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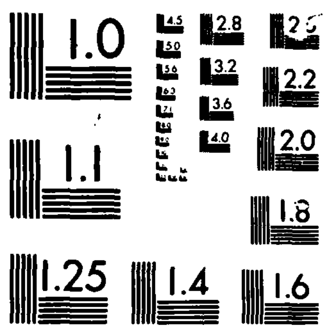


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Michael John Sabochick, Capt., USAF
1986, 224 pages
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Massachusetts Institute of Technology

Abstract

Defect properties of copper are calculated using molecular statics with an interatomic potential recently derived from first principles. Tri- and tetravacancies are found to be very mobile with migration energies of 0.56 and 0.39 eV, respectively, compared to previously calculated single and divacancy migration energies of 0.82 and 0.55 eV, respectively. Using the binding and migration energies calculated with the interatomic potential, annealing kinetics in copper and modeled using rate equations. The effective activation energy of annealing in the model is within 0.02 eV of single vacancy migration energy over a wide range of sink and initial single vacancy concentrations, which conforms to experimental results. In two cases, however, the larger clusters affect the activation energy and no definitive conclusions about whether or not the calculated cluster migration energies are correct for copper can be made.

The stability and structure of larger vacancy clusters with ten to forty vacancies were also investigated using the first principles copper potential. The stacking fault energy was first calculated and, for the potential cutoff radius used in the defect calculations, yielded of a value of 65 $mJ/m^2$ compared to the experimental value of $\sim$70 $mJ/m^2$. To investigate the large clusters, vacancy platelets of various sizes were created in a close-packed plane and the system was relaxed to the minimum energy configuration. Small vacancy platelets with as few as ten vacancies collapsed into stacking fault tetrahedra and faulted loops, depending on the shape of the platelet. Stacking fault tetrahedra are found to be the most stable large clusters.

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AN ANALYSIS OF AN ANALYTICAL QUEUEING TECHNIQUE
FOR USE AS A PROGRAMMING AID BY UNITED STATES
AIR FORCE CIVIL ENGINEERING SQUADRONS

A Thesis

Presented in Partial Fulfillment of the Requirements for
the degree Master of Science in the
Graduate School of the Ohio State University

by

Robert Arthur Hamel, B.I.E.

* * * * *

The Ohio State University

1985

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and Systems Engineering

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problem. The problem arises from having such a large backlog that the reasonable time criteria is often violated.

A reasonable amount of time to complete work affects the customer service provided by CE. There are different recommended time criteria for the different types of work a shop completes. The time criteria refers to the amount of time that passes between work identification and work completion. If the backlog is too large, a task that a craftsman can perform in an hour may take several weeks or longer before it is worked into the schedule, resulting in a dissatisfied customer. What the programmer needs is something that can serve as a guide for determining what is an appropriate backlog.

To help understand the programming effort, a discussion of the CE organization follows. Included in this discussion will be a description of the flow of work in CE, from its inception to completion, and a description of the various categories of work in CE.

CIVIL ENGINEERING

Fig. 1 shows the current organizational structure of the typical CE organization. The size of the organization can range from 300 assigned personnel at a small base to in excess of 1000 assigned personnel at a large base. The budget that a Base Civil Engineer (BCE) receives will usually be reflected by the size of the base. The size of

