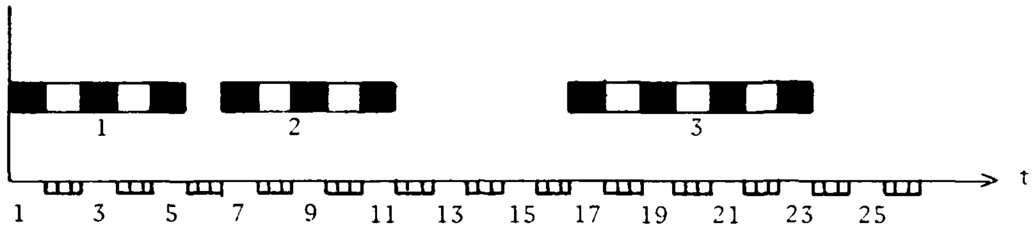
An iterative approach to the complete scheduling problem is now proposed and illustrated by a simple example with only one test station. The following table of data will describe the products of the example.

i	1	2	3
a_i	1	5	13
DT_i	7	11	17
FSP_i	3	5	4

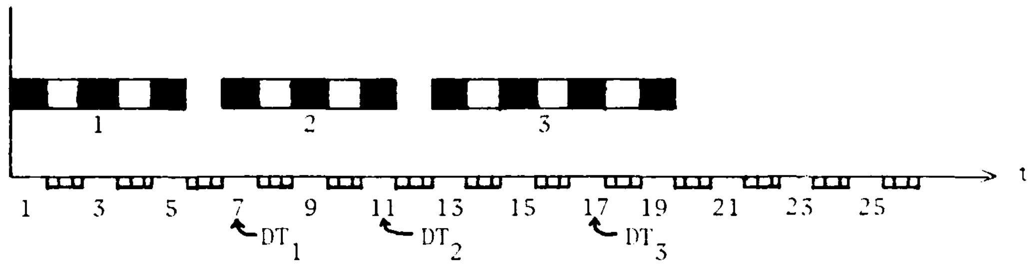
Step 1: Solve the scheduling problem with the reduced formulation.



Step 2: Identify those products which are late and whose lateness is less than the completed processing time prior to the period $DT_i + 1$. Then reduce the processing time on these products by their lateness. In the example, the total processing time, FSP_i, of product 2 is 5 periods but it was completed 2 periods late. Therefore, the new processing requirement, FSP_i', for product 2 would be 3 periods.



Step 3: Solve the scheduling problem again with the reduced formulation and the new processing requirements, FSP_i', for the specified products of step 2. This second solution will then serve to compact the first solution after the reduction of processing times.

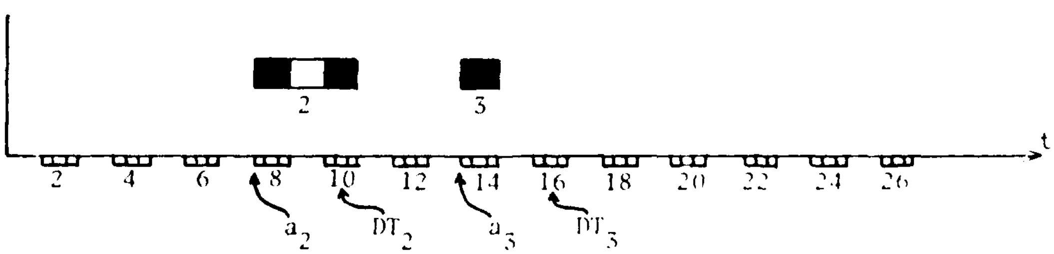


Step 4: Repeat Step 2 for any products in the category which have not previously been reduced or whose previous reduction plus current lateness is less than current processing time prior to the period $DT_i + 1$. In the example, product 3's total processing time, FSP_i, is 4 periods but it was completed 1 period late. Therefore, the new processing requirement, FSP_i', for product 3 would be 3 periods. As another example, if a product, whose total processing requirement is 8 periods, had been reduced 2 periods in Step 2 and is now after Step 4 one period late, the product's processing time would again be reduced by one period.

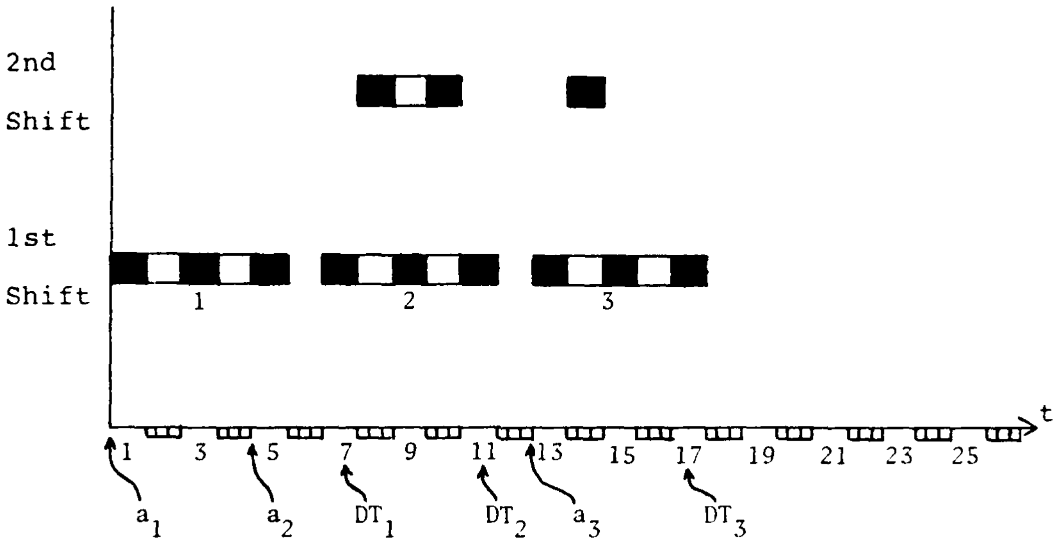
Step 5: This step, in essence, schedules the second shift. Using the reduced formulation, solve a reduced problem considering only the products whose processing requirements have been curtailed in Step 2 or Step 4. Since we are now concerned with second shift, the test station for each of these products is predetermined by the first shift solution of Step 3. Therefore, all other combinations (ij) will be undefined. The arrival times of the products are set by the (first shift processing start time) + 1, also determined in the solution of Step 3, to force arrival at the next second shift period. The due periods, are also set by the solution of Step 3, in that the minimum of the (processing stop time) - 1 and the (due period) - 1 is chosen. This tries to force second shift testing to occur between the periods that the product is undergoing first shift processing. The processing time is the amount of the reductions. The following table displays the reduced problem for the example:

i	2	3
a_i	8	14
DT_i	10	16
P_i	2	1

The testors to be assigned are now the second shift testors, i.e., k is replaced by m in the formulation.



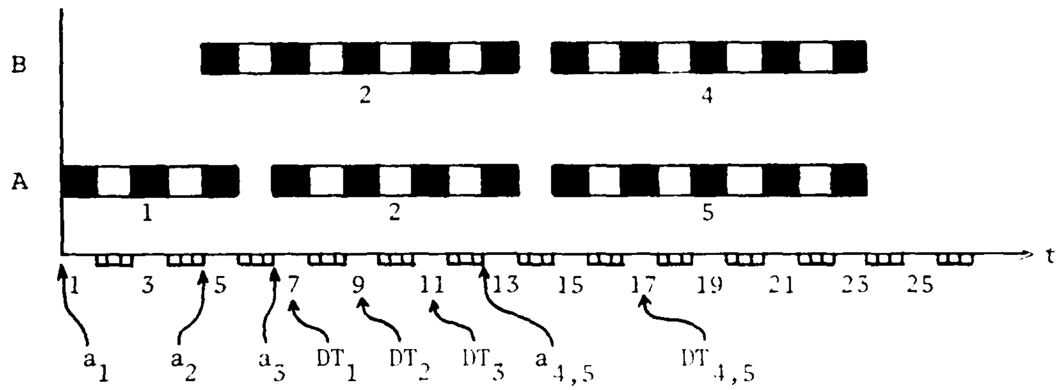
When this solution is combined with the solution of Step 3 and the reductions of Step 4, a complete schedule is obtained.



Due to the scarcity of second shift testors, a qualified second shift testor may not be available to test a product between the periods that the product is undergoing first shift testing. With the preceding iterative approach, this would result in the second shift testing of the product extending past or occurring after the (first shift processing stop time) + 1. This would be a violation of the established second shift due date and Systems Test operating procedure. The following example, with two test stations, will illustrate this situation and the rectifying procedure.

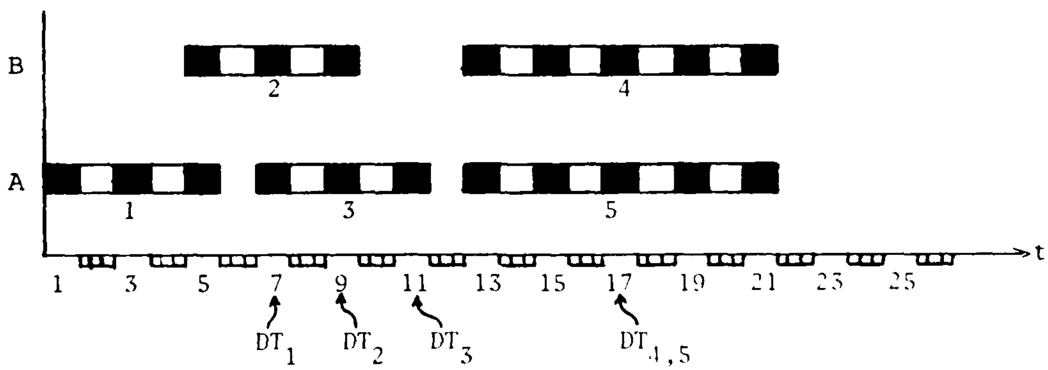
i	1	2	3	4	5
a_i	1	5	7	13	13
DT_i	7	9	11	17	17
FSP_i	3	5	4	5	5

Step 1:

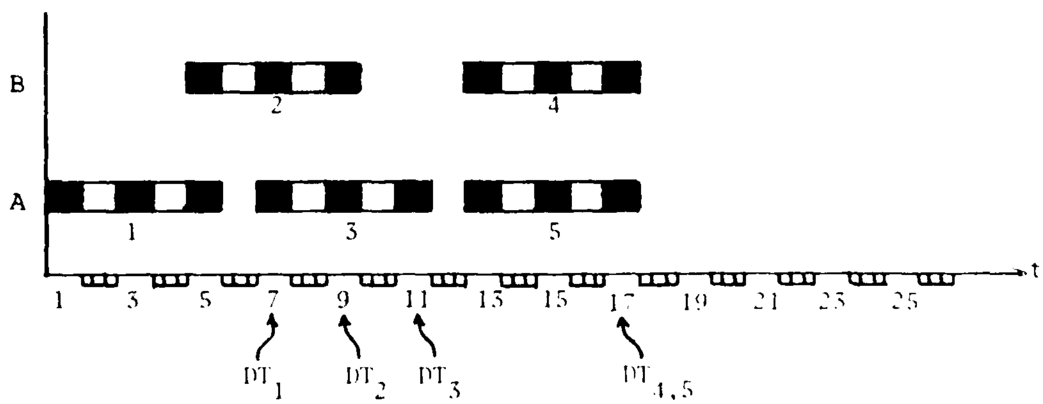


Step 2: Products 2 and 3 may be reduced.

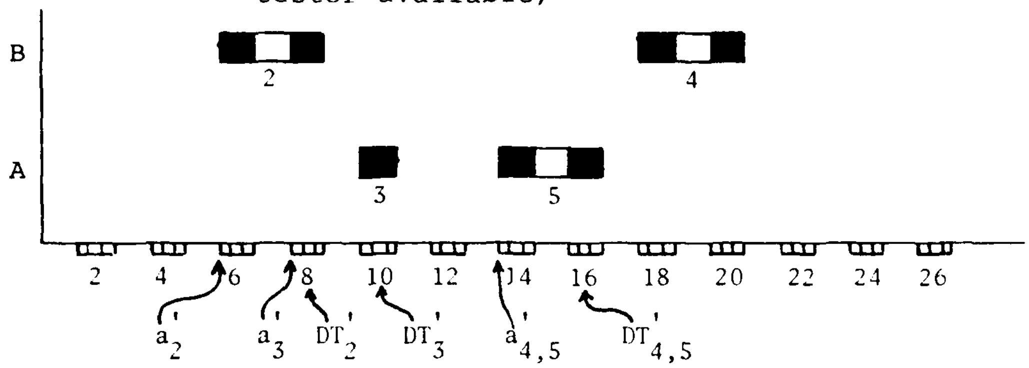
Step 3:



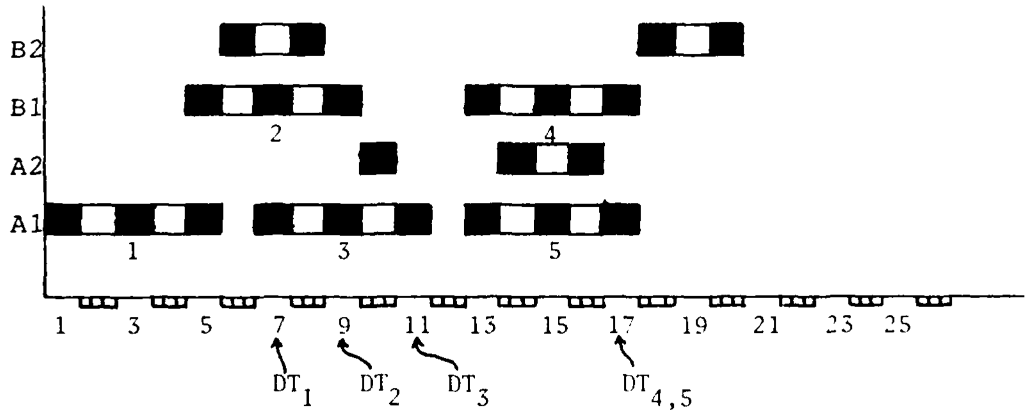
Step 4: Products 4 and 5 may be reduced.



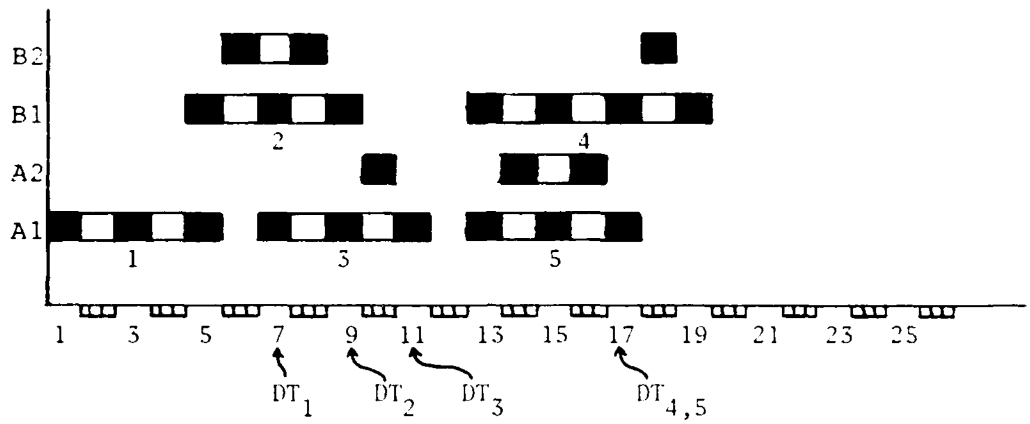
Step 5: (Assuming only one qualified second shift testor available)



Combining the solution of Step 5 with the solution of Step 4, it is apparent that the second shift testing of product 4 extends past its first shift processing stop time in excess of one period.



It is now necessary to return to the solution of Step 4 to determine if this "lateness" can be processed on first shift in a "processing gap" produced by the previous reduction of processing time in this step. If so, a feasible solution is obtained.



In this example, it was possible to find such a gap. However, if a product had been reduced both in Step 4 and Step 2 the "lateness" may not fit in the "processing gap". In this situation, it would be necessary to return to the solution of Step 2 followed by Step 5 without the condensing step, Step 3, and the second reduction step, Step 4. This would ensure that any subsequent "lateness" would fit in the "processing gap."

The preceding iterative approach to the complete scheduling problem terminates with a feasible solution in a maximum of seven steps. However, the solution is not optimal due to the possible requirement of a return to Step 2 and the subsequent loss of the condensing step. If, however, the number and qualifications of the second shift testors mirrored the first shift testors, an optimal solution could be obtained through this procedure by returning to Step 3 after Step 4 until no reduction could take place in Step 4. Since reductions are not allowed to exceed the completed processing time prior to the period DT_i

+ 1, it is ensured that the second shift processing requirement will not exceed the time on first shift. Additionally, since testors are mirrored on first and second shifts, it is also ensured that a qualified second shift testor will be available during the second shift periods following any first shift testing.

Capacity Model

If instead of scheduling, the focus is placed on capacity, the model may be greatly simplified by assumptions with the objective of obtaining a gross capacity estimate. The assumptions made in this formulation are (1) that testors are readily available and (2) that products are immediately available.

In contrast to the scheduling model, neither testors nor time are a parameter of the formulation. Therefore, testor qualifications and specific product arrival times are not taken into consideration. By not considering testor qualifications, all testors are considered capable of testing all products and only the number of available testors has an impact on the solution. By not considering arrival times, the dynamic structure of the complete scheduling model is converted to a static structure by ignoring the nonsimultaneous arrivals of products to Systems Test. Additionally, unlike the complete scheduling model, a criterion does not exist for second shift testing and, consequently, any product may be tested on second shift.

In order to avoid a third assumption that all test stations are the same, which would be questionable, the assignment of a product to a test station will be treated as a "pair" (ij), as in the scheduling model with (jk) and (jm). In this way a distinction may be made between stations. This is accomplished in the following manner; if product i is not compatible with station j then the "pair" (ij) is undefined and the variables $x_{(ij)}$ and $y_{(ij)}$ are subsequently reduced. This will ensure that a product is assigned only to a compatible test station.

Definitions

W1 = number of first shift testors.

W2 = number of second shift testors.

i = product number, i = 1, 2, ..., I; I = number of systems to be tested in planning horizon.

j = test station number, j = 1, 2, ..., J; J = number of test stations.

P_i = processing time of product i.

$X_{(ij)}$ = duration of job i in test station j on first shift.

$Y_{(ij)}$ = duration of job i in test station j on second shift.

H_1 = number of periods available for testing on first shift = planning horizon x min [J, W1].

H_2 = number of periods available for testing on second shift = planning horizon x min [J, W2].

DT_i = due period for product i.

$\delta_{(ij)}$ = a variable which equals 1 if product i is tested in station j and equals 0 otherwise.

Constraints

Product Assignment

Testing for each product must be started sometime within the planning horizon in a compatible test station. An assignment constraint is required to ensure that each product is tested in only one test station.

$$\sum_j \delta_{ij} = 1$$

for all i, where δ_i is a 0, 1 variable

$$X_{(ij)} \leq \delta_{ij} K$$

for all (ij) pairs, where K is a large positive number.

$$Y_{(ij)} \leq \delta_{ij} K \qquad (1)$$

, for all (ij) pairs, where K is a large positive number. This set of constraints ensures that $x_{(ij)}$ and $y_{(ij)}$, are equal to zero if product i is not assigned to test station j and greater than zero if product i is assigned to test station j. It should be noted that the "pair" (ij) will not be defined if the product is not compatible with the test station.

Processing Time

In this formulation any product may be tested on second shift. The constraint, however, is that the duration of processing time on first and second shift must equal the processing time of the product. Since testors are not a parameter of the formulation, consideration of testor efficiency in calculating processing time, as in the complete scheduling model, is not possible. Therefore, variable processing times are not permitted and the processing requirement for each product is assumed known.

$$X_{(ij)} + Y_{(ij)} = P_i, \text{ for each "pair" } (ij) \quad (2)$$

Processing time on second shift must also be less than the processing time on first shift for each product. This is due to the fact that second shift testors are more scarce than first shift testors and it is desirable to limit their use. Additionally, it is a result of the constraint that a product may not be tested on second shift without first being tested on the immediately preceding first shift.

$$Y_{(ij)} \leq X_{(ij)}, \text{ for each "pair" } (ij) \quad (3)$$

<u>Capacity</u>

A constraint must also be written to force testing to occur within the planning horizon. This is achieved as follows,

$$\sum_i X_{ij} \leq H_{1j}$$

, for every j, where $H_{1j} = H_{1/J}$, and (4)

$$\sum_i Y_{ij} \leq H_{2j}$$

, for every j, where $H_{2j} = H_{2/J}$.

This constraint pair is then a capacity constraint in that the sum of the testing durations are not allowed to exceed a given value, the capacity horizon.

Objective

The objective continues to be the minimization of the number of late jobs. Since time is not a parameter of the formulation, however, a function of time must be introduced in the objective. The following minimum slack function will be used: $[(DT_i-a_i)-P_i]$, where DT_i is the "work day" that the product is due, a_i is the "work day" that the product arrives at Systems Test, and P_i is the product's processing requirement in shifts. Work days are numbered sequentially through the planning horizon. For example, if the planning horizon covered four weeks and the plan was to work five days a week, there would be 20 work days, numbered one to twenty. In this way the minimum slack function indicates if a product will be late when tested only on first shift. This indication is given by a negative value for the function. For a number of examples refer to Table 4.4.

Table 4.4 Minimum Slack Function Example

i	a_i	DT_i	P_i	Min.Slack	Comments
1	5	9	3	1	
2	5	4	3	-4	Product arrived after due date
3	5	9	5	-1	Processing time exceeds slack

By combining the minimum slack function with the second shift testing duration, the desired time link is achieved.

If this function is then minimized,

$$\text{Minimize} \sum_i \sum_j [(DT_i - a_i) - P_i]Y_{(ij)}$$

it forces the jobs with the minimum slack to be tested on second shift. It should be recalled that constraint (3) requires the second shift processing duration to be less than or equal to the first shift duration for each product. Therefore, it would be expected that products with the least slack would receive equal processing on first and second shift, thereby minimizing the chance of the product being late.

Computational Complexity

Using the same technique to demonstrate complexity as with the Scheduling Model and with the input data of Table 4.1 the number of required constraints are presented in Table 4.5.

Table 4.5 Number of Capacity Constraints

Constraint Number	Number Required Data 1	Number Required Data 2
(1)	1,595	638
(2)	770	308
(3)	770	308
(4)	28	28
TOTAL	3,163	1,282

Again, it is obvious by the number of required constraints that the formulation is not within the bounds of a mixed integer programming package.

The assumptions made in the capacity model were very broad and, therefore, the solution, as stated previously, is at best a gross estimate of capacity. However, the solution does give an indication of feasibility of the desired load, i.e., whether it violates the capacity constraint or not. A preliminary check for this violation would be to sum the processing times of the input load and compare the value with the sum of the capacity horizons. If $\sum_i P_i > (H_1 + H_2)$ then you may immediately assume that the desired load is infeasible. However, if $\sum_i P_i \leq (H_1 + H_2)$, there is a possibility that the desired load is feasible.

If it is determined that the desired load is infeasible, either by the preliminary check or the solution of the capacity problem, a decision must be made as to which product to eliminate from the desired load. This heuristic could be based on a number of factors, such as, sold versus stock orders, earliest due date, shortest processing time, or minimum slack. This problem, therefore, demands a separate treatment and will not be investigated here. However, combining an infeasible solution with an appropriate heuristic to determine which products to eliminate from the desired load would ultimately yield a feasible solution.

A feasible solution would give an assignment of products to test stations. However, since the "pairwise" test station constraints and testor qualifications, as delineated in the scheduling model, were not a part of the capacity formulation, the assignment would probably be infeasible. Additionally, a sequencing link does not exist between first and second shift. Therefore, a product may be tested on second shift even though the product was not tested on the immediately preceding first shift.

As stated previously, since time is not a parameter of the formulation, arrival times are not taken into consideration. By reducing the problem to subhorizons, not only could more consideration be given to arrival times but also a reduction in computational complexity would occur through the consideration of less products at one time. In each subhorizon the product input would be those products scheduled to arrive in that subhorizon plus any products eliminated from the previous subhorizon.

The combination of the solutions from the subhorizon problems would again yield an estimate of capacity for the particular product mix but with consideration of scheduled arrival times. Combining this measure of capacity with the previously discussed iterative approach to scheduling would result in a testing schedule approximating the capacity of the system for the specific product mix.

V. Simulation

During the formulation of the scheduling model it became readily apparent that the model's complexity would overshadow its usefulness. Therefore, in order to meet the second of the project objectives, a simulation approach was chosen. Two advantages of this approach were that it permitted controlled experimentation, especially in regard to resource constraints, and it permitted sensitivity analysis by allowing manipulation of input variables. The objectives of the simulation were:

1. Develop a simulation to model the Systems Test assignment functions with regard to resource constraints.
2. Compare and evaluate alternative system designs in an effort to make scheduling procedure and operation recommendations;
3. Develop a sequential simulation program, without randomization, which would allow the manager of an UPS test facility to determine whether he would be able to meet monthly test requirements.

The simulation portion of the study was accomplished in the following four phases:

Phase 1. Formulation of a sequential simulation model and program and its subsequent validation.

Phase 2. Collection of supporting data and randomization of the sequential simulation model and program.

Phase 3. Design of experiment.

Phase 4. Analysis of simulation output.

Phase I. Sequential Simulation Development

Simulation Model

In formulating the simulation model a flow-approach was used. Using the observed assignment sequence, Figure 2.3, the information from the problem definition phase, and the insight gathered from the scheduling model formulation, a sequential simulation model was developed which incorporated time and organized queues. A flow diagram of the model is presented in Figure 5.1.

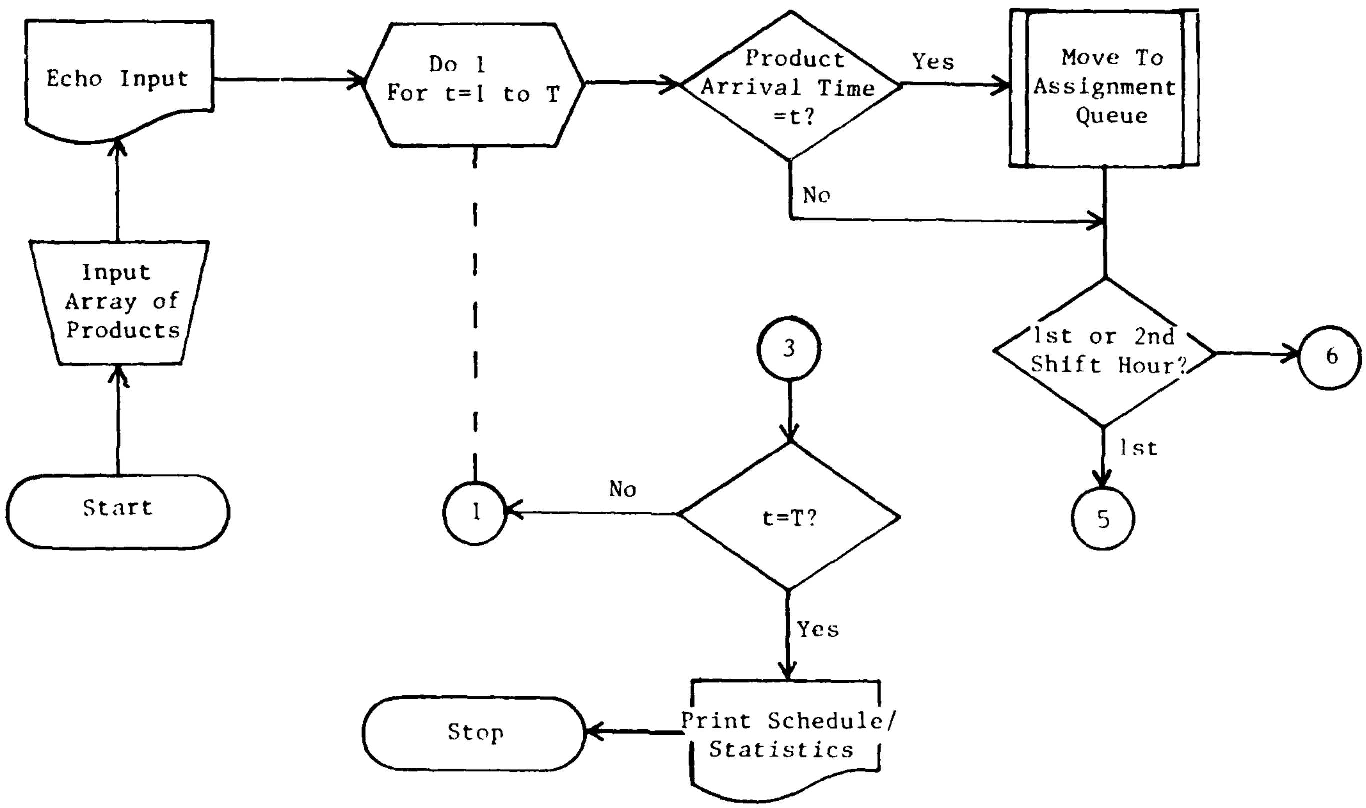


Figure 5.1 Simulation Flow Chart

Figure 5.1 (continued)

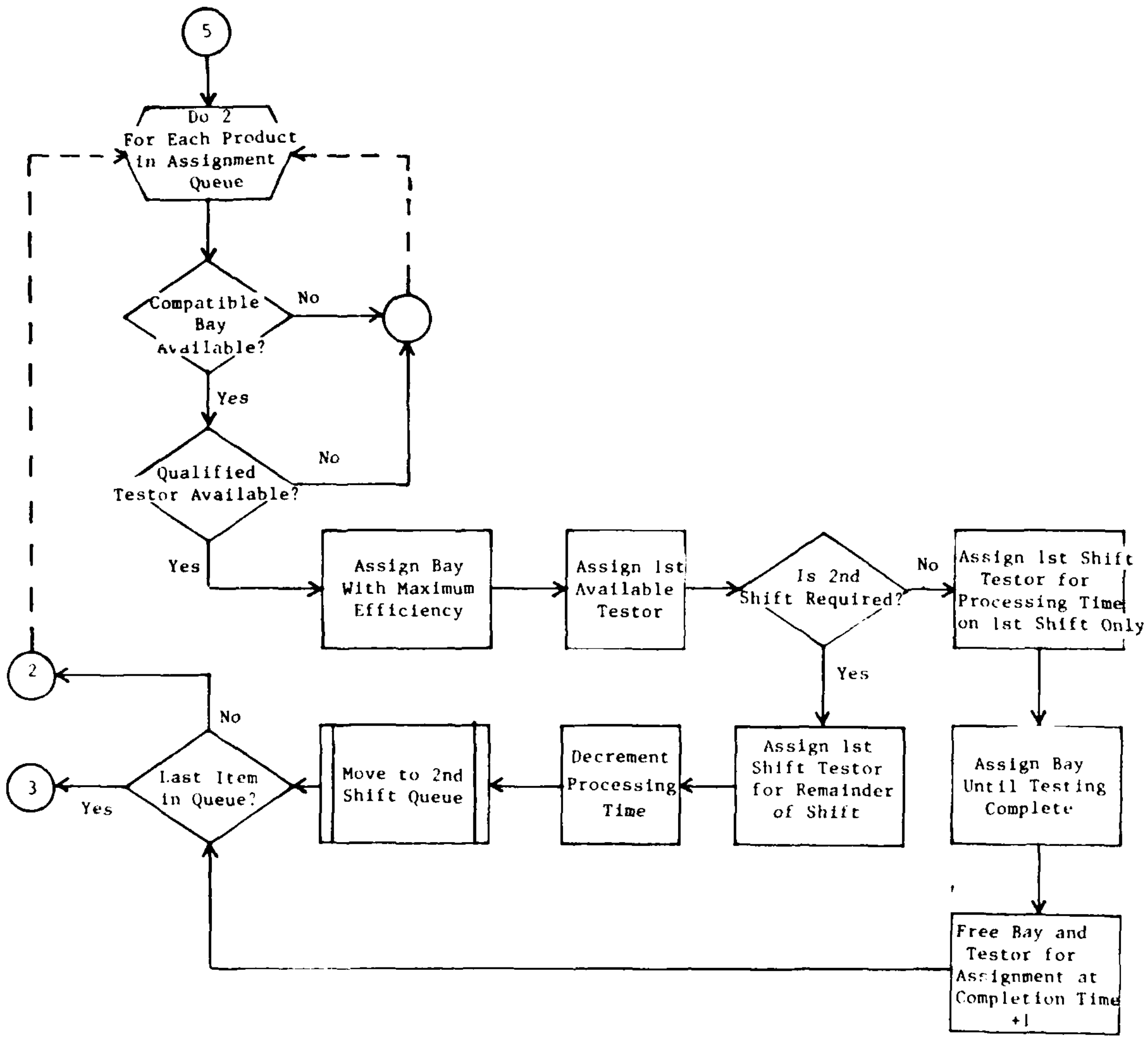
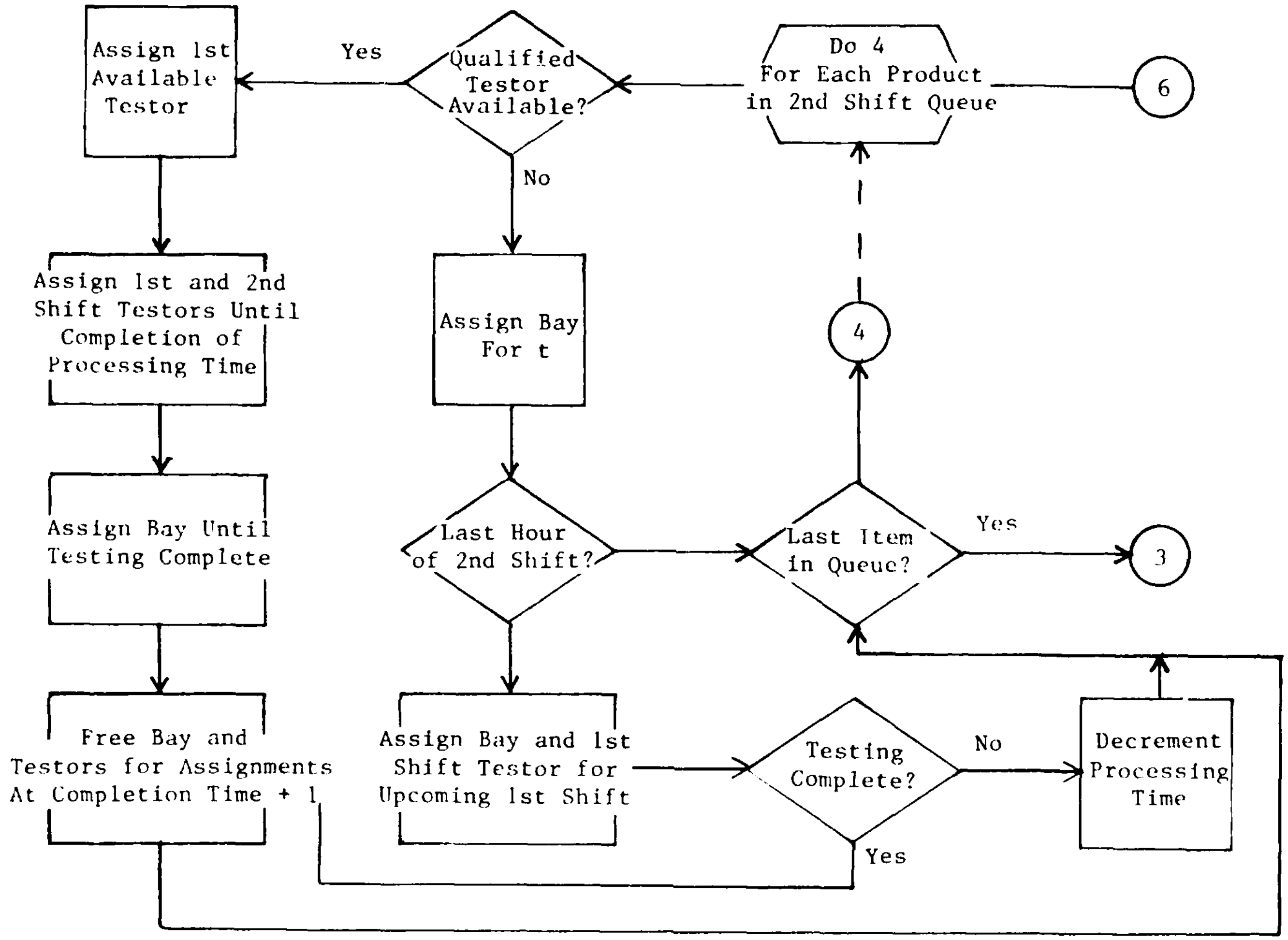


Figure 5.1 (continued)



Specification of Sequential Simulation Components

The model requires three inputs: (1) test station versus product efficiency, (2) testor qualifications versus product lines, and (3) products scheduled to be tested. The first of these required an update to the Test Facility Capability Study, Appendix B. In that study it was specified which test stations could handle which products. It remained to determine the efficiency with which a given product could be tested at a given test station. In order to arrive at this information expeditiously the supervisor and a number of senior testors were requested to rate their test station assignment preferences for each product. These preferences were then treated as efficiency ratings and are presented in Appendix J. Testor qualifications were obtained from Systems Test personnel records and are represented by a zero-one variable with one indicating qualification to test that specific product line as shown in Appendix K. The final required input is the list of products scheduled to be tested. This is handled by a simple array of records with each record containing all pertinent technical data for the specific product.

Four major decisions are required in the processing of a product: (1) is a test station available to test the product, (2) is a first shift testor available to begin testing the product, (3) is second shift required, and (4) if second shift is required, is a second shift testor available to test the product. The decision on whether second shift is required or not is arrived at by determining if the number of first shift periods from the first shift testor assignment time until the due period is greater than the required processing time. If so, then second shift is required, since processing only on first shift will make the product late.

Three major assignments are also made in the processing of a product: (1) assignment of a test station, (2) assignment of a first shift testor, and (3) assignment of a second shift testor, if required. All of these assignments commit the specific resource for the duration of the requirement in order to ensure continuity of testing.

Formulation of Program

A main objective in formulating the program was to maintain flexibility for user defined variables. Examples of used defined variables are number of hours in a shift, number of days in a work week, and planning horizon. By allowing these elements to remain flexible it was felt that the utility of the simulation would expand.

In following the flexibility theme it was also a decided advantage to employ dynamic data structures for queue management. It then became relatively easy to order and modify the lists, again increasing utility.

The program was coded in Pascal to facilitate the eventual use of the simulation by a manager as a desk-side reference through the use of a personal computer. By length alone, the program is complex and with the use of dynamic data structures the complexity increases substantially. This may be viewed as a disadvantage, as an uninformed user may have some hesitation to use the product.

Additionally, it should be noted that the "pair-wise" bay constraints as noted in the scheduling model formulation and Appendix B were coded as a procedure which was called prior to any test station assignment.

Two queues were established as indicated in Figure 5.1. A product entered the assignment queue if it was scheduled to arrive at Systems Test at time t, the present time period. All products were assumed to arrive at 1200 hours on the arrival date. This queue was processed during first shift time periods, with a product leaving only after assignment of a test station and a first shift testor. The assignments were made with regard to availability, maximum efficiency and qualification. If required, the product would also enter the second shift testor queue. As with the assignment queue, second shift testors are assigned with regard to availability and qualification. This queue was processed only during second shift time periods. Time in the simulator is clock oriented with a fixed increment of advance. This increment was chosen as one hour. The number of time periods in a day is set by the user and represents the number of hours worked by first and second shift together. Work days are treated as sequential with the clock running continuously. A listing of the program is at Appendix L.

Evaluation of the Model

The evaluation of the model was broken into two phases, the conceptual phase and the implementation phase. In the conceptual phase the logical flow of the model as presented in Figure 5.1 was reviewed by the manager of Systems Test. Once his confirmation that the model accurately reflected the assignment process was received, program formulation began.

In the implementation phase, the validity of the model was tested with the use of actual schedules. The comparison involved the number of tested hours and consistency of assignment. It was determined that the simulation model was a realistic representation of the system as number of tested hours were equal and there were no breaks in assignments until testing of a product was complete.

Phase II. Input Data Analysis

The following four steps are essential in the development of a valid model for input data and constituted the basis for the input data analysis:

Step 1. Collection of raw data.

Step 2. Identification of the underlying statistical distribution.

Step 3. Estimation of parameters that characterize the distribution.

Step 4. Test of the distributional assumption and the associated parameter estimates for goodness of fit.

It was determined through analysis of the system that data on the following areas needed to be collected and analyzed: product mix, arrival times, interarrival times, processing times, and resource availability (testors and test stations).

Product Mix

Data on the first of these areas, product mix, was obtained from the planning department in the form of a 12 month rolling sales plan, Appendix M. This plan identifies by month the number of products by series that are forecasted for the year. The specific voltage configuration of the products was not addressed. By totaling the number of each product type through the 12 month projection and dividing by the total number of projected products for the period, a probability was associated with each product type. It should be noted that projections are based on sales and that no dependence exists between products. Taking advantage of these probabilities a valid product mix model is arrived at through the use of a uniform distribution and the cumulative distribution function for the 12 month projection, reference Table 5.1.

As stated previously, the voltage configuration data was not a part of the 12 month projection. This information could be collected from historical data and fitted to a suitable distribution. It is assumed, however, that the voltage configuration follows a uniform distribution and, therefore, each feasible voltage configuration has an equal probability of occurring.

Table 5.1 12 Month Projection

Product Type	Projected For 12 Month Period	Probability	Cumulative Probability
2015	60	.08	0.080
2030	134	.179	0.259
2045	93	.124	0.380
2715	27	.036	0.419
2730	4	.005	0.424
Sub-Total 2000	318	.424	
3060	77	.103	0.526
3100	70	.093	0.620
3180	33	.044	0.664
3250	24	.032	0.696
3330	30	.04	0.736
3450	76	.101	0.837
3600	12	.016	0.853
Sub-Total 3000	322	.429	
4080	41	.055	0.908
5060	22	.029	0.937
5100	12	.026	0.953
5160	9	.012	0.965
5200	12	.016	0.981
5300	13	.017	0.998
5400	1	.001	1.000
Sub-Total 5000	69	.092	
TOTAL	750		

It should be noted that the Hertz description of the product is a function of series and voltage and, in essence, has already been accomplished. In addition to all 5000 series products, all 2000 series products with an input voltage of 400 or 415 volts have a 50 Hertz rating. All 4000 series products have a 415 Hertz rating and all other products have a 60 Hertz rating. This completes the input model for the product mix as all technical data required to completely describe the product has been formulated. This section is summarized by the partial flow diagram presented in Figure 5.2.

Processing Times

In the development of a valid input model for processing times, data was collected on the actual processing times of 149 products. In order to limit the collection period it was decided that products should be grouped in accordance with the standard allotted test hour scheme, reference Appendix F.

2000 Series

For the 2000 series UPS, data was collected for 60 products, presented in Table 5.2. A frequency distribution or histogram was then constructed, reference Figure 5.3, in order to infer a known probability distribution function. Based on the shape of the histogram, a normal distribution was assumed.

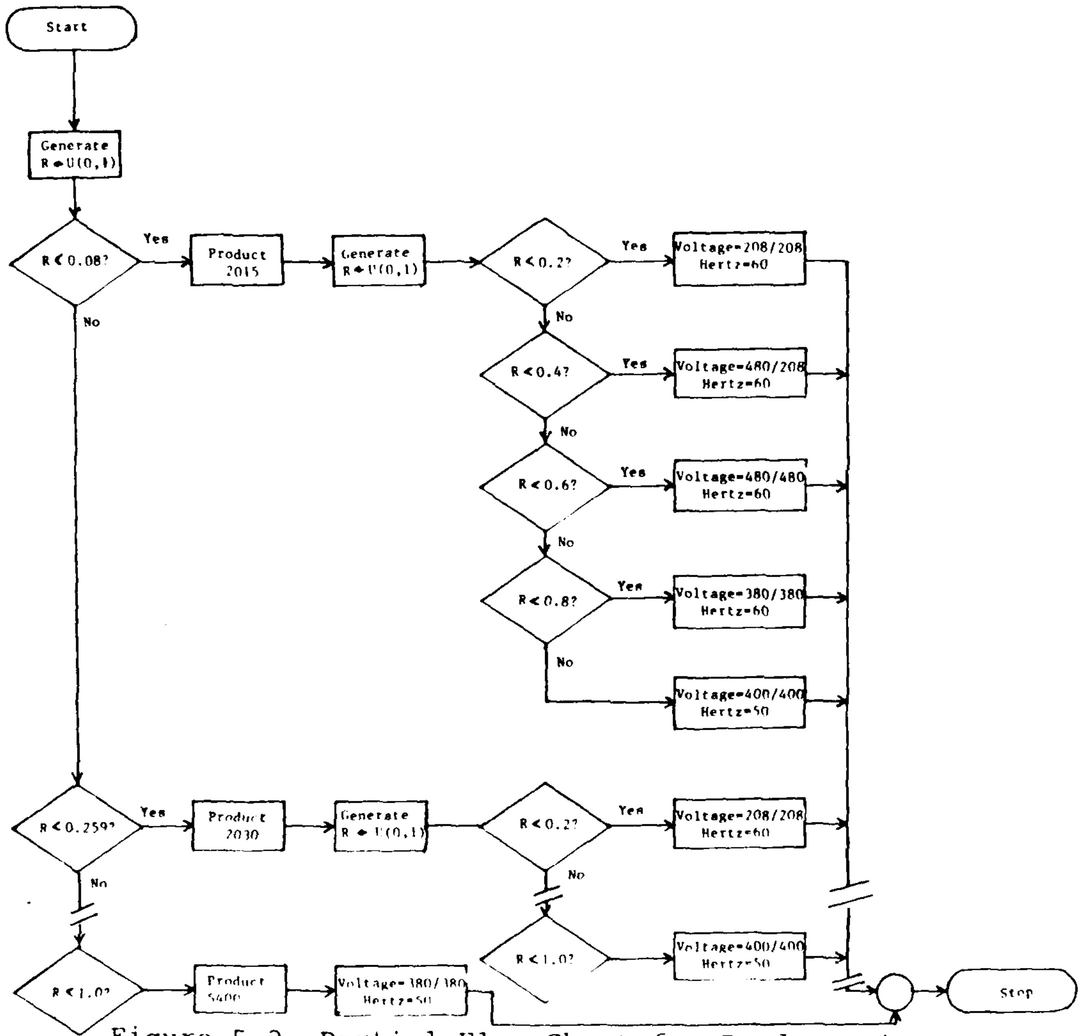


Figure 5.2 Partial Flow Chart for Product Mix

The next step was to estimate the parameters of the distribution. For the normal distribution, the parameters are the mean, u, and the variance, σ^2. The corresponding estimators are the sample mean, $\overline{X}$, and the sample variance S^2, respectively.

Table 5.2 Actual Processing Times for 2000 Series UPS

30	37	52	39.5	28	65
45.5	77	55	67.5	38	25
29.5	39	25.5	16.5	43.5	41.5
69.5	27	48	36	39	37
33	47	47.5	37.5	41.3	34
48.5	30	49	29	27	51
34.5	66.5	3	15.5	17.5	24
41.5	34.2	10.5	18.5	50	43
25	54	61.5	18	66	49.5
31.5	61.5	50	35.6	12.5	19.5

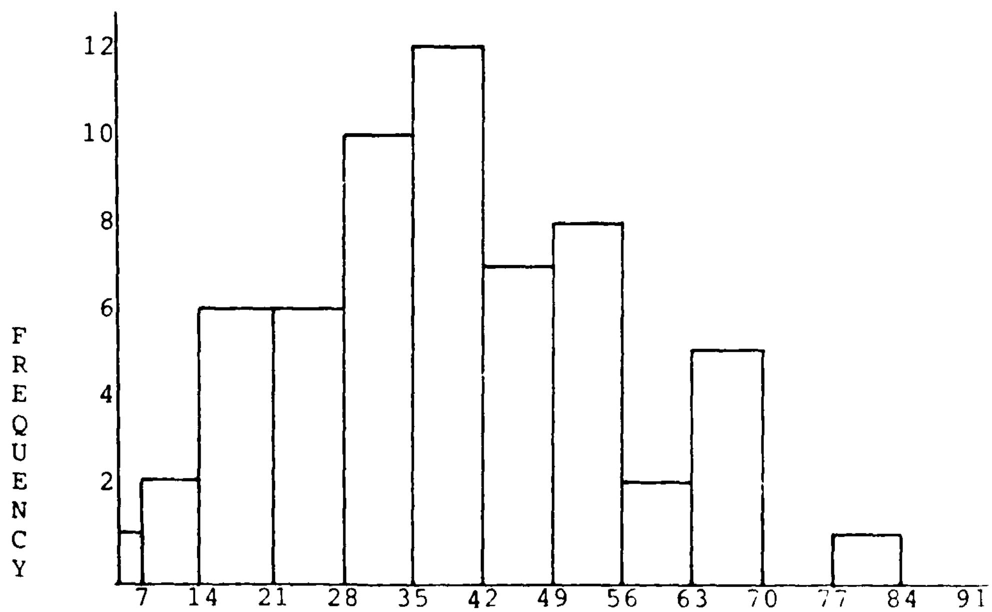


Figure 5.3 2000 Series UPS Processing Time Histogram

If the observations in a sample of size n are x_1, $x_2, \ldots, x_n$, the sample mean ($\bar{x}$) is defined by

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

and the sample variance (S^2) is defined by

$$S^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}$$

For the 60 products of Table 5.2, x=38.827 and S^2=259.92 (S=16.122).

In applying a goodness-of-fit test the Geary Test of Normality was used. This procedure is based on the ratio of the average absolute deviation to the square root of the average squared deviation. A random variable U is defined by:

$$U = \frac{\sqrt{\pi/2}\,\sum|x_i - \bar{x}|/n}{\sqrt{\sum(x_i - \bar{x})^2/n}} = \frac{1.2533\,\sum|x_i - \bar{x}|/n}{\sqrt{\sum(x_i - \bar{x})^2/n}}$$

When the underlying distribution is normal, both the numerator and denominator of U estimate σ, and the expected value of U is approximately 1. A departure from normality is indicated by a value of U which differs considerably from 1. The resulting hypotheses and corresponding test statistic are:

H_o: the underlying distribution is normal

H_a: the underlying distribution is not normal

Test Statistic: $Z = \dfrac{U - 1}{.2661/\sqrt{n}}$

Rejection Region: Either $Z \geq z_{\alpha/2}$ or $Z \leq -z_{\alpha/2}$.

In computing U, it can be noted that $\sum|x_i - \bar{x}| = 2(\sum' x_i - n'\bar{x})$, where n' denotes the number of X_i's which exceed $\bar{X}$ and $\sum'$ is the sum of those n' observations.

For the specific problem; $\bar{X}$=38.827, n=60, n'=29 and $\sum' x_i$=1509.8.

$$\sum|x_i - \bar{x}|/n = 2(\sum' x_i - n'\bar{x})/n = \frac{2(1509.8 - 29(38.827))}{60} = 12.7939$$

$$\left[\frac{\sum(x_i - \bar{x})^2}{n}\right]^{1/2} = \left[\frac{1409.435}{60}\right]^{1/2} = 15.710631$$

$$U = \frac{(1.2533)(12.7939)}{15.710631} = 1.0210587$$

$$Z = \frac{1.0210587 - 1}{.2661/\sqrt{60}} = .6130026$$

Using a confidence level of 95%, $\alpha/2$=.025, $Z_{.025}$=1.96. Since $Z < Z_{\alpha/2}$, the assumption that the underlying distribution is normal is accepted.

<u>3000 Series ≤ 100 Kw</u>

The procedure for arriving at the input model for the 3000 Series UPS with Kw ≤ 100 was the same as the procedure for the 2000 Series UPS. A sample size of 35 products was taken with actual processing durations exhibited in Table 5.3.

The resulting histogram is Figure 5.4. Based on the histogram a normal distribution was assumed.

Table 5.3 Actual Processing Times for 3000 Series UPS with $Kw \leq 100$

34	19.5	49	55	41.5	41.5
39	79	39.5	5	30	5.5
77.5	41	3	46	24	5.5
52.5	22.5	36	41.5	54.5	14.5
17.5	64	24.5	13.5	25	9
57	16	19.5	16.2		

The estimates of the parameters u and σ^2 are $\bar{X}=32.918$ and $S^2=417.0$, respectively.