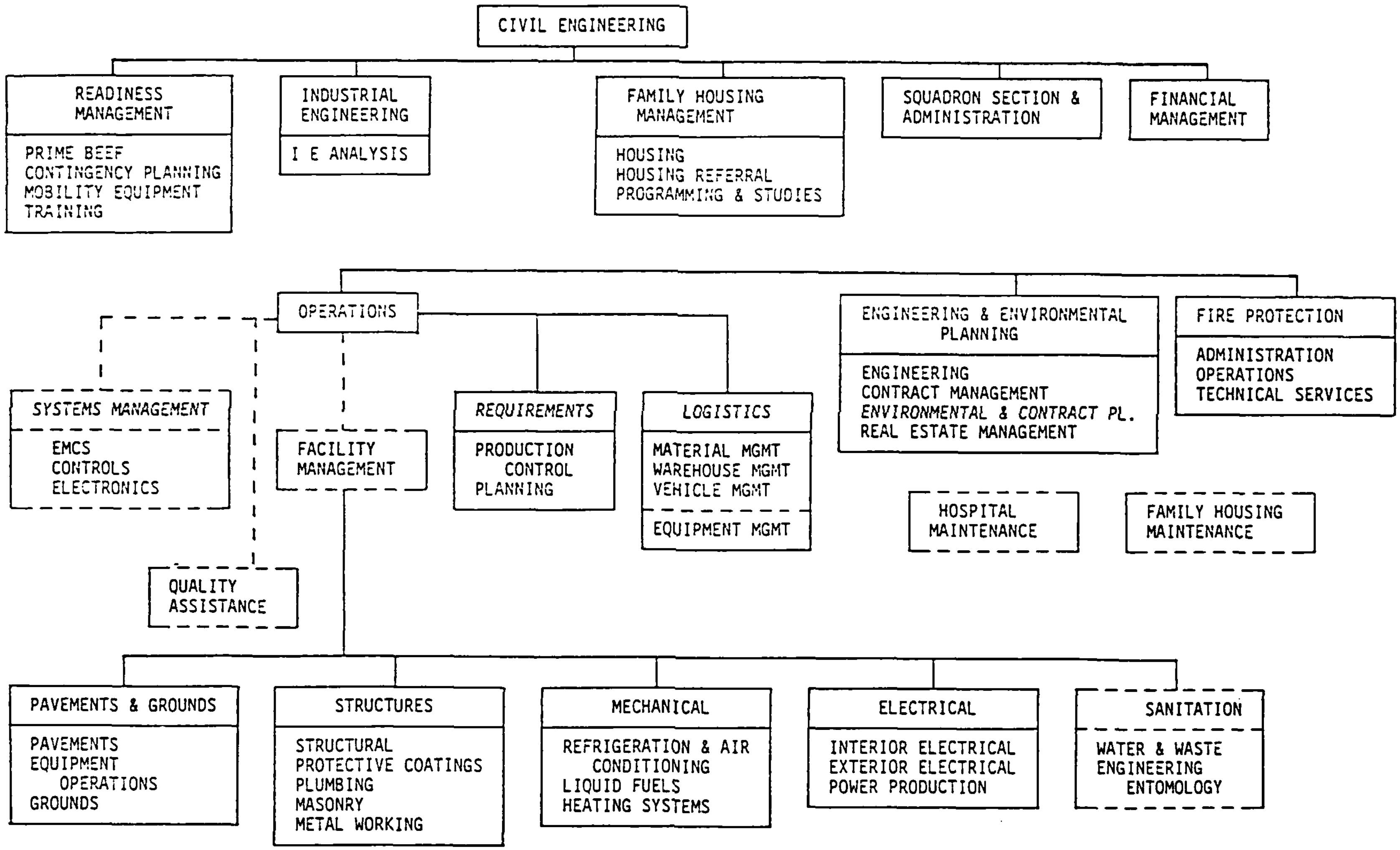


Fig 1: Civil Engineering Organization Chart

the budgets and workforce will determine the programming avenues available to the BCE to accomplish the work requirements at the base.

Paraphrased from Air Force Regulation (AFR) 86-1, programming consists of three major elements. The first is determining facility requirements needed to accomplish the mission. The second is evaluating existing assets and determining the most economical means of satisfying the requirement. And the last element is acquiring any additional facilities that are needed or work that must be done on existing facilities. [4]

Determining facility requirements is critical. All work requested of CE is not necessarily done. The BCE must work within his budget allocation and is guided by regulations that often reflect laws enacted by the Congress. The key is to "determine true need, not book requirements." [4]

In determining the most economical means of satisfying requirements , work can be contracted to a civilian agency, can be accomplished by the in-service workforce of CE, or some combination of both. For example, CE is not manned and in most cases does not have the equipment to construct new facilities. In this case it is more economical to hire a contractor to perform the construction. After the construction, CE will assume the maintenance responsibility for the facility since it is less costly and more efficient to use in-house personnel rather than keeping a contractor on call.