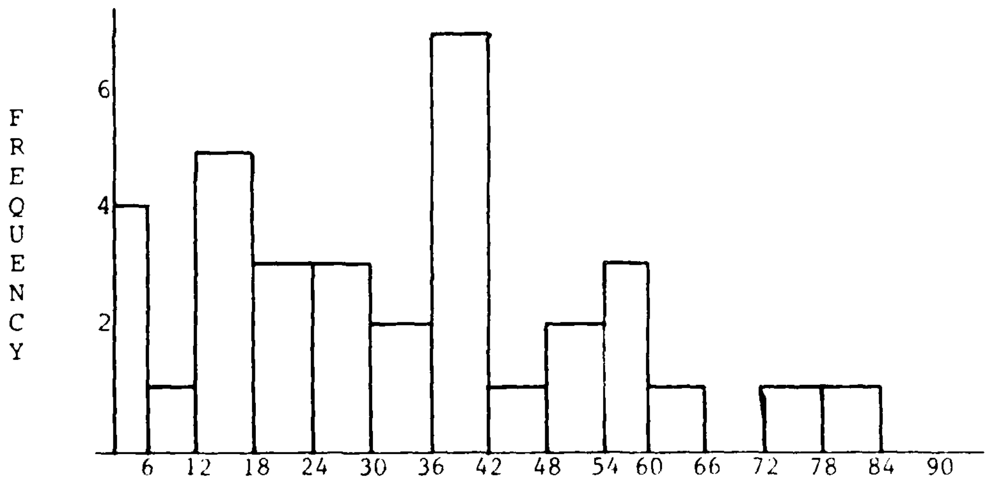


Figure 5.4. Histogram for 3000 Series $K \leq 100$

Again, using Geary's Test of Normality:

H_o: the underlying distribution is normal

H_a: the underlying distribution is not normal

For the specific problem; $\overline{X}=32.918$, $n=34$, $n'=17$, $\sum' x_i=848.5$.

$$\frac{\sum |x_i - \overline{x}|}{n} = \frac{2(\sum' x_i - n'\overline{x})}{n} = \frac{2(848.5 - 17(32.918))}{34} = 16.994$$

$$\left[\frac{\sum (x_i - \overline{x})^2}{n}\right]^{1/2} = \left[\frac{13761.009}{34}\right]^{1/2} = 20.118$$

$$U = \frac{(1.2533)(16.994)}{20.118} = 1.059$$

$$Z = \frac{1.059 - 1}{.2661/\sqrt{37}} = 1.349$$

Using a confidence level of 95%, $\alpha/2=.025$, $Z_{.025}=1.96$. Since $Z < Z_{\alpha/2}$, the hypothesis that the underlying distribution is normal is accepted.

<u>3000 Series, $180 \leq Kw \leq 450$</u>

A sample size of 30 products was taken with actual processing durations exhibited in Table 5.4. The resulting histogram is Figure 5.5. Based on the shape of the histogram a normal distribution was assumed. The estimates of the parameters u and σ^2 are $\overline{X}=38.157$ and $S^2=246.505$, respectively.

Using Geary's Test of Normality:

H_0: the underlying distribution is normal

H_a: the underlying distribution is not normal.

For the specific problem; $\overline{X}=38.157$, $n=30$, $n'=15$, $\sum' x_i = 771.7$

$$\frac{\sum|x_i - \overline{x}|}{n} = \frac{2(\sum' x_i - n'\overline{x})}{n} = \frac{2(771.7 - 15(38.157))}{30} = 13.29$$

$$\left[\frac{\sum(x_i - \overline{x})^2}{n}\right]^{1/2} = \left[\frac{7152.19}{30}\right]^{1/2} = 15.440$$

$$U = \frac{(1.2533)(13.29)}{15.440} = 1.079$$

$$Z = \frac{1.079 - 1}{.2661/\sqrt{30}} = 1.626$$

Using a confidence level of 95%, $\alpha/2=.025$, $Z_{.025}=1.96$.

since $Z < Z_{\alpha/2}$, the hypothesis that the underlying distribution is normal is accepted.

Table 5.4 Actual Processing Times for 300 Series $180 \leq Kw \leq 450$

32	44.5	41.5	27.5	20
63	49.5	28.5	17	32
29.5	42.2	34	17.5	18.5
60	64	43.5	19	58.5
41.5	60	50.5	33	25
47.5	51	33.5	54.5	6

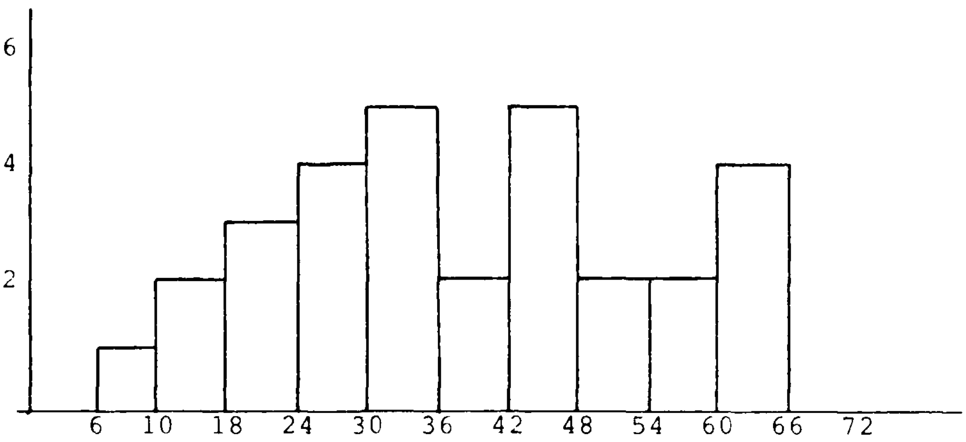


Figure 5.5 Histogram for 3000 Series 180 $\leq$ Kw $\leq$ 450

3000 Series, Kw=600

A sample size of 5 products was taken with actual processing durations exhibited in Table 5.5.

Table 5.5 Actual Processing Times for 3600 UPS

21	56.6	88
9	78.5	

The sample average, $\overline{X}$, is equal to 50.6 The standard allotted test hours for this type product is 50. Due to the lack of sufficient data, the assumption will be made that the underlying distribution is normal and that u=50. The standard deviation, σ^2, will be assumed to be equal to 17. This figure falls between the maximum and minimum standard deviations previously observed.

4000 Series

Actual test data was available for only two 4000 series UPS. As with the 3600 UPS, the assumption will be made that the underlying distribution for the processing durations of the 4000 series UPS is normal. The mean is assumed to be equal to the standard allotted test hours, $\mu=35$, and the standard deviation is assumed to equal 17.

5000 Series

A sample size of 18 products was taken with actual processing durations exhibited in Table 5.6. Due to the lack of sufficient data, the assumption will be made that the underlying distribution is normal. Since the sample mean, $\overline{X}=36.294$, differs significantly from the standard allotted test hours, 50, the sample mean and sample standard deviation, S=13.909, will be used as estimators for u and σ^2 , respectively.

Table 5.6 Actual Processing Times for 5000 Series UPS

6	50.5	55	26.3
32	36.5	34.5	31
20	62.5	35	57
36	32.8	45.5	
23	37	32.7	

Table 5.7 presents a summary of the parameters resulting from the processing time input analysis.

Table 5.7 Parameters for Processing Times

Product	μ	σ
2000	38.827	16.122
3000 Kw ≤ 100	32.918	20.421
3000 180 ≤ Kw ≤ 450	38.157	15.701
3000 Kw=600	50.0	17.0
4000	35.0	17.0
5000	36.294	13.909

All processing times were found or assumed to fit a normal distribution. The distributions will be trunctated to the left of the value 3, the minimum observed test time. Processing time generation is illustrated in Figure 5.6.

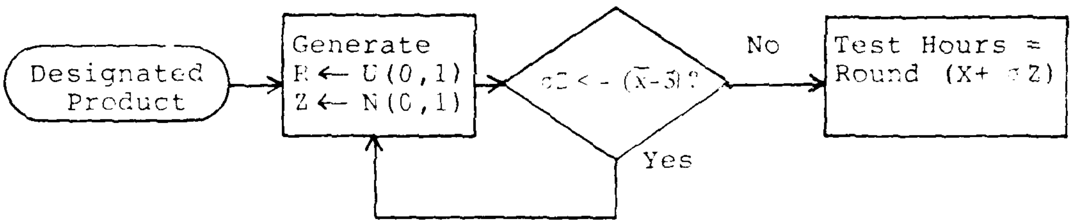


Figure 5.6 Processing Time Generation

Arrival and Interarrival Times

All attempts to collect data on arrival and interarrival times failed. It was observed, however, that the maximum number of UPS completed in a month was 93 and that on the average three to four products arrived each day. It has also been shown that in numerous situations, such as the arrival of jobs at a job shop, arrivals occur according to a Poisson process. Although Systems Test is not a job shop, numerous similarities exist. Checking the assumptions associated with a Poisson process the following was observed:

1. Products are completed by the production line one at a time. Since this is the source of products for systems Test, products can be assumed to arrive at Systems Test one at a time.

2. Arrivals are completely at random throughout the first shift without rush or slack periods.

3. A large or small number of arrivals on one shift had no effect on the number of arrivals in subsequent shifts.

Arrivals to Systems Test, therefore, met the assumptions associated with a Poisson process. Accordingly, a Poisson distribution with $\lambda = 4$, will be assumed to model arrivals.

The relationship between arrival date and due date was then investigated with the use of the PM01 Report, Appendix D. Two dates were of interest; the Original Operations Promise Date (Appendix D, #8), and the Original Scheduled Start for Systems Test (Appendix D, #1). By taking the difference of these two dates and subtracting nonworking days (weekends, holidays, etc.) and the standard lead time for packing and shipping, a distribution for planned test window times was developed for each product category as with processing times.

3000 Series, Kw ≤ 100

A sample size of 53 products was taken with planned test window times, calculated as described previously, exhibited in Table 5.8. The resulting histogram is Figure 5.7. An attempt was made to fit the data to a number of distributions, all of which failed the goodness-of-fit test. Based on the shape of the histogram and the fact that lead times often follow a gamma distribution the determination was made to fit a gamma distribution to the data.

Table 5.8 Test Window Times for 3000 Series UPS with Kw ≤ 100

3	13	10	9	15	8	10	13
14	28	5	8	14	8	10	13
14	6	13	11	9	7	10	13
9	8	23	8	24	8	0	13
14	7	9	8	8	7	10	30
10	15	10	10	8	6	8	14
			9	9	10	10	10

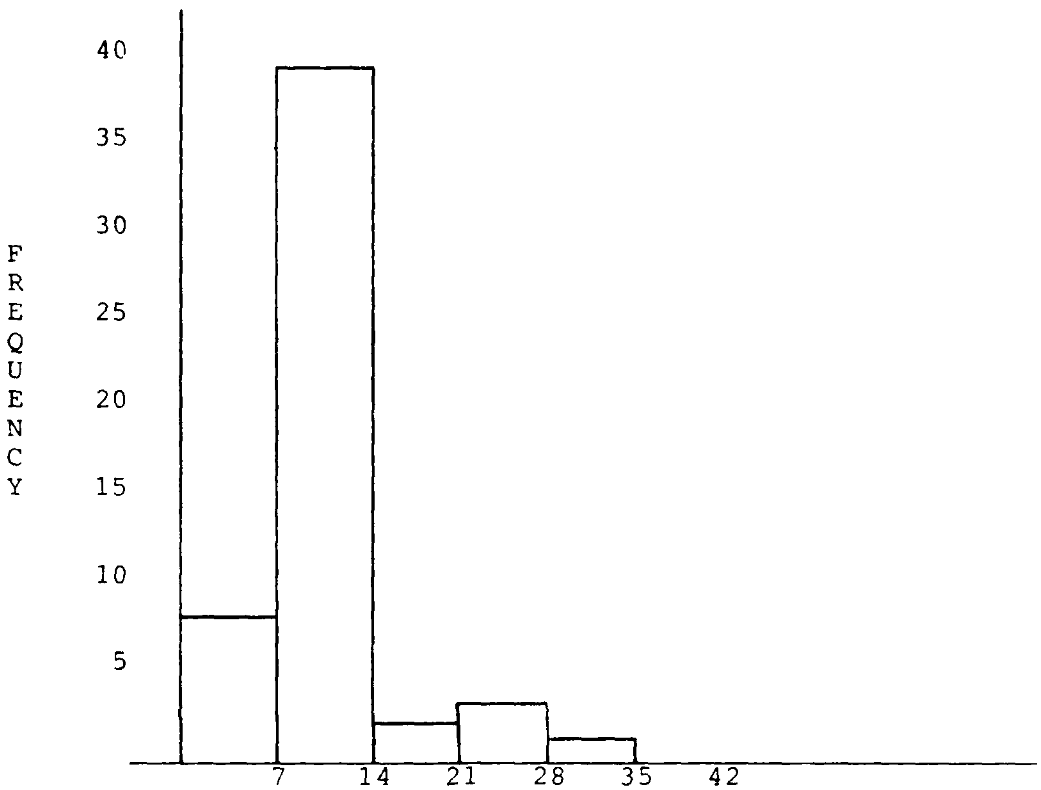


Figure 5.7 Test Window Times Histogram for 3000 Series UPS with Kw ≤100

The gamma distribution has the following density function:

$$f_Y(y) = \begin{cases} \dfrac{\theta^r y^{r-1} e^{-\theta y}}{\Gamma(r)} & , \text{ if } y \geq 0 \\ 0 & , \text{ if } y < 0 \end{cases}$$

Where θ and r are positive numbers and $\Gamma(r)$ is the gamma function.

To find values of θ and r from the data in Table 5.8, the mean and sample variance must first be calculated.

$$\hat{u}_Y = \frac{\sum_{i=1}^{n} x_i}{n} = 10.925$$

$$\sigma_Y^2 = \frac{\sum_{i=1}^{n} (x_i - \hat{u}_Y)^2}{n} = 28.447$$

The parameters Θ and r are now determined:

$$\hat{\Theta} = \frac{\hat{u}_Y}{\sigma_Y^2} = \frac{10.925}{28.447} = 0.384$$

$$\hat{r} = \frac{(u_Y)^2}{\sigma_Y^2} = \frac{(10.925)^2}{28.447} = 4.196$$

3000 Series, $180 \leq Kw \leq 450$

A sample size of 41 products was taken with planned test window times exhibited in Table 5.9. The resulting histogram is Figure 5.8. Again the data was not found to fit a standard distribution and it was determined that a gamma distribution would be fit to the data.

To find values of Θ and r from the data in Table 5.9, the mean and sample variance were first calculated with u_Y=11.935 and σ^2_Y=24.206. The values of Θ and r were then determined to be 0.493 and 5.885, respectively.

Table 5.9 Test Window Times for 3000 Series UPS with $180 \leq Kw \leq 450$

17.5	9.5	10.5	9.5	11.5	10.5	8.5	10.5	10.5
15.5	12.5	26.5	10.5	3.5	16.5	23.5	9.5	10.5
10.5	12.5	14.5	3.5	10.5	26.5	12.5	5.5	9.5
9.5	9.5	14.5	10.5	11.5	16.5	12.5	8.5	10.5
12.5	8.5	14.5	9.5	14.5	16.5	15.5	.5	12.5
9.5								

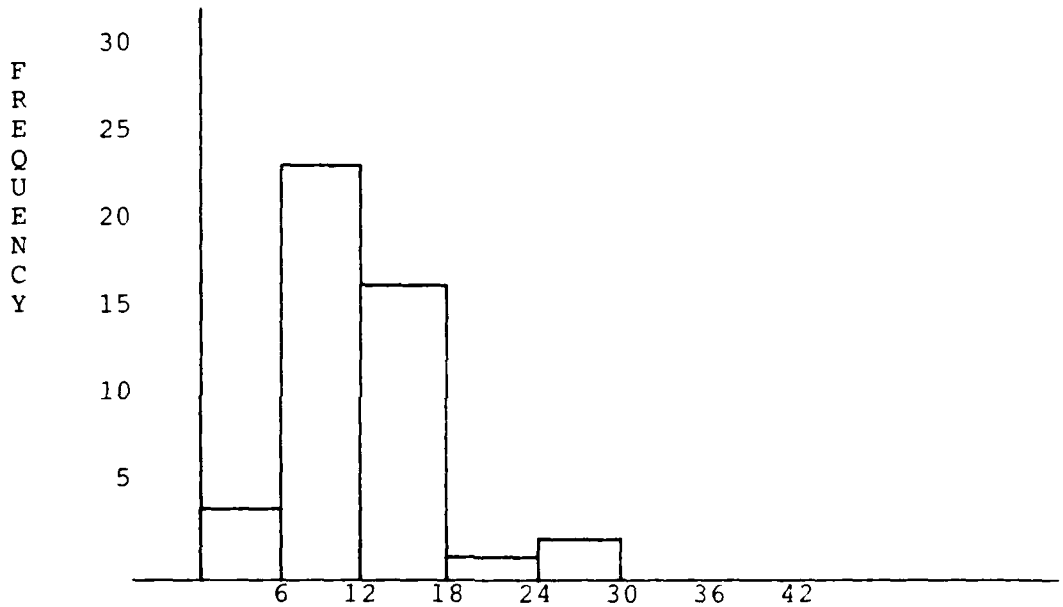


Figure 5.8 Test Window Times Histogram for 3000 Series UPS with $180 \leq Kw \leq 450$

3000 Series, Kw=600

A sample of seven products was taken with planned test window times exhibited in Table 5.10. The resulting histogram is Figure 5.9. The mean and sample variance for the data are $\bar{X}=10.643$ and $S^2=25.807$. Due to the lack of sufficient data a normal distribution will be assumed.

Table 5.10 Test Window Times for 3600 UPS

4.5	11.5	6.5
17.5	16.6	
11.5	6.5	

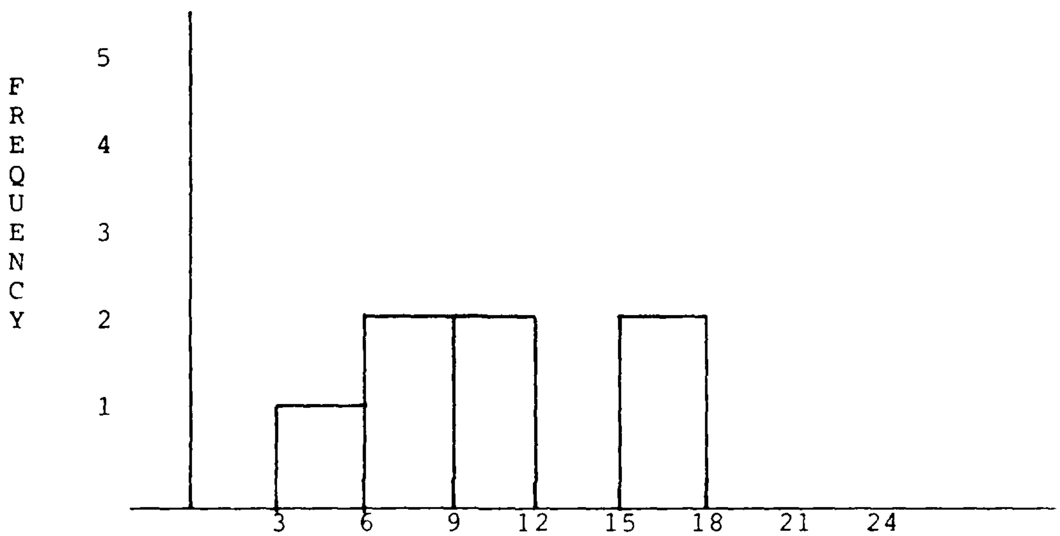


Figure 5.9 Test Window Times Histogram for 3600 UPS

4000 Series

A sample of 15 products was taken with planned test window times exhibited in Table 5.11. The resulting histogram is Figure 5.10. The mean and sample variance for the data are $\overline{X}=12.0$ and $S^2=24.711$. Based on the shape of the histogram and the lack of sufficient data a normal distribution is assumed.

Table 5.11 Test Window Times for 4000 Series UPS

18	14	9	7	9
17	9	14	12	21
9	9	17	2	13

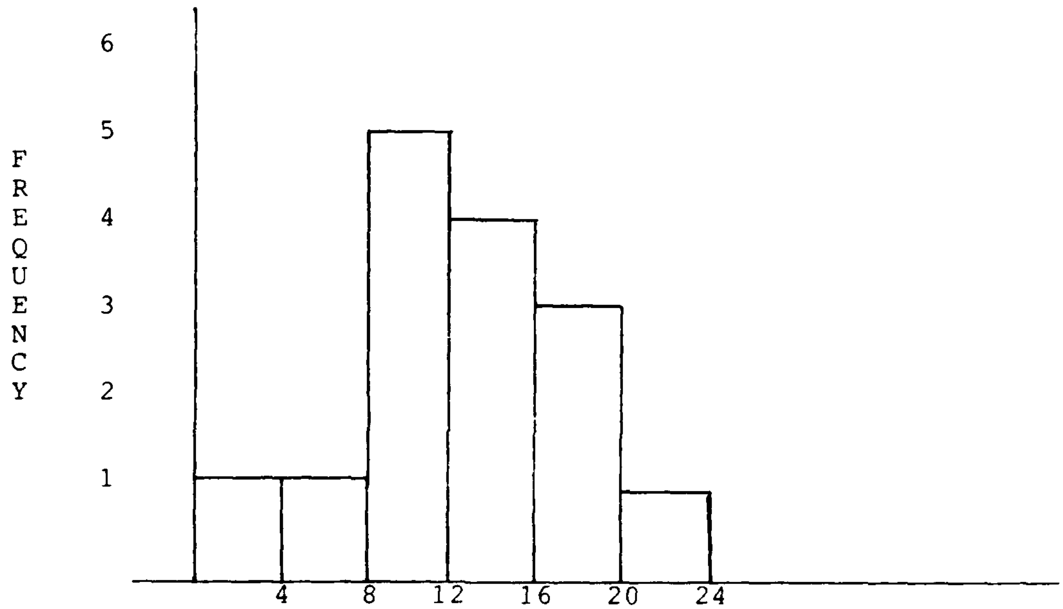


Figure 5.10 Test Window Times Histogram for 4000 Series UPS

5000 Series

A sample size of 30 products was taken with planned test window times exhibited in Table 5.12. The resulting histogram is Figure 5.11. Based on the shape of the histogram a normal distribution was assumed. The estimates of the parameters u and σ^2 are $\overline{X}$=11.833 and S^2=19.395, respectively. Using Geary's Test of Normality, as described in the processing time section:

H_o: the underlying distribution is normal

H_a: the underlying distribution is not normal

For the specific problem; $\overline{X}=11.833$, $n=30$, $n'=11$, $\sum' X_i=177$.

$$\frac{\sum|x_i - \overline{x}|}{n} = \frac{2(\sum' x_i - n'\overline{x})}{n} = \frac{2(177 - 11(11.833))}{30} = 3.123$$

$$\left[\frac{\sum(x_i - \overline{x})^2}{n}\right]^{1/2} = \left[\frac{474.257}{30}\right] = 3.976$$

$$U = \frac{(1.2533)(3.123)}{3.976} = .984$$

$$Z = \frac{.984 - 1}{.2661/\sqrt{30}} = -.329$$

Table 5.12 Test Window Times for 5000 Series UPS

14	9	9	14	14	11	8	9	10	11
24	9	14	14	22	11	9	9	10	14
19	9	14	14	9	8	9	9	8	11

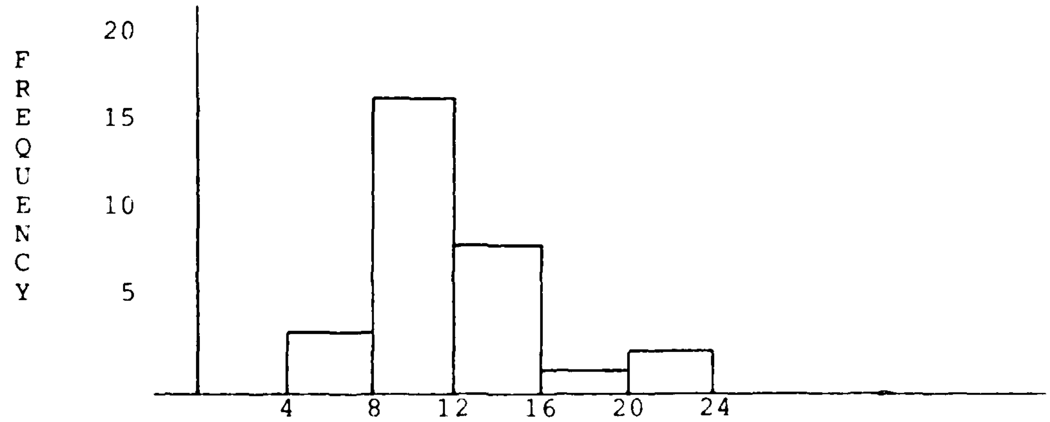


Figure 5.11 Test Window Times Histogram for 5000 Series UPS

Using a confidence level of 95%, $\alpha/2=.025$, $Z_{.025}=1.96$.

Since $Z > -Z_{\alpha/2}$, the hypothesis that the distribution is normal is accepted.

2000 Series

Only two products were available for investigation. Each of these products had a planned test window time of eight days. Due to the lack of sufficient data a normal distribution is assumed with $u=8$ and $\sigma^2=25$. The value for the variance was chosen to fall within the observations taken from the other product categories.

A link between planned test window times and actual test window times must now be developed. During the problem definition phase, it was determined that approximately one half of the products arrive two to four days late and that the other half arrive on time or one to two days early. A uniform distribution will be used to determine if the arriving UPS is early or late with 0.5 being the decision point. The number of days that an early product arrives early will be drawn from a Poisson distribution with $\lambda=1$. The number of days that a late product arrives late will be drawn from a Poisson distribution with $\lambda=3$.

It was also determined in the problem definition phase that a carryover of products that were not tested in the previous month contributes significantly to monthly commitment. In order to simulate this carryover, products will be generated for two months with statistics being taken on the scheduling that occurs in the second month.