These are just a few of the considerations in the programming function. For purposes of this thesis, the scope will be limited to analyzing practices involving the in-service workforce and work being performed on existing facilities.

The office of primary responsibility (OPR) for programming this type of work is the Production Control Unit. As seen in fig. 1, they are a part of the Operations Branch under the Requirements Section. All work requested of CE will come to Production Control initially, and from there be routed as necessary.

Work identification (or requests) will normally come from three general sources. The first is from other organizations on base. They will identify general repair items (broken floor tile, faulty door lock, etc.), or identify new requirements that are needed (additional space, new layout, etc.). A second source is CE. Work planners identify needs during their facility inspections. Craftsmen also identify needed work they might discover. A third source is higher headquarters directives. An example of this type of work identification would be the basing of a new weapons system (B-1 bomber, MX missile, etc.). Production Control receives these requests, determines the routing of the work (contract vs. in-service), and if in-service, classifies the work.

## WORK CLASSIFICATION

AFR 85-1 gives guidance for classifying work [2]. In general, there are four classifications of work types. Job orders are a fast way to authorize work that does not need detailed planning. Work orders are used to control large or complex jobs. Recurring work consists of operations, recurring maintenance, services work, and other recurring tasks for which the scope and level of effort is known without an earlier visit to the jobsite each time the work is scheduled. Utility operations involves the running of major utility systems such as an Electric Power Plant or a Central Heating Plant. Job orders are subdivided further.

There are three sub-classifications of job orders; emergency, urgent, and routine. In AFR 85-1, an emergency job order is defined as

> "Any work required to correct an emergency condition that is detrimental to the mission or reduces operational effectiveness" [2].

Examples include such items as the failure of any utility, fire protection, environmental control, or security alarm system, and items such as a stopped-up sewer. An urgent job order is defined as follows in AFR 85-1:

> "Work that is not an emergency but that should be done within 5 workdays" [2].

These include the eliminations of some types of fire, health, and safety hazards. Finally, any work that falls in the concept of job orders but does not meet the definitions above is a routine job order.

Although the primary activities of the in-service workforce is maintenance and repair, some construction is allowed. It is classified as minor construction (MC) and defined by AFR 86-1 as follows:

> "Work required to erect, install, or assemble a new facility; addition to, alteration, expansion or extension, conversion, or replacement of an existing facility; procurement and installation of Real Property Installed Equipment (RPIE), relocation of existing facilities, and relocation of RPIE from one installation to another. The funded cost for this work cannot exceed $200,000." [4]

Most MC work is still accomplished by contract. The $200,000 guideline is critical because construction projects over $200,000 are classified as major construction and require Congressional approval. If minor construction work is within the capabilities of the existing assets of the in-service workforce, it can be accomplished in-house. However, the BCE is limited to spending only 5% of the total available direct work hours available in the organization per year doing MC work. (There is more information on the concept of direct hours in the next chapter). Because of the work hour restriction and dollar limitations, this work is generally done as a work order to maintain a detailed record. If the funded cost of the required work is known to be less than $2000, it can be accomplished as a routine job order.

Other factors may influence the problem of which classification to use. According to AFR 85-1:

> "The decision to use a work order is based on the need for: Detailed planning, capitalization of real property records, collecting reimbursements, and gathering data for review and analysis. Work that does not need detailed planning, special costing, close coordination between shops, or large bills of material is usually authorized on a job order." [2]

## WORK PROCESSING

When work is needed, the request for work is submitted by phone or a written request. Phone requests are generally accepted only for emergency and urgent job orders. If during the course of a phone conversation, it becomes obvious that the request is not an emergency or urgent requirement, the production control specialist will ask the requestor to submit a written request. Assuming the request is a valid emergency or urgent requirement, an AF Form 1879, BCE Job Order Record is completed to authorize work accomplishment. The job order is sent to the appropriate shop and craftsmen are dispatched to fix the emergency or urgent condition. A detailed flow diagram for processing emergency and urgent job orders has been extracted from AFR 85-1 and is included in Appendix A.