Table 5.13 presents a summary of the distributions and parameters resulting from the arrival time input analysis. Figure 5.12 illustrates the generation of arrival dates and due dates.

Table 5.13 Distributions and Parameters for Planned Test Window Times

Product	Distribution	u	σ^2	θ	r
2000	Normal	8.0	25.0		
3000, Kw 100	Gamma	10.925	28.447	0.384	4.196
3000, 180 Kw 450	Gamma	11.935	24.206	0.493	5.885
3000, Kw=600	Normal	10.643	25.806		
4000	Normal	12.0	24.711		
5000	Normal	11.833	19.393		

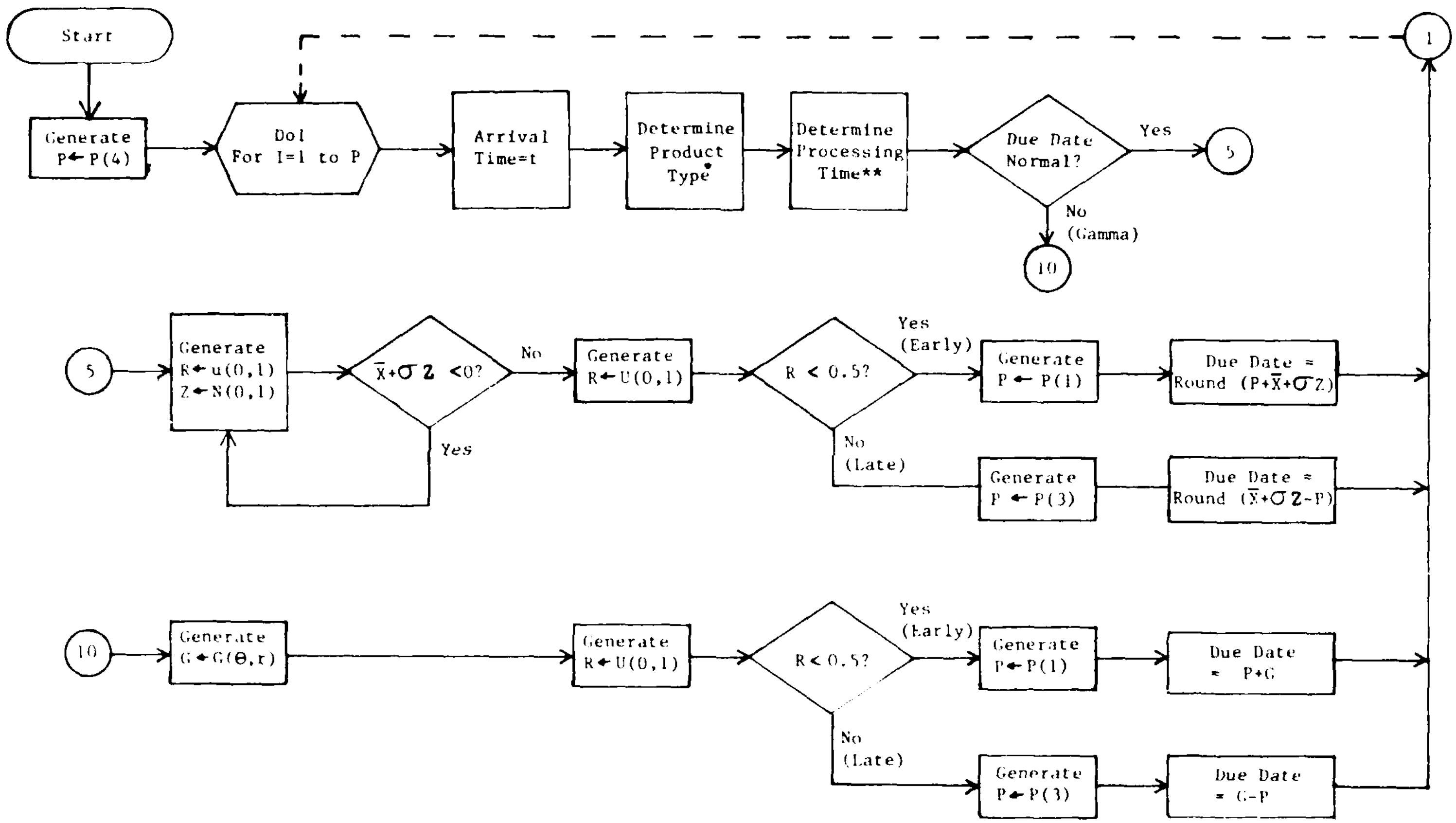


Figure 5.12 Arrival and Due Date Generation

* Figure 5.2 ** Figure .6

Resource Availability

At the time of this study, test station unavailability was negligible. Future plans, however, call for a periodic maintenance schedule based on six month periods which should coincide with plan shutdowns. Again, this unavailability period would be statistically negligible since testing would not be scheduled during the period. Specific data was not available for testor unavailability. However, it was determined that major periods, such as vacations, occur only during plant shutdown. Employee unavailability, therefore, will be assumed negligible.

Phase III. Experiment Design

Prior to the discussion of the experiment design a brief overview of experimentation and a number of pertinent definitions should be covered. Of course, experimentation begins by formulating a number of research hypotheses. The next stage is the selection of an appropriate experimental design within which to maximize the information gained, with respect to the hypotheses, from the experiment. The basic requirements of an experiment are simple: Differential treatments are administered to different groups of subjects (or to the same subjects in different orders) and performance on some response measure is observed and recorded following the administration of the treatments. The input variables (independent variables) to the system, such as the decision variables, the structural assumptions, and the parameters of the random variables, are called factors. Factors may be classified as qualitative or quantitative. Quantitative independent variables are variables that represent variation in amount, such as the number of parallel servers. Qualitative independent variables, on the other hand, represent variations in kind or type, such as queue discipline. Each possible value of a factor is called a level of the factor. A combination of factors all at a specified level is called a treatment. When a simulation is run with the same treatment but an independent stream of random numbers is used, it is said that an independent replication of the experiment has been made. The response variables (dependent variables) are those measures that seem to "capture" the phenomenon being studied most accurately.

Two factors of the Systems Test scheduling problem have been chosen for investigation; Queue discipline (dispatch rules) and criterion for second shift testing consideration. The first of these factors, queue discipline, was chosen with the expectation that the sequential simulation will be used as a manager's desk-side reference in the future. Therefore, it is necessary that an exhaustive test and evaluation of the dispatch rules be conducted in order that the sequential simulation package contain the most suitable dispatch procedure. It was determined that this factor would have the following four levels:

Level 1. First-Come-First-Considered: Th[illegible]
orders the queue with respect to [illegible]

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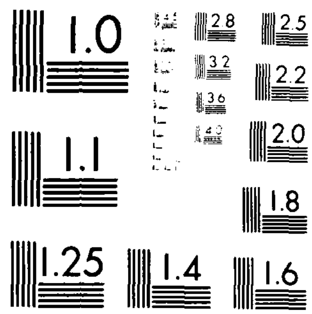
1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

the queue by placing the new arrival at the end of the queue.

Level 2. Earliest Due Date: Products are placed in the queue by due dates with the product having the earlier due date being placed ahead of one with a later date.

Level 3. Shortest Processing Time: Products are ordered with respect to the minimum total processing time remaining at the time of arrival at the queue.

Level 4. Minimum Slack Time: Minimum slack time is defined as the time remaining between the due date and the time at which the job could be completed without delay. Priority jobs are those jobs whose slack is negative. Slack is defined for a job as the due date minus the current time minus the processing time remaining.

The objective of this experiment will be to select that dispatch rule which has the most positive effect in reducing lateness and the number of late jobs. It is recognized that the analysis of these two response variables may yield two different optimizing rules. The experiment will be a single-factor experiment that will be completely randomized. This implies that the replications of the model at each level and for different levels of the factor are based on independent streams of random numbers.

The statistical model for the analysis of this experiment is

$$Y_{rj}=u+\tau_j+\varepsilon_{rj} \quad ,r=1,2,...,R_j;\ j=1,2,...,k,$$

where Y_{rj} is observation r of the response variable for level j of the factor, u is the overall mean effect, τ_j is the effect due to level j of the factor, ε_{nj} is a "random error" in observation r at level j, and R_j is the number of observations made at level j. This model is called a fixed effect model. In this experiment R_j=4 and k=4.

The initial analysis of a single-factor fixed-effects completely randomized experiment consists of a statistical test of the hypothesis

$$H_a: \ \tau_j=o \ (j=1,2...,k)$$

that the levels of the factor have no effect on the response. The applicable statistical test is a one-way analysis of variance (ANOVA). If the computed value of the F statistic is not significant the analysis will be terminated because no differences between the u_j's have been identified. But if H_o is rejected further analysis will follow a multiple comparisons procedure such as the range test.

If an improvement of 10% in lateness or the number of late jobs is observed, when comparison is made with the present system, a recommendation for employment will be made. The present system employs Earliest Due Date with ties broken by kilowatt rating as a dispatch rule.

The last factor to be investigated is the criterion for second shift testing. It is felt that the current criterion is too restrictive and that by expanding this criterion second shift testor utilization will increase and lateness and the number of late jobs will decrease. It was determined that the factor would have the following levels:

Level 1: All products that will be late if tested only on first shift.

Level 2: All products that will be completed within eight yours of their due date.

Level 3: All products that will be completed within 16 hours of their due date.

Level 4: All products that will be completed within 24 hours of their due date.

Level 5: All products that will be completed within 32 hours of their due date.

Level 6: All products that will be completed within 40 hours of their due date.

The objective of this experiment will be to select that criterion which has the most positive effect in reducing lateness and the number of late jobs and increasing second shift testor utilization. The experiment will be a single-factor fixed-effects completely randomized experiment and will follow the procedure of the experiment with queue discipline with R_j=4 and k=6.

If an improvement of 10% in the lateness or the number of late jobs is observed a recommendation will be made for employment of that specific criterion. The present system employs the criterion that if the product will be late when processed only on first shift, it will be considered for second shift testing.

Phase IV. Output Analysis

It should be recalled that the null hypothesis in single factor ANOVA is that the different levels of the factor have no effect on the response:

$$H_o:\ \tau_j=0\ (j=1,2,\ldots,k)\ \text{or}\ H_o:\ u_1=u_2=\ldots=u_k$$

The alternative claim is that there are differences among the responses for the different levels; this can be stated as

$$H_a:\ \tau_j\neq 0\ (j=1,2\ldots,k)\ \text{or}\ H_a:\ \text{at least two of the } u_i\text{'s are unequal}$$

The mean of each level j is computed by the following formula:

$$\overline{Y}_{.j} = \frac{\sum_{r=1}^{R_J} Y_{rj}}{R_J} \quad , \quad \text{for } j = 1,2,\ldots,k$$

, where Y_{rj} is the response variable, r is the replication, and R_J is the total number of replications. The dot in place of the second subscript in $Y._j$ is used to indicate sums over the indicated subscript, in this case r. The average of all observed values in the experiment is given by

$$Y_{..} = \frac{\sum_{r=1}^{R_J} \sum_{j=1}^{k} Y_{rj}}{R}$$

, where j is the level and R is the total number of replications in the experiment. This is often referred to as the grand mean and is equal to 43.25 in Table 5.14. The ANOVA test is based on partitioning the variability of the observed responses Y_{rj}, into two components, one component due to the level of each factor and one due to the inherent variability of the process being simulated. The first of these components is measured by the treatment sum of squares:

$$SS_{treat} = \sum_{j=1}^{k} R_J \, \overline{Y}^2_{\cdot j} - R\overline{Y}^2_{\cdot\cdot}$$

and the second by the error sum of squares:

$$SS_E = \sum_{r=1}^{R_J} \sum_{j=1}^{k} (Y_{rj} - \overline{Y}_{r\cdot})^2$$

This leads to the fundamertal identify of single-factor ANOVA:

$$SS_{total} = SS_{treat} + SS_E$$

where SS_{total} is the total sum of squares:

$$SS_{total} = \sum_{j=1}^{k} \sum_{r=1}^{R_J} Y^2_{rj} - R\overline{Y}^2_{\cdot\cdot}$$

If the assumption of a common variance is correct, the mean square $MS_E = SS_E/(R-k)$ is an unbiased estimate of the variance, σ^2, of the response variable Y. If, in addition, the null hypothesis is correct, the treatment mean square $MS_{treat} = SS_{treat}/(k-1)$ is also an unbiased estimate of σ^2.

In any case, MS_{treat} and MS_E are statistically independent. When H_o is true, SS_{treat}/σ^2 and SS_E/σ^2 have Chi-square distributions with (k-1) and (R-k) degrees of freedom, respectively. The test statistic for testing the hypothesis is computed by:

$$F = \frac{MS_{treat}}{MS_E} = \frac{SS_{treat}/(k-1)}{SS_E/(R-k)}$$

When H_o is true, this test statistic has an F distribution with k-1 and R-k degrees of freedom. The ANOVA test of the null hypothesis is to reject H_o if $F \geq F_{\alpha, k-1, R-k}$.

Queue Discipline

As stated earlier, R=16 replications were made, R_j=4 at each of the k=4 levels, for the queue discipline. The results, Y_{rj}, for the number of late products of replication r and level j, are given in Table 5.14.

Table 5.14 Number of Late Products for Queue Discipline

Replication, r	Number of Late Jobs, Yrj, at Level j of the Queue Discipline: j=1 FCFC	j=2 EDD	j=3 SPT	j=4 MST	Total Mean
1	47	47	45	51	
2	49	45	37	54	
3	47	34	36	38	
4	47	42	33	40	
Totals	190	168	151	183	692
Means	47.5	42	37.75	45.75	43.25

Table 5.15 ANOVA for Number of Late Products with Queue Discipline

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F
Treatment	SS_{treat}=224.5	k-1=3	MS_{treat}=74.833	2.437
Error	SS_E=368.5	R-k=12	MS_E=30.708	
Total	SS_{total}=593	R-1=15		

The ANOVA for the number of late products is shown in Table 5.15. With a 95% confidence level, α=.05, $F_{\alpha,k-1,R-k}$ = 3.49. Since the test statistic, F=2.437, is less than the critical value, the null hypothesis of no treatment effect is accepted.

The results for the mean lateness for replications r and level j are given in Table 5.16. The ANOVA for mean lateness is shown in Table 5.17.

Table 5.16 Mean Lateness for Queue Discipline

Replication, r	Number of Late Jobs, Yrj, at Level j of the Queue Discipline j=1 FCFC	j=2 EDD	j=3 SPT	j=4 MST	Total Mean
1	105	46	210	43	
2	148	90	171	86	
3	61	50	141	38	
4	91	49	155	42	
Totals	405	235	677	209	1526
Means	101.25	58.78	169.25	52.25	95.375

Table 5.17 ANOVA for Mean Lateness with Queue Discipline

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares
Treatment	SS_{treat}=34772.75	k-1=3	MS_{treat}=11590.917
Error	SS_E=9433	R-k=12	MS_E=786.083
Total	SS_{total}=44205.75	R-1=15	

Since the test statistic, F=14.745, is greater than $F_{\alpha,k-1,R-k} = F_{.05,3,12} = 3.49$, the null hypothesis of no treatment effect is rejected at the α=.05 level of significance.

It now remains to determine which of the u_i's are different from one another. A method for carrying out this further analysis is called a multiple comparisons procedure. The procedure which will be used in this case is Tukey's Procedure (the T Method). Tukey's procedure involves the use of the statistic Q called a studentized range statistic. The T method for identifying significantly different u_i's follows the following sequence of steps:

1. Select α and find $Q_{x,k,R-k}$
2. Determine $w = Q_{x,k,R-k} \sqrt{MS_E/R_J}$
3. List the sample means in increasing order and underline those pairs which differ by less than w. Any pair of sample means not underscored by the same line corresponds to a pair of true treatment means which are judged significantly different.

For the specific problem, mean lateness, α is chosen as .05,

$$Q_{\alpha,k,R-k} = Q_{.05,4,12} = 4.20, \text{ and}$$

$$w = 4.20\sqrt{786.083/4} = 58.878.$$

Arranging the four sample means in increasing order, every pair differing by less than 58.878 is underscored:

MST	EDD	FCFC	SPT
$Y_{\cdot 4}$	$Y_{\cdot 2}$	$Y_{\cdot 1}$	$Y_{\cdot 3}$
52.25	55.75	101.25	169.25

Thus queue disciplines MST, EDD, and FCFC are not significantly different from one another in respect to mean lateness, but are significantly lower than SPT.

Preliminary Conclusions

The following conclusions are made in respect to queue discipline:

1. The true average number of late products does not depend on queue discipline.
2. Shortest Processing Time increases the true average mean lateness of products.
3. A recommendation will not be made to change queue discipline.

Second Shift Criterion

As stated earlier, R=24 replications were made, R_j=4 at each of the k=6 levels, for the second shift criterion. The results, Y_{rj}, for the number of late products of replication r and level j, are given in Table 5.18. The ANOVA for the number of late products is shown in Table 5.19. With a 95% confidence level, $\alpha = .05$, $F_{\alpha,k-1,\ R-k} = F_{.05,5,19} = 2.74$. Since the F statistic, F=2.621, is less than the critical value, the null hypothesis of no treatment effect is accepted.

The results for the mean lateness in respect to the criterion are shown in Table 5.20. The corresponding ANOVA is in Table 5.21.

Table 5.18 Number of Late Products with Criterion

	Replication, r					
Level, j	1	2	3	4	Totals	Means
1	47	45	34	42	168	42
2	39	40	29	36	144	36
3	30	40	27	35	132	33
4	36	36	24	30	126	31.5
5	21	39	17	36	113	28.25
6	30	31	23	31	115	28.75
				Total	798	
				Grand Mean	33.25	

Table 5.19 ANOVA for Number of Late Products with Criterion

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F
Treatment	$SS_{treat}=530$	k-1=5	$MS_{treat}=106$	2.621
Error	$SS_E=768.5$	R-k=19	$MS_E=40.447$	
Total	$SS_{total}=1298.5$			

Table 5.20 Mean Lateness with Criterion

	Replication, r					
Level, j	1	2	3	4	Totals	Means
1	46	90	50	49	235	58.75
2	53	91	36	71	251	62.75
3	45	88	48	67	248	62
4	48	99	48	69	264	66
5	60	63	51	47	221	55.25
6	53	88	40	52	233	58.28
				Total	1452	
			Grand Mean		60.5	

Table 5.21 ANOVA for Mean Lateness with Criterion

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F
Treatment	$SS_{treat}=293$	k-1=5	$MS_{treat}=58.$	151
Error	$SS_E=7373$	R-k=19	$MS_E=388.053$	
Total	$SS_{total}=7666$			

The critical value, $F_{.05,5,19}=2.74$, remains the same. Since the F statistic is 0.151, which is less than the critical value, the null hypothesis of no treatment effect is accepted.

The results for the second shift testor utilization with respect to the criterion are exhibited in Table 5.22. These measures were taken for a one month period where the maximum possible utilization figure would be 1120. The ANOVA for mean lateness is shown in Table 5.23. The critical value remains 2.74. Since the F statistic, 1.088, is less than the critical value of the null hypothesis of no treatment effect accepted.

Table 5.22 Testor Utilization with Criterion

	Replication, r					
Level,	1	2	3	4	Totals	Means
1	856	830	775	806	3267	816.75
2	802	879	787	862	3330	832.5
3	937	872	725	860	3394	848.5
4	862	976	767	890	3495	873.75
5	951	961	783	891	3586	896.5
6	977	918	805	933	3633	908.25
				Total	20705	
			Grand Mean		862.708	

Table 5.23 ANOVA for Testor Utilization with Criterion

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares
Treatment	$SS_{treat}=26271.512$	k-1=5	$MS_{treat}=5254.302$
Error	$SS_E=91767.25$	R-k=19	$MS_E=4829.855$
Total	$SS_{total}=118038.76$		

Preliminary Conclusions

The following conclusions are made in respect to the second shift criterion.

1. The true average number of late products does not depend on the second shift criterion.

2. The true average mean lateness of products does not depend on the second shift criterion.

3. The true average second shift testor utilization does not depend on the second shift criterion.

4. A recommendation will not be made to change the second shift criterion.

Conclusions

All of the results appear to be counter-intuitive. In the queue discipline experiment, since there are many favorable comparisons that can be made between Systems Test and the single machine sequencing problem with independent jobs, one would expect that the dispatch rule of shortest processing time would yield the most favorable result. The fact that the dispatch rules were not significantly different from one another leads one to believe that the reason for the large number of late jobs does not rest with Systems Test. This conception is strengthened by the results of the experiment investigating the second shift processing criterion.

In this experiment, one would expect the number of late jobs to decrease and second shift testor utilization to increase as more jobs were considered for second shift processing. The fact that the criteria were shown to produce results not significantly different from one another implies that the second shift testor resource is already committed to products which would be late without a safety factor. The combined results suggest an investigation of why products arrive late to Systems Test and whether lead times for product manufacture are sufficient.

As a result of the nonincrease of second shift testor utilization in the experiment involving the second shift processing criterion, an additional observation can be made. The maximum possible second shift testor utilization for the period under consideration is 1120. The grand mean for this experiment was only 862.7. This result suggests a further investigation into the testor qualifications of second shift personnel as qualifications do not appear to meet the needs of the system. An initial verification of this rationale is obtained by checking the qualification matrix for second shift operators shown below.

$$\begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The sparseness of the matrix supports the conclusion.

VI. Summary and Recommendations

Subsequent to a complete problem definition, an analytical scheduling model was developed to completely describe the Systems Test assignment procedures with regard to limited resources and constraints. In determining the computational complexity of the model, it was determined, however, that the scheduling model could not be solved for an optimum schedule. This was due, primarily, to the unique second shift organization and the desire not to process all products on second shift. By eliminating this consideration and dealing only with a single shift, a reduced formulation was developed which fell within the constraints of a mixed integer programming package. Combining this formulation with an iterative algorithm, a solution, although not optimum, was obtained.

The capacity of Systems Test is a function of the specific product mix. Therefore, an analytical capacity model was also developed. In an effort to reduce the computational complexity of the formulation, the assumptions that products were immediately available and that testors were readily available were made. In this manner, time and testors, unlike the scheduling formulation, were not parameters of the model. Due to these assumptions, however, the solution is at best an estimate of capacity for the specific product mix. A related heuristic remains to be developed which will select products for deletion from an infeasible solution. Computational complexity again overshadowed the usefulness of the formulation and it was determined that a simulation approach would be used.

The concept was to employ simulation both as a tool of design and a tool of operation. As an operational tool, a sequential simulation was developed which is suitable for use by a manager as a desk-side reference. It assists the manager in determining whether he or she will be able to meet monthly test requirements, and in planning shift organization, overtime requirements, et cetera. It fully considers the facility resource constraints, both personnel and equipment.

As a design tool, the sequential simulation was combined with an input simulation to yield a randomized simulator. The input simulation was the result of the collection and analysis of data from the test facility and accurately reflected the technical description of the products and their arrival to Systems Test. It was assumed that product arrival followed a Poisson distribution with $\lambda=4$ and that half of these products were late and half early. The "lateness" was assumed to follow a Poisson distribution with $\lambda=3$ and the "earliness" a Poisson distribution with $\lambda=1$. Probabilities were associated with product types based on an actual 12-month production projection. Due dates were assigned to products based on the analysis of planned test window times and whether the product was determined to be late or early. In two cases a gamma distribution was fit to the collected data of the planned test window times, as the data did not fit a standard known distribution. In all other instances, a normal distribution was shown to be appropriate or assumed. A normal distribution was also shown to be appropriate for product processing requirements.

Two factors of the scheduling procedure were chosen for investigation with the use of the simulator. The first, queue discipline, was tested at four levels, and the second, the second shift processing criterion, was tested at six levels. It was statistically determined that the influence of these factors on the number of late products was not significant. It was also determined that the influence of queue discipline on mean lateness was statistically significant, in that the mean lateness associated with shortest processing time was greater than all other tested queue disciplines. In the case of the second shift processing criterion, it was shown that the influence of the criterion on mean lateness and second shift testor utilization was not significant.

It is recommended that the reduced scheduling model and the related algorithm be employed by the company, both as a planning tool and an operational tool. As a planning tool, it is recommended for use as a capacity model and the first step in a backward planning process. By not considering the planned arrival times of the products and instead assuming that products are immediately available for processing, the reduced formulation and related algorithm could be used to determine capacity for specific product mixes. Additionally, this method could be used to determine best arrival times for products to Systems Test and then, through a backward planning process, related manufacturing times. As an operational tool, it is recommended that the reduced formulation and related algorithm be employed by the manager of Systems Test on receipt of the Monthly Sales Plan in order to develop the manager's Monthly Plan for Test. In this way, the manager will be better able to allocate his resources, such as second shift personnel and overtime hours.

The manager should also employ the sequential simulator as a desk-side reference. Since it was designed to be flexible, he or she can experiment on an as needed basis, perhaps weekly, with changes in user defined variables, such as shift durations and testor shift assignments. The simulator would also provide an immediate scheduling update as information, such as new arrival times, becomes available.

Finally, it is recommended that current procedures with regard to dispatch rules and second shift processing considerations do not change. However, as other changes are made outside Systems Test that may affect arrival times, in relation to due dates, it is recommended that the simulation experiments be repeated with the related changes.

All of the objectives of the project, as detailed in Chapter III, and the simulation objectives of Chapter V, have been accomplished. Many aspects of the Systems Test facility still deserve study, however. Recommendations for continued work are as follows:

1. As indicated in the simulation experiment, second shift testor qualifications may not match the future needs of the system. A development of an improved mix of testor qualifications and numbers is warranted. This could be accomplished by a single-factor fixed-effects completely randomized experiment, with the developed simulator, following the procedure presented in Chapter V of this study.
2. The simulation experiment also indicated that the source of late products lies outside Systems Test. An

investigation of production lead times would further refine the search.

3. As indicated previously, further development of the capacity model and the related heuristic demands a separate treatment.

4. Plans are in the offing at the plant for expansion of Systems Test facilities. A complete investigation of requirements prior to final determination would maximize return of the expansion.

5. Input data collection should continue in order to increase the validity of the simulation, especially in the area of arrival and interarrival times.

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APPENDICES

Appendix A.

UPS Products

Administrative Number	Series and Kw	Voltage In/Out
3000 Series		
1	3025	204/204
3	3030	208/208
4	3030	480/208
5	3030	480/480
6	3050	204/204
8	3060	208/208
9	3060	480/208
10	3060	480/480
54	3060	220/208
14	3100	208/208
15	3100	480/208
16	3100	480/480
17	3180	208/208
18	3180	480/208
19	3180	480/480
63	3200	208/208
20	3250	208/208
21	3250	480/208
22	3250	480/480
23	3330	208/208
24	3330	480/208
25	3330	480/480
26	3400	208/208
27	3400	480/208
28	3400	480/480
29	3450	208/208
30	3450	480/208
31	3450	480/480
32	3600	480/480
2000 Series		
33	2015	208/208
34	2015	480/208
35	2015	480/480
36	2015	380/380
56	2015	400/400
37	2030	208/208
38	2030	480/208
39	2030	480/480
40	2030	380/380
66	2030	400/400
41	2045	208/208
42	2045	480/208
43	2045	480/480
44	2045	380/380
62	2045	600/280

Administrative Number	Series and Kw	Voltage In/Out
Single Phase		
45	2715	208/120
46	2715	480/208
60	2715	480/120
61	2715	415/120
64	2715	400/230
47	2730	208/120
48	2730	480/120
49	2730	400/400
57	2730	400/230
50	2745	400/400
4000 Series		
11	4080	208/208
12	4080	380/208
13	4080	480/208
5000 Series		
2	5025	380/380
7	5050	380/380
53	5060	380/380
65	5060	400/400
68	5060	415/415
55	5100	380/380
58	5160	380/380
67	5300	380/380
Parallel Products		
51	4080	480/208
52	3450	480/480
69	3400	480/480
70	3450	480/480
71	3300	480/480
72	3330	208/208

Appendix B.

Test Facility Capability Study

12/30/80
updated 5/26/83

NOTES:

STA A2, A3, B1	-	No load capability for over 208V
	-	Limited to 60Kw or less
STA B1, B2	-	No 50Hz or gen. test capability
	-	E.G. no 1st article Navy
	-	Limited to one 250Kw or less plus one 60
STA C, D	-	Limited to 330Kw or less
STA G	-	Limited to 480 in and out units, except for 514 Hz= output models Limited to total of 250 Kw Limited to 400A generator (50Hz)
STA E,F,G,H,I,J	-	No 60 or 120 cell DC available
STA A, B	-	100, 120 cell DC available
STA E, F	-	Limited to total of one 50Hz= unit at a time
	-	Limited in inductive load capacity (300 kvars total in both stations)
	-	Limited to one 208V output system in either station
	-	Limited to one 600Kw unit in either station
	-	No 208V inductive load available
STA H, I	-	No permanent 208V supply
	-	No inductive Load
	-	No generator capability
GENERATOR	-	Limited to 425 KVA @ 208 (60Hz) 354 KVA
	-	Limited to 550 KVA @ 480 (60Hz) 450 KVA
STA J	-	No inductive load

Facility Capability Study

5/26/83

Individual Station Notes:

STA A1	-	Maximum size unit - 60 Kw
	-	Load #1 - 119.5 Kw @ 208 (max. V=208) Kvar @ 208 (max. v=208)
	-	Load #2 - 300 Kw @ 240 or 480 (Max. v=208) 750 Kvar @ 240 or 480 (max. v=480) (Notice: this Load #2 is same load as B2 and G load. E.g., only one unit or load at a time.) Voltages available: 208, 480, 380 (or nom. gen. voltage.) Battery: 60 cell Ex-13 (Notice: this battery is common with A2, A3, B1, B2.60 cell battery, hence one system in these stations on battery at one time.)
STA A2, A3	-	Same as A1 except no Load #2
STA B1	-	Same as A1 except no Load #2 and no 380v 50 Hz voltage available
STA B2	-	Max. size unit 250Kw Load: same as Load #2 (station A1) Voltages Available: 208, 480 (No 50 Hz) Battery 1: 60 cell Ex-13 (same battery as Station A1) Battery 2: 192 cell Ex-27 (same battery as C, D, E, F, G.192 cell, hence only one unit in these stations on battery at one time)
STA C	-	Max. size unit: 330Kw Load: 475 Kw @ 240 or 480 350 kvar @ 240 or 480 (Shared with Station D) Voltages available: 208, 480, 380(50Hz) (by conversion of normal 480V 60Hz feeder) Battery 1: 60 or 120 cell FTC-21 (Shared with Station D and 30 charger test area, hence one unit in these station on this battery at one time.) Battery 2: same as battery 2, Station B2
STA D	-	Same as Station C

STA E - Max. size unit 600Kw (max. 208 unit: 480 Kw). (However, can be used for two module parallel sys. testing up to 800 Kw.)

Load #1: 500 Kw @ 480 v only*
300 Kvar @ 480 v only*
Load #2: 400 Kw @ 480 v only*
Load #3: 800 Kw @ 240 or 480*
*Shared with Station F
Voltages available: 208, 480, 380 50Hz (max. of 375 Kva)
Battery: Same as Battery 2, Station B2

STA F - Same as Station E

STA G1, G2 - Max. size unit: 250 Kw (total cap. of G1+G2=250Kw)
Load: same as Load #2, Station A1
Voltage: 480, 380 (50 Hz)
(Only 1 50Hz unit at a time.)
Battery: same as Battery 2, Station B2

STA H - Max. size unit: 600Kw (can be used for up to 4 modules in parallel at 1200 kw)
Load #1: 1200 Kw @ 240 or 480*
Load #2: 1200 Kw @ 240 or 480*
*Shared with Station I
Voltage available: 480 only
Battery: 192 cell Ex-33B (shared with Stations I, J)

STA I - Same as Station H

STA J - Max. size unit: 600 Kw
(Up to 3 units at 1000 KW total in parallel system)
Load #1: 500 Kw @ 240 or 480
Load #2: 500 Kw A 240 or 480
Voltages: 208, 480, max. of 2 units on 208; max. of 3 units on 480
Battery: Same as Station H

PRODUCT TYPES VS BAYS

	TEST STATION													
	A1	A2	A3	B1	B2	C	D	E	F	G1	G2	H	I	J
PRODUCT	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	X	X	X	O	O	X	O	O	O	O	O	O	O	O
2	X	O	O	O	O	X	O	O	O	O	O	O	O	O
3	X	X	X	X	X	X	O	O	O	O	O	O	O	O
4	X	X	X	X	O	X	O	O	O	O	O	O	O	O
5	X	O	O	O	X	X	O	O	O	O	O	O	O	O
6	X	X	X	O	O	X	O	O	O	O	O	O	O	O
7	X	O	O	O	O	X	O	O	O	O	O	O	O	O
8	X	X	X	X	X	X	O	O	O	O	O	O	O	O
9	X	X	X	X	X	X	O	O	O	O	O	O	O	O
10	X	O	O	O	X	X	O	O	O	O	O	O	O	O
11	O	O	O	X	X	X	X	X	X	O	O	X	X	X
12	O	O	O	O	O	X	X	O	O	X	X	O	O	O
13	O	O	O	X	X	X	X	X	X	X	X	X	X	X
14	O	O	O	X	X	X	X	O	O	O	O	O	O	O
15	O	O	O	X	X	X	X	O	O	O	O	O	O	O
16	O	O	O	X	X	X	X	O	O	O	O	O	O	O
17	O	O	O	X	X	X	X	X	X	O	O	O	O	X
18	O	O	O	X	X	X	X	X	X	O	O	O	O	X
19	O	O	O	X	X	X	X	X	X	X	X	X	X	X
20	O	O	O	O	X	X	X	X	X	O	O	O	O	X
21	O	O	O	O	X	X	X	X	X	O	O	O	O	X
22	O	O	O	O	X	X	X	X	X	X	X	X	X	X
23	O	O	O	O	O	X	X	X	X	O	O	O	X	X
24	O	O	O	O	O	X	X	X	X	O	O	O	X	X
25	O	O	O	O	O	X	X	X	X	O	O	X	X	X
26	O	O	O	O	O	O	O	X	X	O	O	O	O	X
27	O	O	O	O	O	O	O	X	X	O	O	O	O	X
28	O	O	O	O	O	X	X	X	X	O	O	X	X	X
29	O	O	O	O	O	O	O	X	X	O	O	O	O	X
30	O	O	O	O	O	O	O	X	X	O	O	O	O	X
31	O	O	O	O	O	O	O	X	X	O	O	X	X	X
32	O	O	O	O	O	O	O	X	X	O	O	X	X	X
33	X	X	X	O	X	O	O	O	O	X	X	O	O	O
34	X	X	X	O	X	O	O	O	O	X	X	O	O	O
35	X	O	O	O	O	O	O	O	O	X	X	O	O	O
36	X	X	X	O	X	O	O	O	O	X	X	O	O	O
37	X	X	X	O	X	O	O	O	O	X	X	O	O	O
38	X	O	O	X	O	O	O	O	O	X	X	O	O	O
39	X	X	X	O	X	O	O	O	O	O	O	O	O	O

40	*	X	X	X	O	X	O	O	O	O	O	O	O	O	O
41	*	X	O	O	X	O	O	O	O	O	X	O	O	O	O
42	*	X	O	O	O	O	O	O	O	O	X	O	O	O	O
43	*	X	O	O	O	O	O	O	O	O	X	O	O	O	O
44	*	X	O	O	O	O	O	O	O	O	X	O	O	O	O
45	*	X	X	X	O	X	O	O	O	O	O	O	O	O	O
46	*	X	X	X	O	X	O	O	O	O	O	O	O	O	O
47	*	X	X	X	O	X	O	O	O	O	O	O	O	O	O
48	*	X	X	X	O	X	O	O	O	O	O	O	O	O	O
49	*	O	O	O	X	X	O	O	O	O	X	O	O	O	O
50	*	O	O	O	X	X	O	O	O	O	X	O	O	O	O
51	*	O	O	O	O	O	O	O	O	O	O	O	X	X	X
52	*	O	O	O	O	O	O	O	O	O	O	O	X	X	X
53	*	X	X	X	O	O	X	X	O	O	O	O	O	O	O
54	*	O	O	O	O	O	X	X	O	O	O	O	O	O	O
55	*	O	O	O	O	O	X	X	X	X	O	O	O	O	O
56	*	X	O	O	O	O	O	O	O	O	X	X	O	O	O
57	*	X	O	O	O	O	O	O	O	O	X	X	O	O	O
58	*	O	O	O	O	O	X	X	X	X	O	O	O	O	O
59	*	X	O	O	O	O	O	O	O	O	X	X	O	O	O
60	*	O	X	X	X	X	O	O	O	O	X	X	O	O	O
61	*	X	O	O	O	O	O	O	O	O	X	X	O	O	O
62	*	O	O	O	O	X	O		O	O	O	O	O	O	O
63	*	O	O	O	O	O	X	X	X	X	O	O	O	O	X
64	*	X	X	X	O	O	X	X	O	O	O	O	O	O	O
65	*	X	X	X	O	O	O	O	O	O	X	X	O	O	O
66	*	X	O	O	O	O	O	O	O	O	X	X	O	O	O
67	*	O	O	O	O	O	X	X	X	X	O	O	O	O	O
68	*	X	X	X	O	O	X	X	O	O	O	O	O	O	O
69	*	O	O	O	O	O	O	O	O	O	O	O	X	X	X
70	*	O	O	O	O	O	O	O	O	O	O	O	X	X	X
71	*	O	O	O	O	O	O	O	O	O	O	O	X	X	X
72	*	O	O	O	O	O	O	O	O	O	O	O	O	X	X

Appendix C. Project Management System PM 21 Report

SYNUM	CNAME	EQUIP	RLNUM	BATTS	OPOPR	RACKS	OPCPR
978	STOCK 45KW JANUS	2045 400/400/50HZ		00/00/00	10/14/83	00/00/00	10/14/83
979	STOCK 45KW JANUS	2045 400/400/50HZ		00/00/00	10/14/83	00/00/00	10/14/83
983	STOCK 45KW JANUS 1P	2045 480/208/60HZ		00/00/00	10/14/83	00/00/00	10/14/83
984	STOCK 45KW JANUS 1P	2045 480/480/60HZ		00/00/00	10/14/83	00/00/00	10/14/83
985		2045 208/208/60HZ	RL87639	00/00/00	[illegible]	[illegible]	[illegible]
987	STOCK 15KW JANUS 1P	2715 400/230/50HZ		00/00/00	10/14/83	00/00/00	10/14/83
988	STOCK 15KW JANUS 1P	2715 400/230/50HZ		00/00/00	10/14/83	00/00/00	10/14/83
1008		5060 RT 220/220	RL86917	00/00/00	10/14/83	00/00/00	10/14/83
1026		3250 RT 480/208	RL87429	00/00/00	10/14/83	00/00/00	10/14/83
1029		3450 RT 480/480	RL87146	00/00/00	10/21/83	00/00/00	10/14/83
1033		3600 RT 480/480	RL87094	00/00/00	10/21/83	00/00/00	10/14/83
1036		5200 RT 400/400	RL87118	00/00/00	10/14/83	00/00/00	10/14/83
2002	PENDING	2015 480/208/60HZ	RL87330	00/00/00	10/14/83	00/00/00	10/14/83
2003		2015 480/208/60HZ	RL87488	00/00/00	10/14/83	00/00/00	10/14/83
2004	PENDING	2015 208/208/60HZ		00/00/00	10/14/83	00/00/00	10/14/83
2010		2030 208/208/60HZ	RL87148	00/00/00	10/14/83	00/00/00	10/14/83
2011		2030 480/208/60HZ	RL87178	00/00/00	10/14/83	00/00/00	10/14/83

Appendix D. Project Management System PM 01 Report

```
199  CUSTOMER    $PENDING                        RLNUM RL87356          BTYP1          BATTS 00/00/00  OPOPR 02/24/84
     EQUIPMENT   3330 RT 208/208                 KWSIZ 3330             BTYP2          RACKS 00/00/00  OPCPR 02/24/84
                                                 TTYPE P                BTYP3          FPMON           MRPWY
                                                 PENGR SOWDEN           BDAYR          DCLFS
     COMMENT     [illegible]                     PLABE CC               BRNUM          BNTOR
                 W/19&E200,ADDED 9/13/83         DTYPE S                TWSYN          ENTRY 09/06/83

     SYSEQ ACTCD RESCD  MRSTC  OSCHS     CSCHS     ACTLS     OSCHC     CSCHC     ACTLC     PSEQ1     PSEQ2
     19906 EPREL               00/00/00  00/00/00  00/00/00  10/14/83  10/14/83  00/00/00
     19907 EMREL               00/00/00  00/00/00  00/00/00  11/18/83  11/18/83  00/00/00
     19910 KIT   STK           00/00/00  00/00/00  00/00/00  01/13/84  01/13/84  00/00/00
     19913 [illegible]         [illegible] [illegible] 00/00/00 [illegible] [illegible] 00/00/00
     19915 TESTF TFS           02/04/84  02/04/84  00/00/00  02/17/84  02/17/84  00/00/00
     19917 TESTW TFS           00/00/00  00/00/00  00/00/00  02/20/84  02/20/84  00/00/00

     SYPCR PONUM VENDR         SCODE PDESC                  REQSH     PPMSH     OIDSH     DOLLS     DATEP
     19901                           BATT & RACKS ON SYS# 196  00/00/00 00/00/00 00/00/00           00/00/0

     SYMAT PTNUM               QUANP PDESC                  KVAMP     SCDE1     SCDE2     LSTDT     LSTWK
     [illegible]                                            

200  CUSTOMER    $PENDING                        RLNUM RL[illegible]    BTYP1          BATTS 00/00/00  OPOPR 02/24/84
     EQUIPMENT   3330 RT 208/208                 KWSIZ 3330             BTYP2          RACKS 00/00/00  OPCPR 02/24/84
                                                 TTYPE P                BTYP3          FPMON           MRPWY
                                                 PENGR SOWDEN           BDAYR          DCLFS
     COMMENT     [illegible]                     PLABE CC               BRNUM          PRIOR
                 W/19&E199,ADDED 9/13/83         DTYPE S                TWSYN          ENTRY 09/06/83

     SYSEQ ACTCD RESCD  MRSTC  OSCHS     CSCHS     ACTLS     OSCHC     CSCHC     ACTLC     PSEQ1     PSEQ2
     20006 EPREL               00/00/00  00/00/00  00/00/00  10/14/83  10/15/83  00/00/00
     20007 EMREL               00/00/00  00/00/00  00/00/00  11/18/83  11/18/83  00/00/00
     20010 KIT   STK           00/00/00  00/00/00  00/00/00  01/13/84  01/13/84  00/00/00
     20011 PROD  801           01/16/84  01/16/84  00/00/00  02/03/84  02/03/84  00/00/00
     20013 TESTF TFS           02/04/84  02/04/84  00/00/00  02/17/84  02/17/84  00/00/00
     20017 TESTW TFS           00/00/00  00/00/00  00/00/00  02/20/84  02/20/84  00/00/00

     SYPCR PONUM VENDR         SCODE PDESC                  REQSH     PPMSH     OIDSH     DOLLS     DATEP
     20001                           BATT & RACKS ON SYS# 196  00/00/00 00/00/00 00/00/00           00/00/0

     SYMAT PTNUM               QUANP PDESC                  KVAMP     SCDE1     SCDE2     LSTDT     LSTWK
     20001 1019D0031-2-P73         1 330KW 480-277/480V P3 MOD          P                   01/13/84  1127
```

Appendix E. Special/Standard Order Data Sheet

☒ SPECIAL ☐ STANDARD PROD ORDER DATA SHEET. REV [illegible] DATE [illegible]

RL # [illegible] SYS. # [illegible]
CUSTOMER [redacted]
USER [illegible]
AE [illegible] SPE [illegible]

DATE
CUST P.O. [illegible]
AE REC'V [illegible]
REQ'D SHIP [illegible]

☒ REV TRANS
☐ PIGGY BACK
☐ MULTI MOD
☐

CUSTOMER DRAWINGS
☒ INFO ONLY
☒ APVL BEFORE MFG
☐ APVL BEFORE ENG
SUBMIT [illegible]
RETURN

INITIAL RATING [illegible] KVA [illegible] KW
INITIAL CONFIGURATION ☐ REL ☒ CAP
FUTURE RATING KVA KW
FUTURE CONFIGURATION ☐ REL ☐ CAP
MODULE AC INPUT [illegible] VAC 3Ø [illegible] HZ
OUTPUT/BYPASS [illegible] VAC 3Ø [illegible] HZ

BATTERY [illegible] KV
STRINGS QTY/STRING CELL TYPE
[illegible] DEV (PL) [illegible] (EQ) [illegible]
▲ – REQUIRED FOR SYSTEM TEST TOGETHER
● – COMPLETED BY SPECIAL PROD MFG.
(A) – ACTUAL COMPLETION DATE ● – DROP SHIP TO SITE

TECH REV	ITEM	DESCRIPTION	QTY	PART NO	CUSTOMER DRAWING NOS.	PARTIAL PARTS REL.	FINAL PARTS REL.	MFG RELEASE	COMPLETE PROD	COMPLETE TEST	SPECIAL TEST	SHIP
A	1 a	[illegible]	1	[illegible]-B7145		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
	1 b	[illegible]	[illegible]	[illegible]								
	1 c	[illegible]	[illegible]	[illegible]								
A	1 c	Maint Bypass [illegible] Ass'y	[illegible]	SK-B7145-[illegible]								
	1 d											
	2	Input Filter	1	[illegible]		8/4/83	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
A	[illegible]	Input & Maint Bypass Cabinet (same as RL [illegible])	1	[illegible]-B7196			[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
	[illegible]	Static Disc Switch	1	145910012								[illegible]
	[illegible]	600 Amp Fuses	2	128 [illegible]								
A	[illegible]	Bat. Test Kit (same as [illegible])	1	RLB7908-10			[illegible]					[illegible]
A	[illegible]	Witness Test	1	ET-665							[illegible]	
A	7	Manuals	[illegible]	RLB7902 HDBK [illegible]				[illegible]				[illegible]
A	8	Battery	188	[illegible]-3555								[illegible]
A	9	[illegible]	8	80440								[illegible]
		FRT - UPS										
		FRT - BATT										
		PPA										
		TAXES										
		START UP										

RL

Appendix F.

Allotted Test Times

		Hrs.
30 - 100 kw	3000 Series	30
180 - 450 kw	3000 Series	40
600 kw	3000 Series	50
80 kw 415Hz	4000 Series	35
15 - 45 kw	2000 Series	15
30 UPS 50Hz	5000 Series	50
Standard Factory Witness Test		8
Custom Content		25
Multimodule, Swg		90
Voltage Change Retest		8

Appendix G. Monthly Sales Plan

ACK	MODEL	CUSTOMER	SYS#	BL NO.	UNSCH'S	WEEK #1	WEEK #2	WEEK #3	WEEK #4	WEEK #5	TOTAL	COMMENTS	NO ORDER	DRAWING APPROVAL	CREDIT APPROVAL	LETTER OF CREDIT	SHIPPING PAPERS	WITNESS TEST
	3180		110	85428				67.5			67.5							
	3990		936	87722	80.9									X				X
	4080		1011		35.0								X					
	4080		1012		35.0								X					
MI 10-20	3100		1021		50.0								X					
	3180		1023	87914	75.8										X			
	4080		1106		35.0								X					
	4080		1107		35.0								X					
	4080		1108		35.0								X					
	4080		1109		35.0								X					
	3060		1112	87444			47.0				47.0							
	3160		1113	87334			50.1				50.1							
	3100		1114	87891	54.4										X			
	3100		1115	87106				48.2			48.2							
	3060		1016	[illegible]			42.0				42.0							
	3100		1116	87106				48.2			48.2							
	3100		1117		50.0								X					
	3180		1117		61.0								X					

Appendix H. Systems Test Manager's Plan for Test

SYS. NO.	QTY.	SUPV.	CUSTOMER	RL#	kW	VOLT.	CHARGE NUMBER	TO TEST PLANNED	TO TEST ACTUAL	OUT OF TEST PLANNED	OUT OF TEST ACTUAL	SHIP DATE	W.T.	SPECIAL FEATURES
414	P				80	4/2		6/13	6/13	6/21	6/28		(NO CON)	MKTINU-VOLT CHG
130	P				80	4/2		STOCK	6/13	⊥	⊥			" " " "
131	P				80	4/2		STOCK	6/13				⊥	" " " "
717				85911	250	4/4		[illegible]		6/3				
107				85273	180	4/4		5/31		6/10	6/16		√ 6/13	72 HR BURN-IN
173				"	180	4/4		5/31		6/10	6/16		√ 6/13	↓
116				"	180	4/4		5/31		6/10	6/16		√ 6/13	
102				84918	100	4/2		6/3	6/3	6/9	6/14		√ 6/13	
111	Benson			85733	100	4/2		6/[illegible]	6/10	6/17	6/15			
227	[illegible]				100	4/2		5/31		6/9	6/9			
175	[illegible]			85413	30	4/2		6/9	6/16	6/15	6/20			1½ WORK [illegible]
224	[illegible]			85730	100	4/4		6/9	6/16	6/17	6/21			
394	[illegible]			85645	330	4/2		[illegible]	6/9	6/[illegible]	6/16			MKT INV-VOLT CHG
760				85628	30	4/4		6/15	6/17	6/22				72 HR BURN-IN
761				85639	30	4/4		[illegible]	⊥	6/22	6/28			" " " "
762				85700	30	4/4		6/16		6/22	⊥			" " " "
759	[illegible]			85708	60	4/4		6/16	6/16	6/17				
763	[illegible]			85721	250	4/4		6/20	6/20	[illegible]	6/29			
294	[illegible]			84186	600	4/4				6/16	6/23		√ 6/15	12 HR [illegible]
295				"	600	4/4				6/16			√	
306	[illegible]			"	600	4/4				6/16	⊥		√ ⊥	⊥
275				85355	30	2/2		N/A		N/A			√ N/A	CONST [illegible]
276				85356	30	2/2							√	UNIT TESTING
277				85353	30	2/2							√	
278				85354	30	2/2		⊥		⊥			√ ⊥	⊥
200	[illegible]			84502	330	4/4				6/17	6/22		√√ 6/22	
202				"	330	4/4				6/17			√√	
203				"	330	4/4				6/17	⊥		√√ ⊥	
411				85308	450	4/4		6/7 [illegible]	6/3	6/15 6/9	6/10	6/10 →	√ 6/16	2 MKT INV-[illegible]
412				"	450	4/4		6/7 6/3	6/3	6/15	6/10		√ 6/16	3 FROM PARATOR
718				86102	250	4/2				TC 6/12	[illegible]		√ 6/6	
712				85453	60	4/2		6/[illegible]	6/23	6/27	6/29			
713				"	60	4/2		6/[illegible]	6/23	6/27	6/29			
730	[illegible]			85647	30	2/2		6/16	6/17	6/19	6/27		√ 6/19	
731	[illegible]			"	30	2/2		6/16	6/20	6/19	6/27		√ 6/19	

Appendix I. Ups Production Plan

SYSTEM #	D/I	CUSTOMER NAME	RL #	MODEL / VOLT	COMPLETE KIT			COMPLETE STD. MFG.			COMPLETE CUST. MFG.			COMPLETE TEST			WIT TEST	COMPLETE SHIP			RMP	SPARE	SMC	SWGR	FILTER	COMMENTS
					ORG	CUR	ACT	ORG	CUR	ACT	ORG	CUR	ACT	ORG	CUR	ACT	CUR	ORG	CUR	ACT						
170	I			5025 / 3/3	1/13			12/31	2/22	2/27				1/5	3/2	3/6		1/13	2/10							
171	I			5025 / 3/3	12/22			1/5	2/24	2/28				1/20	3/2	3/5		1/27	2/10							
176	D			4080 / 4/2	12/8			12/15	2/24	2/22				12/22	3/10			1/6	2/10							
177	I			4080 / 4/2	12/8			12/15	2/24	2/23				12/22	3/10			1/6	2/10							
178	D			4080 / 4/2	12/22			1/5	2/8	2/11				1/12	3/17			1/20	2/10							completed manuf. 2/11/84 (RF Test)
179	D			4080 / 4/2	12/22			1/5	2/24	2/29				1/12	3/17			1/20	2/10							
198	D			3600 / 4/4	12/19			1/9	2/24	2/27				1/18	3/6	3/5		1/27	2/10							
204	I			5060 / 3/3	1/10			1/18	2/22	2/27				1/26	3/8	3/5		2/3	2/17							
208	D			4080 / 4/2	1/12			1/19	2/15	2/20				1/26	3/17			2/3	2/10							completed manuf. 2/20/84 (RF Test)
209	D			4080 / 4/2	1/12			1/19	2/22	2/24				1/26	3/17			2/3	2/10							
212	D		88371	3660 / 2/2	1/12			1/19	3/5		2/5			1/26	3/12			2/3								

Appendix J.