Written requests are accomplished using the AF Form

1135, BCE Real Property Maintenance Request, or the AF Form 332, BCE Work Request. The written requests also serve as approval documents. In other words, they serve as documentation as to whether or not CE determines the request is a valid requirement based on the programming guidelines of AFR 86-1. If disapproved, the document is returned to the requestor with an explanation of why it is disapproved. If approved, the processing continues according to the decided method of accomplishment. If the work is to be accomplished by the in-service workforce, the work will be authorized as a routine job order using AF Form 1879 or as a work order using AF Form 327, Base Civil Engineer Work Order. A detailed flow diagram for processing written work requests has been extracted from AFR 85-1 and is included in Appendix A.

Routine job orders will flow through the Operations Branch in much the same way as an emergency or urgent job order. The only difference is the scheduling. Routines are placed in a hopper and completed as the shops perform work in the particular zone of the base the hopper represents. A detailed flow diagram for processing routine job orders has been extracted from AFR 85-1 and is included in Appendix A.

Work orders have the longest processing time of the various kinds of in-service work types. First it is sent to the Planning Unit. It is planned in detail, materials needed are identified, and estimated time to complete the work is determined. From there, the Logistics Section gets the package to order the materials. Once materials are complete, the scheduler in Production Control receives the work order to schedule. It finally is scheduled and the shop(s) complete the work. A detailed flow diagram for processing work orders has been extracted from AFR 85-1 and is included in Appendix A.

Recurring work needs are known. By the nature of the type of work, it is known how frequently required tasks will arise. Frequencies are identified as weekly, semi-monthly, monthly, bi-monthly, quarterly, every 4 months, semi-annually, or annually. Shop supervisors and superintendents periodically review their recurring work tasks to insure it is still a valid need, but there is no formal processing of this work. Utility operations are a daily function and also have no flow, per se, through CE.

## SUMMARY

The problem is to find a method to aid a programmer in Production Control in determining what is an adequate backlog of work requirements to keep the in-service workforce busy while completing tasks in a reasonable amount of time. For the purpose of this analysis, a further limitation will be added. Because of the size and different skills of the in-service workforce, this analysis will involve determining an adequate backlog for a single shop. The concept of programming in CE has been discussed. The different work classifications and their flow through CE have also been discussed. The following chapters define the problem parameters for the single shop backlog effort and the analysis followed to find a method to aid a programmer in determining an adequate backlog.

CHAPTER II

# MODEL DEVELOPMENT AND METHOD SELECTION

## Labor Utilization Code Concept

The basic measurement of work accomplishment by the in-service workforce is time. Each craftsmen's time spent working a job is recorded using the AF Form 1734, BCE Daily Work Schedule, by work controllers. All time is recorded in hours, with the minimum time allowed by AFR 85-1 being .1 hours. Daily, the labor hours for each shop are loaded in the Base Engineer Automated Management System (BEAMS) [1]. Through the series of programs in BEAMS, this translates to dollars according to the calculated shop-rate for each shop.

Not all of the time spent by craftsmen during the week is directed toward job tasks. Sick leave, vacations, training, and supervision are also recorded. This leads to the breakout of work as direct labor and indirect labor. Direct labor consists of labor expended completing the different work classification types. Indirect labor is the time spent in other endeavors. Labor reporting is accumulated further using the labor utilization codes (LUC).

The actual LUCs and what they represent are shown in table 1.

TABLE 1
LABOR UTILIZATION CODES

| Direct Labor | | Indirect Labor | |
|---|---|---|---|
| LUC | Description | LUC | Description |
| 11 | Recurring Work | 31 | Supervision |
| 12 | Emergency Job Orders | 32 | Training |
| 14 | Urgent Job Orders | 33 | Leave |
| 15 | Minor Construction | 34 | All Other |
| 16 | Routine Job Orders | | |
| 18 | Other Work Orders | | |
| 19 | Utility Operations | | |

Source: AFM 171-200, Volume II

The division of labor between direct and indirect hours allows the computation of the availability rate. The availability rate is defined as the percentage of time spent performing direct labor tasks and is computed as follows:

$$\text{Availability Rate} = \frac{\text{Direct Hours}}{\text{Total Hours}} \times 100\% \qquad (1)$$

The goal in CE is to attain a 70% availability rate for each shop.