Test Station Efficiencies

PRODUCT	TEST STATION 1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	1	0	0	2	0	0	0	[illegible]	0	0	0	0
2	1	0	0	0	0	2	0	0	0	[illegible]	0	0	0	0
3	1	1	1	2	3	4	0	0	0	[illegible]	0	0	0	0
4	1	1	1	2	0	3	0	0	0	[illegible]	0	0	0	0
5	2	0	0	0	1	3	0	0	0	[illegible]	0	0	0	0
6	1	1	1	0	0	0	0	0	0	[illegible]	0	0	0	0
7	1	0	0	0	0	2	0	0	0	[illegible]	0	0	0	0
8	1	1	1	2	2	3	0	0	0	[illegible]	0	0	0	0
9	1	1	1	2	2	3	0	0	0	[illegible]	0	0	0	0
10	3	0	0	0	1	2	0	0	0	[illegible]	0	0	0	0
11	0	0	0	6	7	2	3	4	5	[illegible]	0	8	9	1
12	0	0	0	0	0	1	2	0	0	[illegible]	3	0	0	0
13	0	0	0	10	10	9	4	5	6	[illegible]	8	3	2	1
14	0	0	0	2	2	1	1	0	0	[illegible]	0	0	0	0
15	0	0	0	2	2	1	1	0	0	[illegible]	0	0	0	0
16	0	0	0	0	2	1	1	0	0	[illegible]	0	0	0	0
17	0	0	0	4	4	1	1	2	2	[illegible]	0	0	0	3
18	0	0	0	4	4	1	1	2	2	[illegible]	0	0	0	3
19	0	0	0	4	4	1	1	2	2	[illegible]	6	3	5	7
20	0	0	0	0	5	3	1	2	2	[illegible]	0	0	0	4
21	0	0	0	0	5	3	1	2	2	[illegible]	0	0	0	4
22	0	0	0	0	6	1	1	1	1	[illegible]	5	2	2	3
23	0	0	0	0	0	5	4	1	1	[illegible]	0	0	3	2
24	0	0	0	0	0	5	4	1	1	[illegible]	0	0	3	2
25	0	0	0	0	0	3	3	1	1	[illegible]	0	0	2	4
26	0	0	0	0	0	0	0	1	1	[illegible]	0	0	0	2
27	0	0	0	0	0	0	0	1	1	[illegible]	0	0	0	2
28	0	0	0	0	0	3	3	1	1	[illegible]	0	2	2	4
29	0	0	0	0	0	0	0	1	1	[illegible]	0	0	0	1
30	0	0	0	0	0	0	0	1	1	[illegible]	0	0	0	1
31	0	0	0	0	0	0	0	1	1	[illegible]	0	1	1	2
32	0	0	0	0	0	0	0	2	2	[illegible]	0	1	1	3
33	3	1	1	0	2	0	0	0	0	[illegible]	4	0	0	0
34	3	1	1	0	2	0	0	0	0	[illegible]	4	0	0	0
35	2	0	0	0	0	0	0	0	0	[illegible]	1	0	0	0
36	3	1	1	0	2	0	0	0	0	[illegible]	4	0	0	0
37	3	1	1	0	2	0	0	0	0	[illegible]	4	0	0	0
38	2	0	0	2	0	0	0	0	0	[illegible]	1	0	0	0
39	1	1	1	0	2	0	0	0	0	[illegible]	0	0	0	0
40	1	1	1	0	2	0	0	0	0	[illegible]	0	0	0	0

41	*	3	0	0	1	0	0	0	0	0	*	0	0	0	0
42	*	1	0	0	0	0	0	0	0	0	*	0	0	0	0
43	*	1	0	0	0	0	0	0	0	0	*	0	0	0	0
44	*	1	0	0	0	0	0	0	0	0	*	0	0	0	0
45	*	1	1	1	0	0	0	0	0	0	*	0	0	0	0
46	*	1	1	1	0	2	0	0	0	0	*	0	0	0	0
47	*	1	1	1	0	2	0	0	0	0	*	0	0	0	0
48	*	1	1	1	0	2	0	0	0	0	*	0	0	0	0
49	*	0	0	0	2	2	0	0	0	0	*	0	0	0	0
50	*	0	0	0	2	2	0	0	0	0	*	0	0	0	0
51	*	0	0	0	0	0	0	0	0	0	*	0	3	2	1
52	*	0	0	0	0	0	0	0	0	0	*	0	1	1	2
53	*	1	1	1	0	0	2	2	0	0	*	0	0	0	0
54	*	0	0	0	0	0	1	1	0	0	*	0	0	0	0
55	*	0	0	0	0	0	1	1	2	2	*	0	0	0	0
56	*	1	0	0	0	0	0	0	0	0	*	2	0	0	0
57	*	1	0	0	0	0	0	0	0	0	*	2	0	0	0
58	*	0	0	0	0	0	1	1	0	0	*	0	0	0	0
59	*	1	0	0	0	0	0	0	0	0	*	2	0	0	0
60	*	0	1	1	2	2	0	0	0	0	*	3	0	0	0
61	*	1	0	0	0	0	0	0	0	0	*	2	0	0	0
62	*	0	0	0	0	1	0	0	0	0	*	0	0	0	0
63	*	0	0	0	0	0	3	1	2	2	*	0	0	0	4
64	*	1	1	1	0	0	2	2	0	0	*	0	0	0	0
65	*	1	1	1	0	0	0	0	0	0	*	0	0	0	0
66	*	1	0	0	0	0	0	0	0	0	*	2	0	0	0
67	*	0	0	0	0	0	2	2	1	1	*	0	0	0	0
68	*	1	1	1	0	0	0	0	0	0	*	0	0	0	0
69	*	0	0	0	0	0	0	0	0	0	*	0	1	1	2
70	*	0	0	0	0	0	0	0	0	0	*	0	1	1	2
71	*	0	0	0	0	0	0	0	0	0	*	0	1	1	2
72	*	0	0	0	0	0	0	0	0	0	*	0	0	0	1

Appendix K.

<u>Testor Qualifications</u>

TESTOR

SERIES	1	2	3	4	5	6	7	8	9	10
2	1	0	0	0	0	1	0	1	1	0
3	1	1	1	1	1	1	1	0	0	1
4	1	1	1	1	1	1	0	0	0	1
5	1	1	1	1	1	1	1	0	0	1

TESTOR

SERIES	11	12	13	14	15	16	17	18	19	20
2	0	1	0	0	0	1	1	1	1	1
3	1	0	1	1	1	0	0	0	0	0
4	1	0	1	1	1	0	0	0	0	0
5	1	0	1	1	1	0	0	0	0	0

Appendix L.

Sequential Simulation Program Listing

```
PROGRAM        (INPUT,OUTPUT);

(*PURPOSE:  TO SCHEDULE MULTIPRODUCTS IN AN UPS TEST FACILITY WITH REGARD*)
(*TO LIMITED AVAILABILITY OF RESOURCES.                                  *)
(*                                                                       *)
(*PROGRAMMER:  CHARLES J. VENABLE                                        *)
(*                                                                       *)
(*INPUT:  INPUT IS DIVIDED INTO THE FOLLOWING FOUR SECTIONS:            *)
(*                                                                       *)
(*             1.  TEST STATION EFFICIENCY DATA                          *)
(*             2.  SERIES VERSUS TESTOR QUALIFICATIONS                   *)
(*             3.  PRODUCTS SCHEDULED TO BE TESTED                       *)
(*             4.  PARRALLEL SYSTEM COMPONENT ARRAY                      *)
(*                                                                       *)
(*   THE FIRST OF THESE, TEST STATION EFFICIENCY DATA, REPRESENTS THE    *)
(*COMPATIBILITY AND PREFERENCE RATING FOR THE TEST STATION AND THE       *)
(*SPECIFIC PRODUCT TYPE.  A ZERO REPRESENTS A NONCOMPATIBLE SITUATION AND*)
(*THE NUMBERS 1 TO 10 ARE USED TO INDICATE PREFERENCE/EFFICIENCY FOR THE *)
(*TEST STATION AND THE SPECIFIC PRODUCT TYPE.  THE NUMBER 1 IS THE MOST  *)
(*PREFERED/HIGHEST EFFICIENCY AND THE NUMBER 10 IS THE LEAST PREFERED/   *)
(*LOWEST EFFICIENCY.  THE FORMAT OF THIS DATA IS AS FOLLOWS:            *)
(*                                                                       *)
(*             ADMINISTRATIVE LINE                                       *)
(*             E11  E12 . . . E1B                                        *)
(*             E21            E2B                                        *)
(*              .              .                                         *)
(*              .              .                                         *)
(*              .              .                                         *)
(*             EU1  EU2 . . . EUB                                        *)
(*                                                                       *)
(*WHERE EIJ IS THE EFFICIENCY RATING FOR PRODUCT I IN TEST STATION J,   *)
(*B IS THE NUMBER OF THE TEST STATIONS, AND U IS THE NUMBER OF PRODUCT  *)
(*TYPES.                                                                 *)
(*                                                                       *)
(*   THE SECOND IS SERIES VERSUS TESTOR QUALIFICATIONS.  THIS IS A 0,1   *)
(*MATRIX WITH 0 INDICATING THAT THE TESTOR IS UNQUALIFIED TO TEST THE    *)
(*SPECIFIC PRODUCT LINE AND 1 INDICATING THAT THE TESTOR IS QUALIFIED.   *)
(*THE DATA FOLLOWS THAT OF EFFICIENCY IN THE FOLLOWING FORMAT:          *)
(*                                                                       *)
(*             ADMINISTRATIVE LINE                                       *)
(*             Q21  Q22 . . . Q2W                                        *)
(*             Q31            Q3W                                        *)
(*              .              .                                         *)
(*              .              .                                         *)
(*              .              .                                         *)
(*             Q51  Q52 . . . Q5W                                        *)
(*                                                                       *)
(*WHERE QIJ IS THE QUALIFICATION RATING FOR SERIES I AND TESTOR J AND   *)
(*W IS THE TOTAL NUMBER OF TESTORS.                                      *)
(*                                                                       *)
(*   THE THIRD SECTION, PRODUCTS TO BE TESTED, CONSISTS OF AN ARRAY OF   *)
(*ALL PERTINENT DATA FOR EACH PRODUCT SCHEDULED TO BE TESTED IN THE      *)
(*PLANNING HORIZON.  IT CONSISTS OF 13 COLUMNS ORGANIZED IN THE FOLLOWING*)
(*FORMAT:                                                                *)
(*                                                                       *)
(*             COLUMN     DESCRIPTION                                    *)
(*                 1.     ADMINISTRATION NUMBER.  THIS IS A SEQUENTIAL NUMBER *)
(*                        FROM 1 TO N, WHERE N = NUMBER OF PRODUCTS TO BE *)
(*                        TESTED IN THE HORIZON.                         *)
(*                 2.     SYSTEM NUMBER                                  *)
(*                 3.     SERIES                                         *)
(*                 4.     INPUT VOLTAGE                                  *)
(*                 5.     KW                                             *)
(*                 6.     OUTPUT VOLTAGE                                 *)
(*                 7.     HERTZ RATING                                   *)
(*                 8.     PRODUCT TYPE NUMBER                            *)
(*                 9.     PARALLEL SYSTEM INDICATOR.  IF = 0 THEN PRODUCT IS *)
(*                        NOT PART OF A PARALLEL SYSTEM.  OTHERWISE, THE *)
(*                        ADMINISTRATION NUMBER OF THE PARALLEL UNIT IS ENTERED.*)
(*                        FOR EXAMPLE, IF THE PRODUCT IS A PART OF PARALLEL *)
(*                        SYSTEM 2 A 2 IS ENTERED.                       *)
(*                10.     COMPONENT NUMBER.  IF = 0 THEN NOT A PARALLEL SYSTEM *)
(*                        COMPONENT.  OTHERWISE, THE COMPONENT NUMBER IS *)
(*                        ENTERED.  FOR EXAMPLE, IF THE PRODUCT IS THE SECOND *)
(*                        COMPONENT OF A PARALLEL SYSTEM THEN 2 IS ENTERED. *)
(*                11.     NUMBER OF REQUIRED TEST HOURS                  *)
(*                12.     CURRENT SCHEDULED ARRIVAL DATE.  THIS DATE IS GIVEN *)
(*                        IN NUMBER OF WORK DAYS FROM START OF PLANNING  *)
(*                        HORIZON.                                       *)
(*                13.     CURRENT DUE DATE.  THIS DATE IS GIVEN IN NUMBER OF *)
(*                        WORK DAYS FROM START OF PLANNING HORIZON.      *)
```

```
(*                                                                      *)
(*THIS MATRIX IS IN THE FOLLOWING FORMAT:                               *)
(*                                                                      *)
(*              ADMINISTATIVE LINE                                      *)
(*              P1,1  P1,2 . . . P1,13                                  *)
(*              P2,1             P2,13                                  *)
(*               .                 .                                    *)
(*               .                 .                                    *)
(*               .                 .                                    *)
(*              PN,1  PN,2 . . . PN,13                                  *)
(*                                                                      *)
(*WHERE PIJ IS DATA OF PRODUCT I IN COLUMN J, AND N IS THE NUMBER OF    *)
(*PRODUCTS TO BE TESTED IN THE PLANNING HORIZON.  PARALLEL PRODUCTS MUST*)
(*BE FIRST IN THE SEQUENCE WITH ARRIVAL TIME EQUAL TO ZERO.  ALL OTHER  *)
(*PRODUCTS MUST BE ORDERED BY ARRIVAL DATES, EARLIEST FIRST.            *)
(*                                                                      *)
(*   THE LAST SECTION OF INPUT CONCERNS THE PARALLEL SYSTEMS SCHEDULED  *)
(*TO BE TESTED.  THIS IS A 0,1 MATRIX.  IF = 0 THEN THIS COMPONENT IS   *)
(*PRESENT. IF = 1 THEN THE COMPONENT IS NOT PRESENT.  THE MAXIMUM       *)
(*NUMBER OF COMPONENTS FOR ONE SYSTEM IS FOUR.  THE COMPONENT ARRAY IS  *)
(*IN THE FOLLOWING FORMAT:                                              *)
(*                                                                      *)
(*              ADMINISTRATIVE LINE                                     *)
(*              C11  C12 . . . C14                                      *)
(*              C21            C24                                      *)
(*               .              .                                       *)
(*               .              .                                       *)
(*               .              .                                       *)
(*              CNPSYS1  . . . CNPSYS4                                  *)
(*                                                                      *)
(*WHERE CIJ IS THE 0,1 VARIABLE REPRESENTATION OF COMPONENT J OF        *)
(*PARALLEL SYSTEM I, AND NPSYS IS THE NUMBER OF PARALLEL SYSTEMS        *)
(*SCHEDULED TO BE TESTED IN THE HORIZON.  FOR EXAMPLE, THE LINE: 0 0 1 1*)
(*INDICATES THAT THE PARALLEL SYSTEM IS COMPOSED OF TWO COMPONENTS.     *)
(*                                                                      *)
(*OUTPUT:  THE FIRST THREE SECTIONS OF THE INPUT ARE ECHOED FOLLOWED BY *)
(*A LIST OF THE PRODUCTS WHICH WILL BE LATE OR EXCEED THE HORIZON.  THIS*)
(*IS FOLLOWED BY AN ASSIGNMENT SUMMARY IN THE FOLLOWING 7 COLUMNS OF    *)
(*DATA FOR EACH PRODUCT:                                                *)
(*                                                                      *)
(*              COLUMN     DESCRIPTION                                  *)
(*                 1.    ADMINISTRATIVE NUMBER                          *)
(*                 2.    SYSTEM NUMBER                                  *)
(*                 3.    TEST STATION ASSIGNMENT                        *)
(*                 4.    FIRST SHIFT TESTOR ASSIGNMENT                  *)
(*                 5.    SECOND SHIFT TESTOR ASSIGNMENT                 *)
(*                 6.    TESTING START TIME                             *)
(*                 7.    TESTING COMPLETION TIME                        *)
(*                                                                      *)
(*IT SHOULD BE NOTED THAT IF ALL ASSIGNMENT NUMBERS ARE ZERO THAT THE   *)
(*PRODUCT NEVER BEGAN TESTING IN THE HORIZON AND WILL NOT BE REFLECTED  *)
(*IN THE STATISTICS FOLLOWING THE ASSIGNMENT SUMMARY.                   *)
(*                                                                      *)
(*   THE FOLLOWING STATISTICS ARE NOW OUTPUTED:                         *)
(*                                                                      *)
(*                 1.    NUMBER OF LATE PRODUCTS                        *)
(*                 2.    MEAN LATENESS                                  *)
(*                 3.    PROPORTION OF JOBS TARDY                       *)
(*                 4.    MEAN JOB FLOW TIME                             *)
(*                                                                      *)
(*THIS IS FOLLOWED BY A STATEMENT SPECIFING WHICH DISPATCH RULE WAS     *)
(*USED.  IF DESIRED A COMPLETE SCHEDULE FOLLOWS BY DAY AND HOUR OF TEST *)
(*STATION AND TESTOR ASSIGNMENTS.                                       *)
(*                                                                      *)
(*ASSUMPTIONS:  ALL PRODUCTS ARE ASSUMED TO ARRIVE AT 1200HRS ON THE    *)
(*ARRIVAL DAY.  ALL PRODUCTS ARE ASSUMED DUE AT 1200HRS ON THE DUE DATE.*)
(*TEST STATIONS ARE ASSUMED EMPTY AT START OF HORIZON.  THIS CAN BE     *)
(*CHANGED, HOWEVER, BY INSERTING ASSIGNMENT STATEMENTS AFTER INITIAL-   *)
(*IZATION OF ASSIGNMENT MATRICES.  PRODUCTS ARE ASSIGNED TO SECOND SHIFT*)
(*ONLY IF THEY WILL BE LATE IF PROCESSED COMPLETELY ON FIRST SHIFT.     *)
(*FIRST SHIFT TESTOR ASSIGNMENT OCCURS IN CONJUNCTION WITH TEST STATION *)
(*ASSIGNMENT AND PRIOR TO SECOND SHIFT TESTOR ASSIGNMENT.               *)
(*                                                                      *)
(*LIMITATIONS:  THE ARRIVAL AND DUE DATES MUST BE INPUTED AS THE NUMBER *)
(*OF WORK DAYS UNTIL THE ACTUAL DATE.  THEREFORE, A DUE DATE MUST BE    *)
(*CHANGED IF, FOR INSTANCE, AN ADDITIONAL DAY IS ADDED TO THE WORK WEEK *)
(*PRIOR TO THE ACTUAL DUE DATE.  PRODUCTS WHICH ARE NOT ASSIGNED OR     *)
(*WORKED ON DURING THE PLANNING HORIZON ARE NOT A PART OF THE TERMINAL  *)
(*STATISTICS.                                                           *)
(*                                                                      *)
(*ERROR CHECKING AND RESPONSES:  IF A PRODUCT CAN NOT COMPLETE TESTING  *)
(*IN THE PLANNING HORIZON A STATEMENT TO THAT EFFECT IS PRINTED ALONG   *)
(*WITH THE MESSAGE THAT IT WILL BE LATE.                                *)
```

```
(*                                                                  *)
(*ALGORITHM/STRATEGY:                                               *)
(*                                                                  *)
(*        DO FOR T=1 TO T                                           *)
(*           IF PRODUCT ARRIVAL TIME=T THEN                         *)
(*              MOVE PRODUCT TO ASSIGNMENT QUEUE                    *)
(*           IF FIRST SHIFT HOUR THEN                               *)
(*              DO FOR EACH PRODUCT IN ASSIGNMENT QUEUE             *)
(*                 IF COMPATIBLE BAY AVAILABLE THEN                 *)
(*                    IF QUALIFIED TESTOR AVAILABLE THEN            *)
(*                       ASSIGN BAY WITH MAX EFFICIENCY             *)
(*                       ASSIGN FIRST SHIFT TESTOR                  *)
(*                 IF SECOND SHIFT REQUIRED                         *)
(*                    ASSIGN FIRST SHIFT TESTOR FOR REMAINDER       *)
(*                       OF SHIFT                                   *)
(*                    DECREMENT PROCESSING TIME                     *)
(*                    MOVE PRODUCT TO SECOND SHIFT TESTOR           *)
(*                       QUEUE                                      *)
(*                 ELSE                                             *)
(*                    ASSIGN FIRST SHIFT TESTOR UNTIL TESTING       *)
(*                       COMPLETE                                   *)
(*                    ASSIGN BAY UNTIL TESTING COMPLETE             *)
(*                    FREE BAY AND TESTOR FOR ASSIGNMENT AT         *)
(*                       COMPLETION TIME + 1                        *)
(*           ELSE                                                   *)
(*              DO FOR EACH PRODUCT IN SECOND SHIFT TESTOR          *)
(*                 QUEUE                                            *)
(*                 IF QUALIFIED TESTOR AVAILABLE THEN               *)
(*                    ASSIGN SECOND SHIFT TESTOR                    *)
(*                    ASSIGN FIRST AND SECOND SHIFT TESTORS         *)
(*                       UNTIL TESTING COMPLETE                     *)
(*                    ASSIGN BAY UNTIL TESTING COMPLETE             *)
(*                    FREE BAY AND TESTORS FOR ASSIGNMENT AT        *)
(*                       COMPLETION TIME + 1                        *)
(*                 ELSE                                             *)
(*                    ASSIGN BAY FOR T                              *)
(*                    IF LAST HOUR OF SECOND SHIFT THEN             *)
(*                       ASSIGN BAY AND FIRST SHIFT TESTOR FOR      *)
(*                          UPCOMING FIRST SHIFT                    *)
(*                       IF TESTING COMPLETE THEN                   *)
(*                          FREE BAY AND TESTORS AT COMPLETION      *)
(*                             TIME + 1                             *)
(*                       ELSE                                       *)
(*                          DECREMENT PROCESSING TIME               *)
(*                                                                  *)
(*$ C+,S 200000,X 0,P 0 *)
CONST
   N      =  107;  (*NUMBER OF MACHINES TO BE TESTED                 *)
   W1     =   15;  (*NUMBER OF TESTORS ON FIRST SHIFT                *)
   W2     =    7;  (*NUMBER OF TESTORS ON SECOND SHIFT               *)
   B      =   14;  (*NUMBER OF TEST STATIONS                         *)
   U      =   72;  (*NUMBER OF PRODUCT TYPES                         *)
   W      =   20;  (*NUMBER OF TOTAL TESTORS                         *)
   HOR    =    5;  (*PLANNING HORIZON IN WEEKS                       *)
   DAY    =   16;  (*NUMBER OF HOURS IN WORK DAY                     *)
   WK     =    5;  (*NUMBER OF DAYS IN WORK WEEK                     *)
   TIME   =  400;  (*NUMBER OF HOURS IN PLANNING HORIZON=HOR*DAY*WK  *)
   SHIFT  =    8;  (*NUMBER OF HOURS IN SHIFT                        *)
   NPSYS  =    4;  (*NUMBER OF PARALLEL SYSTEMS                      *)
   PRINT  =    0;  (*PRINTED SCHEDULE SPECIFIER:  IF = 1 PRINT       *)

TYPE
   QPOINTER = @SYSTEMNODE; (*QUEUE POINTER                           *)
   PROD = RECORD
      SERIES  : INTEGER;     (*SERIES                                *)
      VOLTIN  : INTEGER;     (*INPUT VOLTAGE                         *)
      KW      : INTEGER;     (*POWER SIZE                            *)
      VOLTOUT: INTEGER;      (*OUTPUT VOLTAGE                        *)
      HERTZ   : INTEGER;     (*HERTZ                                 *)
      PRODNUM: INTEGER       (*ADMIN NUMBER ASSIGNED TO PRODUCT TYPE *)
   END; (*PROD*)
```

```
    SYSTEM = RECORD
       ADMIN   : INTEGER;    (*SEQUENCE NUMBER                                  *)
       SYSNUM  : INTEGER;    (*SYSTEM NUMBER                                    *)
       SYS     : PROD;       (*UPS DESCRIPTION                                  *)
       PL      : INTEGER;    (*NUMBER OF PARALLEL SYSTEM TO WHICH THIS          *)
                             (*COMPONENT BELONGS                                *)
       COMP    : INTEGER;    (*NUMBER OF COMPONENT IN PARALLEL SYSTEM           *)
       TESTHR  : INTEGER;    (*NUMBER OF HOURS REQUIRED TO TEST UPS             *)
       CSCHS   : INTEGER;    (*CURRENT ARRIVAL DATE TO TEST                     *)
       DUEDT   : INTEGER;    (*CURRENT PROMISE DATE                             *)
       START   : INTEGER;    (*TIME PRODUCT FIRST ASSIGNED TO TEST STATION      *)
       FINISH  : INTEGER;    (*TIME TESTING COMPLETED ON PRODUCT                *)
       FLAGP   : INTEGER;    (*PARALLEL SYSTEM ALREADY IN BAY QUEUE IF = 1      *)
       FLAG2   : INTEGER;    (*PRODUCT ALREADY IN SECOND SHIFT QUEUE IF = 1     *)
       BAY     : INTEGER;    (*NUMBER OF ASSIGNED BAY                          *)
       T1      : INTEGER;    (*NUMBER OF ASSIGNED FIRST SHIFT TESTOR            *)
       T2      : INTEGER   (*NUMBER OF ASSIGNED SECOND SHIFT TESTOR            *)
    END; (*SYSTEM*)

    SYSTEMNODE = RECORD
       SYSINFO: SYSTEM;
       LINK   : QPOINTER
    END; (*SYSTEMNODE*)

    UPS = ARRAY@1..N@ OF SYSTEM; (*ARRAY OF PRODUCTS TO BE TESTED           *)

 VAR
    Q1HEAD,Q2HEAD,NEXT,P,Q,R,S : QPOINTER;
    E,I,J,K,L,M,X : INTEGER;
    PRODUCT : UPS;
    EFF      : ARRAY@1..U,1..B@ OF INTEGER; (*BAY EFFICIENCY                     *)
    QUAL     : ARRAY@2..5,1..W@ OF INTEGER; (*TESTOR QUALIFICATIONS              *)
    BASSIGN : ARRAY@1..B,0..TIME@ OF INTEGER; (*BAY ASSIGNMENT                  *)
    TASSIGN : ARRAY@1..W,0..TIME@ OF INTEGER; (*TESTOR ASSIGNMENT               *)
    T        : INTEGER; (*TIME                                                   *)
    FLAG     : INTEGER; (*CHECK FLAG: IF = 1 VIOLATION                           *)
    TESTOR1 : INTEGER; (*FIRST SHIFT TESTOR NUMBER                              *)
    TESTOR2 : INTEGER; (*SECOND SHIFT TESTOR NUMBER                             *)
    MAX      : INTEGER; (*MAXIMUM NUMBER IN SEARCH                               *)
    TEST1,TEST2 : INTEGER; (*TESTOR ASSIGNMENT FLAG: IF = 1 TESTOR ASSIGNED *)
    PCOMP    : ARRAY@1..NPSYS,1..4@ OF INTEGER; (*PARALLEL SYS COMPONENT ARRAY*)
    LATE     : INTEGER; (*NUMBER OF LATE PRODUCTS                                *)
    LATENESS: INTEGER; (*TOTAL NUMBER OF LATE PERIODS                            *)
    FLOW     : INTEGER; (*AMOUNT OF TIME IN SYSTEM                               *)

 PROCEDURE QCREATE (VAR QHEAD:QPOINTER);
 (*PURPOSE:  CREATES A QUEUE WITH QHEAD POINTING TO THE FIRST (DUMMY) ELEMENT*)

 BEGIN
 NEW(QHEAD);
 WITH QHEAD@, SYSINFO DO
    BEGIN
    ADMIN := 0;
    SYSNUM := 0;
    SYS.SERIES := 0;
    SYS.VOLTIN := 0;
    SYS.KW := 0;
    SYS.VOLTOUT := 0;
    SYS.HERTZ := 0;
    SYS.PRODNUM := 0;
    PL := 0;
    COMP := 0;
    TESTHR := 0;
    CSCHS := 0;
    DUEDT := 0;
    START := 0;
    FINISH := 0;
    FLAGP := 0;
    FLAG2 := 0;
    BAY := 0;
    T1 := 0;
    T2 := 0;
    LINK := NIL
    END
 END; (*QCREATE*)

 PROCEDURE CREATENODE (I:INTEGER; VAR NEXT:QPOINTER);
 (*PURPOSE:  ALLOCATES A NEW NODE FOR STORAGE OF THE NEXT PRODUCT IN THE QUEUE*)

 BEGIN
 NEW(NEXT);
 NEXT@.SYSINFO := PRODUCT@I@;
 NEXT@.LINK := NIL
 END; (*CREATENODE*)
```

```
PROCEDURE CHECK (J,T:INTEGER; G:@POINTER; VAR FLAG:INTEGER);
(*PURPOSE:  CHECKS TO SEE IF BAY CONSTRAINTS ARE VIOLATED BY POSSIBLE ASSIGN- *)
(*MENT                                                                        *)

VAR
   K,I : INTEGER;

BEGIN
IF (J=4) OR (J=5) THEN
   BEGIN
   (*50HZ UNITS NOT ALLOWED IN B1 OR B2*)
   IF G@.SYSINFO.SYS.HERTZ = 50 THEN
      FLAG := 1;
   (*IF 250KW UNIT IN B1 OR B2, MAX SIZE IN OTHER IS 60KW*)
   IF G@.SYSINFO.SYS.KW = 250 THEN
      BEGIN
      IF BASSIGN@4,T@ <> 0 THEN
         IF PRODUCT@BASSIGN@4,T@@.SYS.KW > 60 THEN
            FLAG := 1;
      IF BASSIGN@5,T@ <> 0 THEN
         IF PRODUCT@BASSIGN@5,T@@.SYS.KW > 60 THEN
            FLAG := 1
      END;
   IF G@.SYSINFO.SYS.KW = 60 THEN
      BEGIN
      IF BASSIGN@4,T@ <> 0 THEN
         IF PRODUCT@BASSIGN@4,T@@.SYS.KW > 250 THEN
            FLAG := 1;
      IF BASSIGN@5,T@ <> 0 THEN
         IF PRODUCT@BASSIGN@5,T@@.SYS.KW > 250 THEN
            FLAG := 1
      END
   END;

IF (J=6) OR (J=7) THEN
   BEGIN
   (*C+D<=330KW*)
   IF BASSIGN@6,T@ <> 0 THEN
      IF (PRODUCT@BASSIGN@6,T@@.SYS.KW + G@.SYSINFO.SYS.KW) > 330 THEN
         FLAG := 1;
   IF BASSIGN@7,T@ <> 0 THEN
      IF (PRODUCT@BASSIGN@7,T@@.SYS.KW + G@.SYSINFO.SYS.KW) > 330 THEN
         FLAG := 1
   END;

IF (J=8) OR (J=9) THEN
   BEGIN
   IF BASSIGN@8,T@ <> 0 THEN
      BEGIN
      (*E+F<=600KW*)
      IF (PRODUCT@BASSIGN@8,T@@.SYS.KW + G@.SYSINFO.SYS.KW) > 600 THEN
         FLAG := 1;
      (*E+F<=1(50HZ)*)
      IF PRODUCT@BASSIGN@8,T@@.SYS.HERTZ = 50 THEN
         IF G@.SYSINFO.SYS.HERTZ = 50 THEN
            FLAG := 1;
      (*E+F<=1(208OUT)*)
      IF PRODUCT@BASSIGN@8,T@@.SYS.VOLTOUT = 208 THEN
         IF G@.SYSINFO.SYS.VOLTOUT = 208 THEN
            FLAG := 1
      END
   END;

IF (J=10) OR (J=11) THEN
   BEGIN
   IF BASSIGN@10,T@ <> 0 THEN
      BEGIN
      (*G1+G2<=250KW*)
      IF (PRODUCT@BASSIGN@10,T@@.SYS.KW + G@.SYSINFO.SYS.KW) > 250 THEN
         FLAG := 1;
      (*G1+G2<=1(50HZ)*)
      IF PRODUCT@BASSIGN@10,T@@.SYS.HERTZ = 50 THEN
         IF G@.SYSINFO.SYS.HERTZ = 50 THEN
            FLAG := 1
      END;
   IF BASSIGN@11,T@ <> 0 THEN
      BEGIN
      IF (PRODUCT@BASSIGN@11,T@@.SYS.KW + G@.SYSINFO.SYS.KW) > 250 THEN
         FLAG := 1;
      IF PRODUCT@BASSIGN@11,T@@.SYS.HERTZ = 50 THEN
         IF G@.SYSINFO.SYS.HERTZ = 50 THEN
            FLAG := 1
      END
   END
END; (*CHECK*)
```

```
PROCEDURE QINSERT (NEXT,QHEAD:QPOINTER);
(*PURPOSE:  INSERT PRODUCT IN QUEUE WITH DESIRED DISPATCH RULE. CODE    *)
(*REQUIRES ALTERATION IF OTHER THAN PRESENT DISPATCH RULE, EARLIEST DUE*)
(*DATE WITH TIES BROKEN BY GREATEST KW, IS DESIRED.                     *)
(*INSERT PRODUCT IN LIST WITH EARLIEST DUE DATE FIRST*)

VAR
   A,B,C :QPOINTER;
   I,K,L,M : INTEGER;

PROCEDURE INSERTNODE (NEXT.QPOINTER; VAR D:QPOINTER; E:QPOINTER);

   BEGIN
   D@.LINK := NEXT;
   NEXT@.LINK := E
   END; (*INSERTNODE*)

BEGIN
(*SEARCH FOR CORRECT POSITION*)
B := QHEAD;
WHILE (NEXT@.SYSINFO.DUEDT > B@.SYSINFO.DUEDT) AND (B@.LINK <> NIL) DO
   BEGIN
   A := B@.LINK;
   C := B;
   B := C@.LINK;
   A := B@.LINK
   END; (*WHILE*)

(*INSERT PRODUCT IN PROPER POSITION*)
IF NEXT@.SYSINFO.DUEDT=B@.SYSINFO.DUEDT THEN
   BEGIN
   IF NEXT@.SYSINFO.SYS.KW > B@.SYSINFO.SYS.KW THEN
      (*INSERT BEFORE B*)
      INSERTNODE(NEXT,C,B)
   ELSE IF NEXT@.SYSINFO.SYS.KW = B@.SYSINFO.SYS.KW THEN
      BEGIN
      I := NEXT@.SYSINFO.DUEDT;
      J := B@.SYSINFO.DUEDT;
      L := NEXT@.SYSINFO.SYS.KW;
      M := B@.SYSINFO.SYS.KW;
      WHILE (L=M) AND (I=J) AND (B@.LINK <> NIL) DO
         BEGIN
         A := B@.LINK;
         C := B;
         B := C@.LINK;
         A := B@.LINK;
         J := B@.SYSINFO.DUEDT;
         M := B@.SYSINFO.SYS.KW
         END; (*WHILE*)
      IF (I<>J) OR (L<>M) THEN
         (*INSERT NODE BEFORE B*)
         INSERTNODE(NEXT,C,B)
      ELSE
         (*ATTACH AT END OF QUEUE*)
         INSERTNODE(NEXT,B,NIL)
      END (*ELSE IF*)
   ELSE
      (*INSERT AFTER B*)
      INSERTNODE(NEXT,B,A)
   END
ELSE IF NEXT@.SYSINFO.DUEDT < B@.SYSINFO.DUEDT THEN
   (*INSERT NODE BETWEEN C ANDB*)
   INSERTNODE(NEXT,C,B)
ELSE
   (*ATTACH TO END OF QUEUE*)
   INSERTNODE(NEXT,B,NIL)
END; (*QINSERT*)
```

```
BEGIN (*EXIDE*)
(*READ BAY EFFICIENCY DATA*)
WRITELN;
WRITELN ('PRODUCT VERSUS TEST STATION EFFICIENCY:');
WRITELN;
WRITELN ('TEST STATION':35);
WRITE ('          *');
FOR I := 1 TO B DO
    WRITE (I:3);
WRITELN;
WRITELN ('PRODUCT*********************************************');
READLN;
FOR I := 1 TO U DO
    BEGIN
    WRITE (I:4,'    *');
    FOR J := 1 TO B DO
        BEGIN
        READ (INPUT,EFF[I,J]);
        WRITE (EFF[I,J]:3)
        END;
    READLN;
    WRITELN
    END;
READLN;

(*READ TESTOR QUALIFICATIONS*)
WRITELN;
WRITELN ('SERIES VERSUS TESTOR QUALIFICATIONS:');
WRITELN;
WRITELN ('TESTOR':40);
WRITE ('         *');
FOR I := 1 TO W DO
    WRITE (I:3);
WRITELN;
WRITE ('SERIES');
FOR I := 1 TO 67 DO
    WRITE ('*');
WRITELN;
FOR I := 2 TO 5 DO
    BEGIN
    WRITE (I:4,'   *');
    FOR J := 1 TO W DO
        BEGIN
        READ (INPUT,QUAL[I,J]);
        WRITE (QUAL[I,J]:3)
        END;
    READLN;
    WRITELN
    END;
READLN;

(*INITIALIZE ASSIGNMENT MATRICES TO EMPTY*)
(*INSERT READ STATEMENTS HERE IF STATIONS ARE NOT EMPTY AT TIME ZERO*)
FOR I := 1 TO B DO
    FOR J := 0 TO TIME DO
        BASSIGN[I,J] := 0;

FOR I := 1 TO W DO
    FOR J := 0 TO TIME DO
        TASSIGN[I,J] := 0;

(*READ INPUT DATA*)
WRITELN;
WRITELN ('THE FOLLOWING ARE THE PRODUCTS SCHEDULED TO BE TESTED:');
WRITELN;
WRITE (' ADMIN  SYSNUM  SERIES  VOLTIN     KW   VOLTOUT  HERTZ  PRODNUM');
WRITELN ('    PL      COMP  TESTHR    CSCHS   DUEDT');
```

```
FOR I := 1 TO N DO
   BEGIN
   WITH PRODUCT@I@ DO
      BEGIN
      READ (INPUT,ADMIN,SYSNUM,SYS.SERIES,SYS.VOLTIN,SYS.KW);
      READ (INPUT,SYS.VOLTOUT,SYS.HERTZ,SYS.PRODNUM,PL,COMP,TESTHR,CSCHS);
      READ (INPUT,DUEDT);
      READLN;
      START  := 0;
      FINISH := 0;
      FLAGP  := 0;
      FLAG2  := 0;
      BAY    := 0;
      T1     := 0;
      T2     := 0;
      WRITE (ADMIN:4,SYSNUM:9,SYS.SERIES:7,SYS.VOLTIN:9,SYS.KW:8);
      WRITE (SYS.VOLTOUT:8, SYS.HERTZ:8,SYS.PRODNUM:8,PL:8,COMP:8,TESTHR:7);
      WRITELN (CSCHS:9,DUEDT:8)
      END
   END;

READLN;
(*READ PARALLEL SYSTEM COMPONENT ARRAY*)
FOR I := 1 TO NPSYS DO
   BEGIN
   FOR J := 1 TO 4 DO
      READ (INPUT,PCOMP@I,J@);
   READLN
   END;

WRITELN;
(*INITIALIZE QUEUES*)
QCREATE(Q1HEAD);
QCREATE(Q2HEAD);
(*INITIALIZE ACCUMULATORS*)
LATE := 0;
LATENESS := 0;
FLOW := 0;

(*SINCE TEST BAYS ASSUMED EMPTY AT START,TIME INITIALIZED AT 1200 HOURS*)
(*FIRST DAY*)
T := 3;
E := NPSYS + 1;
(*THE FOLLOWING FOR LOOP IS USED IF ALL PRODUCTS ARRIVE ON THE SAME DAY*)
(*AND SHOULD BE USED IN PLACE OF THE PREVIOUS ASSIGNMENT STATEMENT:     *)
(*                                                                       *)
(*          FOR I := (NPSYS+1) TO N DO                                   *)
(*             BEGIN                                                     *)
(*             CREATENODE(I,NEXT)                                        *)
(*             QINSERT(NEXT,Q1HEAD)                                      *)
(*             END                                                       *)
(*                                                                       *)
(*ADDITIONALLY, THE FOLLOWING STATEMENTS WHICH APPEAR AFTER THE BEGIN   *)
(*OF THE TIME LOOP SHOULD BE DELETED:                                    *)
(*                                                                       *)
(*           FLAG := 0                                                   *)
(*           WHILE (FLAG=0) AND (I<=N) DO                                *)
(*              BEGIN                                                    *)
(*              IF P(PRODUCT@I@.CSCHS-1)*DAY+3) = T THEN                  *)
(*                 BEGIN                                                 *)
(*                 CREATENODE(I,NEXT)                                    *)
(*                 QINSERT(NEXT,Q1HEAD)                                  *)
(*                 I := I+1                                              *)
(*                 END                                                   *)
(*              ELSE                                                     *)
(*                 FLAG := 1                                             *)
(*              END                                                      *)
WHILE T <= TIME DO
   (*RUN TIME LOOP UNTIL END OF PLANNING HORIZON*)
   BEGIN
   FLAG := 0;
   WHILE (FLAG=0) AND (E<=N) DO
      BEGIN
      IF ((PRODUCT@E@.CSCHS-1)*DAY+3) = T THEN
         BEGIN
         CREATENODE(E,NEXT);
         QINSERT(NEXT,Q1HEAD);
         E := E+1
         END
      ELSE
         FLAG := 1
      END;
```

```
(*DETERMINE IF FIRST SHIFT HOUR: IF SO RUN ASSIGNMENT QUEUE*)
IF (NOT ODD(T DIV SHIFT)) OR (T DIV SHIFT = 0) THEN
   BEGIN
   (*ESTABLISH ASSIGNMENT QUEUE POINTERS*)
   Q := Q1HEAD;
   P := Q@.LINK;
   (*MOVE THROUGH ASSIGNMENT QUEUE*)
   WHILE P <> NIL DO
      BEGIN
      MAX := 11;
      TEST1 := 0;
      TESTOR1 := 1;
      FOR J := 1 TO B DO
         BEGIN
         FLAG := 0;
         (*IDENTIFY BAYS AVAILABLE AND DETERMINE BAY WITH MAX EFFICIENCY*
         IF EFF@P@.SYSINFO.SYS.PRODNUM,J@ <> 0 THEN
            BEGIN
            IF BASSIGN@J,T@ = 0 THEN
               BEGIN
               CHECK(J,I,P,FLAG);
               IF FLAG = 0 THEN
                  BEGIN
                  IF EFF@P@.SYSINFO.SYS.PRODNUM,J@ < MAX THEN
                     BEGIN
                     MAX := EFF@P@.SYSINFO.SYS.PRODNUM,J@;
                     X := J
                     END
                  END
               END
            END
         END;

      (*IF COMPATIBLE BAY FOUND CHECK FIRST SHIFT TESTOR AVAILABILITY*)
      IF MAX <> 11 THEN
         BEGIN
         WHILE (TEST1=0) AND (TESTOR1<=W1) DO
            BEGIN
            (*CHECK FIRST SHIFT QUALIFICATIONS FOR PRODUCT*)
            IF QUAL@P@.SYSINFO.SYS.SERIES,TESTOR1@ <> 0 THEN
               BEGIN
               (*IF TESTOR AVAILABLE ASSIGN PRODUCT*)
               IF TASSIGN@TESTOR1,T@ = 0 THEN
                  BEGIN
                  P@.SYSINFO.T1 := TESTOR1;
                  PRODUCT@P@.SYSINFO.ADMIN@.T1 := TESTOR1;
                  TASSIGN@TESTOR1,T@ := P@.SYSINFO.ADMIN;
                  P@.SYSINFO.BAY := X;
                  BASSIGN@P@.SYSINFO.BAY,T@ := P@.SYSINFO.ADMIN;
                  TEST1 := 1;
                  PRODUCT@P@.SYSINFO.ADMIN@.BAY := X;
                  PRODUCT@P@.SYSINFO.ADMIN@.START := T;
                  P@.SYSINFO.START := T
                  END
               END;
            TESTOR1 := TESTOR1 + 1
            END (*WHILE TEST1*)
         END; (*IF MAX*)

      (*CHECK IF SECOND SHIFT REQUIRED*)
      (*CURRENT PREREQUISITE IS IF TESTING ON FIRST SHIFT ONLY WILL*)
      (*CAUSE PRODUCT TO BE LATE.  IF IT IS DESIRED TO EXPAND THIS *)
      (*CATEGORY THE DESIRED NUMBER OF HOURS OF THE EXPANSION      *)
      (*SHOULD BE SUBTRACTED FROM THE FIRST ELEMENT OF THE NEXT IF *)
      (*STATEMENT.  FOR EXAMPLE, IF IT IS DESIRED THAT ALL PRODUCTS*)
      (*THAT ARE SCHEDULED TO BE COMPLETED WITHIN 3 HOURS OF THEIR  *)
      (*DUE DATE WITH FIRST SHIFT TESTING ONLY BE CONSIDERED FOR    *)
      (*SECOND SHIFT TESTING THEN THE NUMBER THREE WOULD BE         *)
      (*SUBTRACTED FROM THE FIRST ELEMENT OF THE NEXT IF STATEMENT.*)
      (*PRODUCTS ARE ASSUMED DUE AT 1200HRS ON DUE DATE*)
      L := (P@.SYSINFO.DUEDT-1)*SHIFT+3;
```

```
IF (L-(T DIV DAY)*SHIFT+(T MOD DAY)) < (P@.SYSINFO.TESTHR) THEN
   BEGIN
   (*SECOND SHIFT REQUIRED*)
   IF TEST1 = 1 THEN
      BEGIN
      (*ASSIGN FIRST SHIFT TESTOR FOR REMAINDER OF SHIFT*)
      FOR K := T TO (T+SHIFT-1-(T MOD SHIFT)) DO
         BEGIN
         M := K;
         IF M > TIME THEN
            M := TIME;
         TASSIGN@TESTOR1-1,M@ := P@.SYSINFO.ADMIN;
         BASSIGN@P@.SYSINFO.BAY,M@ := P@.SYSINFO.ADMIN
         END;
      (*CALCULATE TEST HOURS REMAINING TO BE ASSIGNED*)
      P@.SYSINFO.TESTHR := P@.SYSINFO.TESTHR-SHIFT+(T MOD SHIFT);
      X := T+SHIFT-(T MOD SHIFT);
      M := X;
      IF M > TIME THEN
         M := TIME;
      BASSIGN@P@.SYSINFO.BAY,M@ := P@.SYSINFO.ADMIN;
      (*MOVE PRODUCT TO SECOND SHIFT QUEUE*)
      Q@.LINK := P@.LINK;
      QINSERT(P,Q_HEAD);
      P := Q@.LINK
      END
   ELSE
      (*FIRST SHIFT TESTOR NOT AVAILABLE-PRODUCT MUST REMAIN*)
      BEGIN
      Q := P;
      P := P@.LINK
      END
   END (*IF SECOND SHIFT REQUIRED*)

ELSE
   (*SECOND SHIFT NOT REQUIRED*)
   BEGIN
   IF TEST1 = 1 THEN
      (*ASSIGN FIRST SHIFT TESTOR*)
      BEGIN
      FOR K := T TO (T+SHIFT-1-(T MOD SHIFT)) DO
         BEGIN
         L := K;
         IF L > TIME THEN
            L := TIME;
         TASSIGN@TESTOR1-1,L@ := P@.SYSINFO.ADMIN;
         BASSIGN@P@.SYSINFO.BAY,L@ := P@.SYSINFO.ADMIN
         END;
      (*CALCULATE TEST HOURS REMAINING*)
      L := SHIFT-(T MOD SHIFT);
      P@.SYSINFO.TESTHR := P@.SYSINFO.TESTHR-L;
      X := P@.SYSINFO.TESTHR;
      FOR J := 0 TO ((X DIV SHIFT)-1) DO
         FOR K := 0 TO 7 DO
            BEGIN
            M:=T+L+8+(DAY*J)+K;
            IF M > TIME THEN
               M := TIME;

            TASSIGN@TESTOR1-1,M@ := P@.SYSINFO.ADMIN
            END;
      M := T+L+8+(X DIV SHIFT)*DAY;
      L := M-1+(X MOD SHIFT);
      P@.SYSINFO.FINISH := L;
      PRODUCT@P@.SYSINFO.ADMIN@.FINISH := L;
      IF P@.SYSINFO.COMP <> 0 THEN
         PCOMP@P@.SYSINFO.PL,P@.SYSINFO.COMP@ := L;
      IF L > TIME THEN
         BEGIN
         L := TIME;
         WRITELN ('PRODUCT ',P@.SYSINFO.ADMIN:3,' EXCEEDS HOR')
         END;
      FOR K := M TO L DO
         TASSIGN@TESTOR1-1,K@ := P@.SYSINFO.ADMIN;
      FOR K := T TO L DO
         BASSIGN@P@.SYSINFO.BAY,K@ := P@.SYSINFO.ADMIN;
      L := M-1+(X MOD SHIFT)-((P@.SYSINFO.DUEDT-1)*DAY+3);
```

```
            IF L > 0 TH_N
               BEGIN
               WRITE ('PRODUCT ',P@.SYSINFO.ADMIN:3,' WILL BE ',L:3);
               WRITELN (' TIME PERIODS LATE');
               LATENESS := LATENESS + L;
               LATE := LATE + 1
               END;
            Q@.LINK := P@.LINK;
            DISPOSE(P);
            P := Q@.LINK
            END

         ELSE
            (*FIRST SHIFT TESTOR NOT AVAILABLE-PRODUCT MUST REMAIN IN QUEUE*)
            BEGIN
            Q := P;
            P := P@.LINK
            END
         END (*ELSE*)
      END (*WHILE P <> NIL*)
   END; (*IF NOT ODD*)

(*CHECK IF SECOND SHIFT HOUR-IF SO RUN SECOND SHIFT QUEUE*)
IF ODD(T DIV SHIFT) THEN
   BEGIN
   (*INITIALIZE QUEUE POINTERS*)
   S := Q2HEAD;
   R := S@.LINK;
   (*MOVE THROUGH SECOND SHIFT QUEUE*)
   WHILE R <> NIL DO
      BEGIN
      TEST2 := 0;
      TESTOR2 := W1 + 1;
      WHILE (TEST2=0) AND (TESTOR2<=W) DO
         BEGIN
         (*CHECK SECOND SHIFT QUALIFICATIONS FOR PRODUCT*)
         IF QUAL@R@.SYSINFO.SYS.SERIES,TESTOR2@ <> 0 THEN
            BEGIN
            (*IF TESTOR AVAILABLE ASSIGN PRODUCT*)
            IF TASSIGN@TESTOR2,T@ = 0 THEN
               BEGIN
               TASSIGN@TESTOR2,T@ := R@.SYSINFO.ADMIN;
               BASSIGN@R@.SYSINFO.BAY,T@ := R@.SYSINFO.ADMIN;
               TEST2 := 1;
               R@.SYSINFO.T2 := TESTOR2;
               PRODUCT@R@.SYSINFO.ADMIN@.T2 := TESTOR2
               END
            END; (*IF QUAL*)
         TESTOR2 := TESTOR2 + 1
         END; (*WHILE TEST2*)

      IF TEST2 = 1 THEN
         (*BOTH SHIFTS ASSIGNED*)
         BEGIN
         L := T+R@.SYSINFO.TESTHR-1;
         R@.SYSINFO.FINISH := L;
         PRODUCT@R@.SYSINFO.ADMIN@.FINISH := L;
         IF R@.SYSINFO.COMP <> 0 THEN
            PCOMP@R@.SYSINFO.PL,R@.SYSINFO.COMP@ := L;
         IF L > TIME THEN
            BEGIN
            L := TIME;
            WRITELN ('PRODUCT ',R@.SYSINFO.ADMIN:3,' EXCEEDS HOR')
            END;
         FOR K := T TO L DO
            BEGIN
            IF ODD(K DIV SHIFT) THEN
               (*SECOND SHIFT HOUR-ASSIGN SECOND SHIFT TESTOR*)
               BEGIN
               TASSIGN@TESTOR2-1,K@ := R@.SYSINFO.ADMIN;
               BASSIGN@R@.SYSINFO.BAY,K@ := R@.SYSINFO.ADMIN
               END
            ELSE
               (*FIRST SHIFT HOUR-ASSIGN FIRST SHIFT TESTOR*)
               BEGIN
               TASSIGN@R@.SYSINFO.T1,K@ := R@.SYSINFO.ADMIN;
               BASSIGN@R@.SYSINFO.BAY,K@ := R@.SYSINFO.ADMIN
               END
            END; (*FOR K*)
         L := T+R@.SYSINFO.TESTHR-1-((R@.SYSINFO.DUEDT-1)*DAY+3);
```

```
         IF L > 0 THEN
            BEGIN
            WRITE ('PRODUCT ',R@.SYSINFO.ADMIN:3,' WILL BE ',L:3);
            WRITELN (' TIME PERIODS LATE');
            LATENESS := LATENESS + L;
            LATE := LATE + 1
            END;
         (*PRODUCT IS ASSIGNED ON SECOND SHIFT AND MUST BE REMOVED*)
         S@.LINK := R@.LINK;
         DISPOSE(R);
         R := S@.LINK
         END (*IF TEST2*)

      ELSE
         (*PRODUCT MUST REMAIN IN SECOND SHIFT TESTOR QUEUE*)
         BEGIN
         BASSIGN@R@.SYSINFO.BAY,T@ := R@.SYSINFO.ADMIN;
         BASSIGN@R@.SYSINFO.BAY,T+1@ := R@.SYSINFO.ADMIN;
         IF (T MOD SHIFT) = 7 THEN
            (*ASSIGN FIRST SHIFT TESTOR FOR UPCOMING FIRST SHIFT*)
            BEGIN
            IF R@.SYSINFO.TESTHR > SHIFT THEN
               BEGIN
               L := T + 8;
               IF L > TIME THEN
                  BEGIN
                  L := TIME;
                  WRITELN('PRODUCT ',R@.SYSINFO.ADMIN:3,' EXCEEDS HOR')
                  END;
               FOR K := (T+1) TO L DO
                  BEGIN
                  TASSIGN@R@.SYSINFO.T1,K@ := R@.SYSINFO.ADMIN;
                  BASSIGN@R@.SYSINFO.BAY,K@ := R@.SYSINFO.ADMIN
                  END;
               R@.SYSINFO.TESTHR := R@.SYSINFO.TESTHR-8;
               L := T+9;
               IF L > TIME THEN
                  L := TIME;
               BASSIGN@R@.SYSINFO.BAY,L@ := R@.SYSINFO.ADMIN
               END
            ELSE
               BEGIN
               L := T + R@.SYSINFO.TESTHR;
               R@.SYSINFO.FINISH := L;
               PRODUCT@R@.SYSINFO.ADMIN@.FINISH := L;
               IF R@.SYSINFO.COMP <> 0 THEN
                  PCOMP@R@.SYSINFO.PL,R@.SYSINFO.COMP@ := L;
               IF L > TIME THEN
                  BEGIN
                  L := TIME;
                  WRITELN('PRODUCT ',R@.SYSINFO.ADMIN:3,' EXCEEDS HOR')
                  END;
               FOR K := (T+1) TO L DO
                  BEGIN
                  TASSIGN@R@.SYSINFO.T1,K@ := R@.SYSINFO.ADMIN;
                  BASSIGN@R@.SYSINFO.BAY,K@ := R@.SYSINFO.ADMIN
                  END;
               L := T+R@.SYSINFO.TESTHR-((R@.SYSINFO.DUEDT-1)*DAY+3);
               IF L > 0 THEN
                  BEGIN
                  WRITE ('PRODUCT ',R@.SYSINFO.ADMIN:3,' WILL BE ',L:3);
                  WRITELN (' TIME PERIODS LATE');
                  LATENESS := LATENESS + L;
                  LATE := LATE + 1
                  END;
               S@.LINK := R@.LINK;
               DISPOSE(R);
               R := S
               END
            END;
         S := R;
         R := R@.LINK
         END
      END (*WHILE R <> NIL*)
   END; (*IF ODD*)
```

```
(*DETERMINE IF ALL PARALLEL SYSTEM COMPONENTS HAVE COMPLETED TESTING*)
FOR I := 1 TO NPSYS DO
   BEGIN
   MAX := 1;
   FLAG := 0;
   FOR J := 1 TO 4 DO
      BEGIN
      IF PCOMP@I,J@ > MAX THEN
         MAX := PCOMP@I,J@
      ELSE IF PCOMP@I,J@ = 0 THEN
         FLAG := 1
      END; (*FOR J*)
   IF (FLAG <> 1) AND (PRODUCT@I@.FLAGP = 0) AND (T = MAX) THEN
      (*ALL COMPONENTS COMPLETED-ENTER PARALLEL SYSTEM IN ASSIGNMENT QUEUE*)
      BEGIN
      PRODUCT@I@.CSCHS := (T DIV DAY) + 1;
      PRODUCT@I@.FLAGP := 1;
      CREATENODE(I,NEXT);
      QINSERT(NEXT,Q1HEAD)
      END (*IF FLAG*)
   END; (*FOR I*)

   T := T + 1
   END;

WRITELN;
(*DETERMINE IF ANY PRODUCTS DID NOT BEGIN PROCESSING IN HORIZON*)
FOR I := 1 TO N DO
   IF PRODUCT@I@.START = 0 THEN
      WRITELN ('PRODUCT ',PRODUCT@I@.ADMIN:3,' WAS NOT SCHEDULED');

WRITELN;
WRITELN ('THE FOLLOWING IS THE ASSIGNMENT SUMMARY:');
WRITELN;
WRITELN (' ADMIN  SYSNUM  BAY  TESTOR1  TESTOR2  START  FINISH');
FOR I := 1 TO N DO
   WITH PRODUCT@I@ DO
      WRITELN (ADMIN:5,SYSNUM:8,BAY:6,T1:7,T2:9,START:8,FINISH:8);
WRITELN;
WRITE ('THERE WERE ',LATE:3,' LATE PRODUCTS WITH A MEAN LATENESS OF ');
WRITELN ((LATENESS DIV LATE):3,' TIME PERIODS');
WRITELN ('THE PROPORTION OF JOBS TARDY WAS ',((LATE/N)*100):4,' PERCENT');
FOR I := 1 TO N DO
   FLOW := FLOW+PRODUCT@I@.FINISH-((PRODUCT@I@.CSCHS-1)*DAY+3);
WRITELN ('THE MEAN JOB FLOW TIME WAS ',(FLOW DIV N):4,' TIME PERIODS');
WRITELN;
WRITELN ('THESE ASSIGNMENTS WERE MADE WITH SPT');

IF PRINT = 1 THEN
   BEGIN
   WRITELN;
   WRITELN ('TEST STATION ASSIGNMENTS FOR DAY 1');
   WRITELN;
   WRITE ('  BAY ');
   FOR I := 1 TO 114 DO
      WRITE ('*');
   WRITELN;
   FOR I := 1 TO B DO
      BEGIN
      WRITE (I:4,'   *');
      FOR J := 0 TO (DAY-1) DO
         WRITE (BASSIGN@I,J@:4);
      WRITELN;
      WRITELN
      END;
   WRITE ('       ');
   FOR I := 1 TO 114 DO
      WRITE ('*');
   WRITELN;
   WRITE ('       ');
   FOR I := 0 TO (DAY-1) DO
      WRITE (I:4);
   WRITELN;
   WRITELN ('TIME':55);
   WRITELN;
   WRITELN ('TESTOR ASSIGNMENTS FOR DAY 1');
   WRITELN;
   WRITE ('TESTOR ');
   FOR I := 1 TO 114 DO
      WRITE ('*');
   WRITELN;
```

```
   FOR I := 1 TO W DO
       BEGIN
       WRITE (I:4,'  *');
       FOR J := 0 TO (DAY-1) DO
           WRITE (TASSIGN@I,J@:4);
       WRITELN;
       WRITELN
       END;
   WRITE ('        ');
   FOR I := 1 TO 114 DO
       WRITE ('*');
   WRITELN;
   WRITE ('        ');
   FOR I := 0 TO (DAY-1) DO
       WRITE (I:4);
   WRITELN;
   WRITELN ('TIME':55);
   WRITELN;
   FOR K := 2 TO (HOR*WK) DO
       BEGIN
       WRITELN ('TEST STATION ASSIGNMENTS FOR DAY ',K:2);
       WRITELN;
       WRITE ('  BAY ');
       FOR I := 1 TO 114 DO
           WRITE ('*');
       WRITELN;
       FOR I := 1 TO B DO
           BEGIN
           WRITE (I:4,'  *'),
           FOR J := ((K-1)*DAY) TO (K*(DAY-1)+K-1) DO
               WRITE (BASSIGN@I,J@:4);
           WRITELN;
           WRITELN
           END;
       WRITE ('        ');
       FOR I := 1 TO 114 DO
           WRITE ('*');
       WRITELN;
       WRITE ('        ');
       FOR I := ((K-1)*DAY) TO (K*(DAY-1)+K-1) DO
           WRITE (I:4);
       WRITELN;
       WRITELN ('TIME':55);
       WRITELN;
       WRITELN ('TESTOR ASSIGNMENTS FOR DAY ',K:2);
       WRITELN;
       WRITE ('TESTOR ');
       FOR I := 1 TO 114 DO
           WRITE ('*');
       WRITELN;
       FOR I := 1 TO W DO
           BEGIN
           WRITE (I:4,'  *'),
           FOR J := ((K-1)*DAY) TO (K*(DAY-1)+K-1) DO
               WRITE (TASSIGN@I,J@:4);
           WRITELN;
           WRITELN
           END;
       WRITE ('        ');
       FOR I := 1 TO 114 DO
           WRITE ('*');
       WRITELN;
       WRITE ('        ');
       FOR I := ((K-1)*DAY) TO (K*(DAY-1)+K-1) DO
           WRITE (I:4);
       WRITELN;
       WRITELN ('TIME':55);
       WRITELN
       END
   END
END.
```

Appendix M.

12 Month Rolling Sales Plan

Product Line	Month 1	2	3	4	5	6	7	8	9	10	11	12	TOTAL
Series 2000													
2015	4	6	6	4	5	4	4	5	5	5	7	5	60
2030	15	12	9	10	13	9	10	12	10	11	13	10	134
2045	6	9	7	7	8	8	7	8	8	8	9	8	93
2715	1	2	3	2	5	2	2	2	2	2	2	2	27
2730	0	0	1	0	0	1	0	0	1	0	0	1	4
Sub-Total 2000	26	29	26	23	31	24	23	27	26	26	31	26	318
Series 3000													
3060	9	10	6	7	7	5	5	6	6	5	6	5	77
3100	7	10	7	5	6	5	4	6	6	4	5	5	70
3180	2	6	3	2	2	4	2	2	3	2	2	3	33
3250	3	1	2	2	2	2	2	2	2	2	2	2	24
3330	3	4	3	2	2	2	3	2	2	3	2	2	30
3450	2	7	3	15	6	7	9	6	5	5	6	5	76
3600	3	0	0	1	1	1	1	1	1	1	1	1	12
Sub-Total 3000	29	38	24	34	26	26	26	25	25	22	24	23	322

Product Line	1	2	3	4	Month 5	6	7	8	9	10	11	12	TOTAL
Series 4000													
4036	2	0	0	0	2	2	0	2	0	2	2	2	14
4080	3	4	3	6	3	3	3	3	3	3	4	3	41
Sub-Total 4000	5	4	3	6	5	5	3	5	3	5	6	5	55
Series 5000													
5060	2	2	0	2	2	2	2	2	2	2	2	2	22
5100	0	0	1	1	1	1	1	1	1	1	2	2	12
5160	0	0	0	1	1	1	1	1	1	1	1	1	19
5200	1	0	1	2	1	1	1	1	1	1	1	1	12
5300	2	1	0	1	1	1	1	1	1	1	2	2	13
5400	0	0	0	0	0	0	0	0	0	0	0	0	1
Sub-Total 5000	5	3	3	7	6	6	6	6	6	6	8	8	69
CUMM TOTALS	65	74	55	70	68	61	58	63	60	59	69	62	764

Appendix N.

Goodness-of-Fit Tests for Random Number Generators

Chi-Squared Goodness of Fit Test for Uniform Distribution:

The following procedure was used to generate uniform random numbers, where IX is a uniform random number seed:

```
[illegible] YFL: [illegible];
[illegible])

[illegible]
IY := [illegible];
I[illegible] < [illegible]
   [illegible] := IY+[illegible];
Y[illegible] := IY;
Y[illegible] := Y[illegible])
[illegible];
```

The procedure was called 200 times with the results as indicated in the following table:

Interval	0.0-.1	.1-.2	.2-.3	.3-.4	.4-.5	.5-.6	.6-.7	.7-.8	.8-.9	.9-1.0
Obs Freq	28	22	17	17	19	21	22	14	20	20
Exp Freq	20	20	20	20	20	20	20	20	20	20

The hypotheses and corresponding test statistic are:

H_o: the underlying distribution is uniform

H_a: the underlying distribution is not uniform

$$\chi^2 = \sum \frac{(OBS - EXP)^2}{EXP}$$

Rejection Region: If $\chi^2 \geq \chi^2_{\alpha,k-1}$ Reject H_o

Acceptance Region: If $\chi^2 \leq \chi^2_{\alpha,k-1-m}$ Accept H_o

If $\chi^2_{\alpha,k-1-m} < \chi^2 < \chi^2_{\alpha,k-1}$ Withhold judgment where k= number of cells and m= number of estimated parameters. In this case k= 10 and m= 1 (p).

With a 95% confidence interval α = .05 and

$$\chi^2_{\alpha,k-1} = \chi^2_{.05,9} = 16.919$$
$$\chi^2_{\alpha,k-1-m} = \chi^2_{.05,8} = 15.507$$

For the specific problem,

$$\chi^2 = \sum \frac{(OBS-EXP)^2}{EXP} = 6.4$$

Since $\chi^2 < \chi^2_{\alpha,k-1-m}$ the hypothesis is accepted and the uniform distribution provides a good fit to the data. Therefore, the procedure is an acceptable generator of uniform random numbers.

<u>Chi Squared Goodness of Fit Test for Normal Distribution:</u>

The following procedure was used to generate random numbers from a normal distribution, where J is a uniform random number seed and R is a uniform random number:

```
PROCEDURE [illegible];
  LABEL
     [illegible];
  VAR
     [illegible];
     [illegible];
  BEGIN
  [illegible] := [illegible];
  IF R [illegible]
     [illegible]
     [illegible]
        [illegible]
        [illegible];
        [illegible];
        [illegible]
         [illegible];
       := [illegible]
```

```
      ELSE IF W <= 0.1?? THEN
         BEGIN
         FOR I := 1 TO ???
            BEGIN
            UNFRM(J,L,?);
            J := L;
            T?T := T?T + ?
            END;
         N := 1.?*(T?T-1)
         END
      ELSE IF W <= ?.???? THEN
         BEGIN
25 :     UNFRM(J,L,?);
         J := L;
         ? := ??-?;
         UNFRM(J,L,?);
         J := L;
         Y := ?.5? ?;
         ?? := ??.??????? [illegible] ?.5);
         AY := ???(?);
         IF AY <= 1 THEN
            BEGIN
            IF Y <= ( X=??.?????? ???.?????????(?)
                                    +?.1575?544-A?) THEN
               N := ?
            ELSE
               GOTO 25
            END
         ELSE
            BEGIN
            ?? := ?.??? ??? [illegible] (?-?));
            IF A? <= 1.? THEN
               BEGIN
               IF Y <= ( ?=???-?.???/??44 (1.?-??)) THEN
                  N := ?
               ELSE
                  GOTO ?
               END
            ELSE
               BEGIN
               IF Y <= (?=???) THEN
                  N := ?
               ELSE
                  GOTO ??
               END
            END
         END
      ELSE
         BEGIN
1?? :    UNFRM(J,L,?);
         J := L;
         ? := SQRT(?* ?(-L?(?)));
         UNFRM(J,L,?);
         J := L;
         IF ? <= (3/?) THEN
            BEGIN
            UNFRM(J,L,?);
            J := L;
            IF ? > ?.? THEN
               ? := -?;
            N := ?
            END
         ELSE
            GOTO 1??
         END
      END;
```

The procedure was called 210 times with the results as indicated in the following table:

Cell	(-00,-1.07)	(-1.07,-.57)	(-.57,-.18)	(-.18,.18)	(.18,.57)	(.57,1.07)	(1.07,00)
Obs Freq	35	25	24	34	34	30	28
Exp Freq	30	30	30	30	30	30	30

The hypotheses and corresponding test statistic are:

H_o: the underlying distribution is normal

H_a: the underlying distribution is not normal

$$\chi^2 = \sum \frac{(OBS - EXP)^2}{EXP}$$

Rejection Region: If $\chi^2 \geq \chi^2_{\alpha,k-1}$ Reject H_o

Acceptance Region: If $\chi^2 \leq \chi^2_{\alpha,k-1,m}$ Accept H_o

If $\chi^2_{\alpha,k-1,m} < \chi^2 < \chi^2_{\alpha,k-1}$ Withhold judgment

, where k= number of cells and m= number of estimated parameters. In this case k= 7 and m= 2 $(\hat{u}, \hat{\sigma})$. With a 95% confidence interval α = .05 and

$$\chi^2_{\alpha,k-1} = \chi^2_{.05,6} = 12.592$$

$$\chi^2_{\alpha,k-1-m} = \chi^2_{.05,4} = 9.488$$

For the specific problem

$$\chi^2 = \sum \frac{(OBS - EXP)^2}{EXP} = 4.0667$$

Since $\chi^2 < \chi^2_{\alpha,k-1-m}$ the hypothesis is accepted and the normal distribution provides a good fit to the data.

Therefore, the procedure is an acceptable generator of normal random numbers.

Chi-Squared Goodness-of-Fit Test for Poisson Distribution:

The following procedure was used to generate random numbers from a poisson distribution, where J is a uniform random number seed and Lambda is the mean, λ , for the distribution:

```
PROCEDURE POIS (VAR J:INTEGER;LAMBDA:REAL;VAR P:INTEGER);
   LABEL
      5;
   VAR
      Z,Y : REAL;
      L  : INTEGER;
   BEGIN
   Y := 1;
   P := [illegible];
5  :UNIFRM(J,L,Z);
   J := L;
   Y := Y*Z;
   IF Y > (EXP(-LAMBDA)) THEN
      BEGIN
      P := P+1;
      GOTO 5
      END
   END;(*POIS*)
```

The procedure was called 200 times with $\lambda = 3$. The results are as indicated in the following table.

Xi	Obs Freq		P(Xi)	Exp Freq
0	15		.0498	9.96
1	30		.1494	29.88
2	39		.2240	44.8
3	43		.2240	44.8
4	36		.1680	33.6
5	22		.1008	20.16
6	9		.0504	10.08
7	6			
8	0			
9	0	6	.0334	6.68
10	0			
11	0			

The probabilities associated with various values of x are obtained using the probability mass function for the poisson distribution

$$p(X) = \begin{cases} \frac{e^{-\lambda}\lambda^{x}}{x!} & X = 0,\ 1,\ 2\ldots \\ 0 & \text{otherwise} \end{cases}$$

The hypotheses and corresponding test statistic are:

H_o: the random variable is Poisson distributed

H_a: the random variable is not Poisson distributed

$$\chi^2 = \sum \frac{(OBS - EXP)^2}{EXP}$$

Rejection Region: If $\chi^2 \geq \chi^2_{\alpha,k-1}$ Reject H_o

Acceptance Region: If $\chi^2 \leq \chi^2_{\alpha,k-1-m}$ Accept H_o

$$\text{If } \chi^2_{\alpha,k-1-m} < \chi^2 < \chi^2_{\alpha,k-1} \quad \text{withhold judgement}$$

where k= number of cells and m= number of estimated parameters. In this case k=7 and m=1 ($\hat{\lambda}$). With a 95% confidence interval

α = .05 and

$$\chi^2_{\alpha,k-1} = \chi^2_{.05,6} = 12.592$$

$$\chi^2_{\alpha,k-1-m} = \chi^2_{.05,5} = 11.070$$

For the specific problem

$$\chi^2 = \sum \frac{(OBS - EXP)^2}{EXP} = 3.898$$

Since $\chi^2 < \chi^2_{\alpha,k-1-m}$ the hypothesis is accepted and the Poisson distribution provides a good fit to the data. Therefore, the procedure is an acceptable generator of Poisson random numbers.

Chi Squared Goodness-of-Fit Test for Gamma Distribution:

The following procedure was used to generate random numbers from a Gamma distribution, where IX is a uniform random number seed and Lam and Neta are the parameters of the distribution:

```
PROCEDURE GAMMA (VAR IX:INTEGER; BETA:REAL; VAR G:[illegible]);
(*GENERATES A RANDOM VARIATE FROM THE GAMMA DISTRIBUTION*)

LABEL
    10,50,70,100;

VAR
    F,W,X,Y,Z : REAL;
    IY,N,I : INTEGER;

BEGIN
N := TRUNC(BETA);
F := BETA - N;
IF F <> 0 THEN
    BEGIN
10:UNFRM(IX,IY,X);
    IX := IY;
    IF X >= (F/(F+2.71828)) THEN
        BEGIN
        UNFRM(IX,IY,Y);
        IX := IY;
        Y := EXP(LN(Y)*(1/F));
        UNFRM(IX,IY,X);
        IX := IY;
        IF X <= EXP(-Y) THEN
            GOTO 50
        ELSE
            GOTO 10
        END
    ELSE
        BEGIN
        UNFRM(IX,IY,X);
        IX := IY;
        Y := 1 - LN(X);
        UNFRM(IX,IY,X);
        IX := IY;
        IF X <= (EXP(LN(Y)*(F-1))) THEN
50:           IF N <> 0 THEN
                BEGIN
70:             Z := 1;
                FOR I := 1 TO N DO
                    BEGIN
                    UNFRM(IX,IY,X);
                    IX := IY;
                    Z := Z*X
                    END;
                Y := Y - LN(Z);
                GOTO 100
                END
            ELSE
                GOTO 100
        ELSE
            GOTO 10
        END
    END
ELSE
    BEGIN
    Y := 0;
    GOTO 70
    END;

100: G := TRUNC (Y/[illegible])
END;(*[illegible]*)
```

The procedure was called 200 times with the parameters Lam= 1.0 and Neta= 4.0 with the results as indicated in the following table:

Xi	Obs Freq	P(Xi)	Exp Freq
0	3	.019	3.8
1	24	.124	24.8
2	43	.21	42
3	43	.214	42.8
4	36	.168	33.6
5	23	.114	22.8
6	13	.069	13.8
7	7	.04	8
8	2		
9	3		
10	1 } 8	.042	8.4
11	0		
12	1		
12	1		

The probabilities associated with various values of X are obtained using the probability mass function for the gamma distribution.

$$p(X) = \begin{cases} \dfrac{\Theta^r x^{r-1} e^{-\Theta x}}{\Gamma(r)} & , \text{ if } X \geq 0 \\ 0 & , \text{ if } X < 0 \end{cases}$$

The hypothesis and corresponding test statistic are:

H_o: the random variable is gamma distributed

H_a: the random variable is not gamma distributed

$$\chi^2 = \sum \frac{(\text{OBS} - \text{EXP})^2}{\text{EXP}}$$

Rejection Region: If $\chi^2 \geq \chi^2_{\alpha,k-1}$ Reject H_o

Acceptance Region: If $\chi^2 \leq \chi^2_{\alpha,k-1-m}$ Accept H_o

If $\chi^2_{\alpha,k-1-m} < \chi^2 < \chi^2_{\alpha,k-1}$ withhold judgment

where k= number of cells and m= number of estimated parameters. In this case k=9 and m=2 $(\hat{\theta},\hat{r})$, where $\hat{\theta}$= Lam and $\hat{r}$= Neta. With a 96% confidence interval, $\alpha = .05$ and

$$\chi^2_{\alpha,k-1} = \chi^2_{.05,8} = 15.507$$

$$\chi^2_{\alpha,k-1-m} = \chi^2_{.05,6} = 12.592$$

For the specific problem

$$\chi^2 = \sum \frac{(OBS - EXP)^2}{EXP} = .583$$

Since $\chi^2 < \chi^2_{\alpha,k-1-m}$ the hypothesis is accepted.

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REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Scheduling of Multiproducts with Limited Resources in an UPS Testing Facility	5. TYPE OF REPORT & PERIOD COVERED Final Report 13 Jun 84
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Captain Charles J. Venable	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Student, HQDA, MILPERCEN (DAPC-OPA-E), 200 Stovall Street, Alexandria, VA 22332	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS HQDA, MILPERCEN, ATTN: DAPC-OPA-E, 200 Stovall Street, Alexandria, VA 22332	12. REPORT DATE 13 Jun 84
	13. NUMBER OF PAGES [illegible]
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science: Operations Research Program.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Scheduling
Capacity Loading
Simulation
Operations Research
Uninterruptible Power Supply

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Scheduling procedures in an Uninterruptible Power Supply (UPS) testing facility were investigated. It was determined that the facility was experiencing an inordinate number of missed product due dates. An analytical scheduling model was developed.

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However, due to a unique shift organization the computational complexity of the model overshadowed its usefulness and a reduced formulation was developed. The reduced [illegible] formulation when used with an iterative approach, [illegible] solutions.

It was also determined that due to the [illegible] nature of the industry, test facility capacity was not considered for specific product mixes. An analytical [illegible] was developed to be used in conjunction with a heuristic to estimate capacity. Again, the computational complexity of the model was large and the determination was made to use a simulation approach. An operational tool for the test facility [illegible] was developed in the form of a sequential simulation [illegible] in [illegible] determining capacity and [illegible] restrictions. A simulation experiment was also conducted to determine the preferred queue [illegible] second shift [illegible] criterion. It was [illegible] that neither had an effect on the number of late jobs or [illegible] tardiness, thereby, indicating that the source of the [illegible] capability.

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