Information about labor hours expended appears monthly on the BEAMS product PCN SF100-252, the BCE Monthly Labor

Analysis Report. Information from this report is used to monitor the availability rate, the 5% MC limitation, and to provide historical data to establish trends as an aid in scheduling work. The programmer can use the historical data of the amount of indirect hours used from prior year reports as an aid in determining how many direct hours might be available.

## Data Availability

The monthly labor analysis report is the primary source of data readily available to a programmer. The information extracted will be the total hours spent working a particular LUC, the availability rate, and the percentage of direct hours spent on a particular work type for a previous month. The percentage of direct hours for a work type is calculated by

$$\% \text{ Direct Hours} = \frac{\text{Hours expended for a LUC}}{\text{Total Direct Hours}} \times 100\% \quad (2)$$

The current procedures for recording actual hours expended by work types is totally recorded by work order numbers in BEAMS. Each job order is loaded into BEAMS against a collection work order number (CWON). Recording labor in this way establishes the 'accounting system for' money purposes. Labor expended by LUC is stored as a cumulative figure and used in the labor analysis reports.

The data to determine the amount of time spent by a specific shop on a specific job order is not readily available. An individual must search through the Daily Work Schedule for each shop to backtrack the actual labor hours for a given shop. In the processing of over 2,000 job orders per month in a typical CE organization, there is not enough manpower available to devote to determining average completion rates of job orders per shop.

Actual hours for work orders can be found. The files are on-line in BEAMS up to 60 days after the work order is closed. Information can be found after 60 days by writing a report program, known as a retrieval, against the work order history tape. Response time for a retrieval is usually about a day. The delay is caused because CE must coordinate with the base Data Automation organization to load the tape and access the information on the tape.

Actual hours expended toward recurring work tasks are "lost" in the same way as job orders. The estimated time per task and frequency are known. This makes programming easier for recurring work than for job orders since there are some guidelines as far as task times.

There are drawbacks to the way BEAMS currently works. However, this is how BEAMS was designed to work. When it was implemented in 1967, CE performed most work as work orders. The recurring maintenance tasks were simpler due to the less sophisticated technologies and more people authorized in production control to monitor programming and scheduling. Over the past twenty years CE has attempted to become more responsive to customer needs, evolving the job order system. Since BEAMS programming is not maintained by CE (all software maintenance is performed by the Data Systems Design Office (DSDO), Gunter AFS, AL), BEAMS trailed the initiatives begun by CE. Consequently, there is no automated processing of job orders on BEAMS.

To determine current information needs, the Air Force Engineering and Services Center (AFESC) had an Information Requirements Study performed. The recommendations of the study led to the initial development of the Work Information Management System (WIMS). The WIMS concept involves procuring mini-computer systems for each CE organization using software developed by Air Force Civil Engineers to allow real-time access of work processing information. To test the concept, equipment was leased from the WANG corporation and software developed by civil engineers at Tinker AFB, OK.

As a part of the Operations Branch software, the AF Form 1879, BCE Job Order Record, and the AF Form 1734, BCE Daily Work Schedule, are written electronically rather than manually. This frees the production control specialists from maintaining manual records of job order and work order processing. It also allows the users to access information such as actual completion times of job orders that was not previously available. WIMS is also capable of producing magnetic tapes that transfer data to update BEAMS, and vice-versa. This, in effect, automates much of the work processing paperwork, and increases the amount of reliable data available to CE managers.

Some bases have, on their own initiative, implemented a part of the WIMS program. The 2750 CES located at Wright-Patterson AFB, OH, has some of the Operations Branch software on line. With their permission, data used in this thesis is extracted from the WIMS data base at Wright-Patterson AFB.

## CE Queueing System Discussion

The flow of work to a shop in CE can be modeled as a queueing system. Work requests flowing into the shop are the arrivals. Completion of the work tasks by craftsmen represent the service function. The queue discipline is first-in, first-out.

Work requests arrive at different rates according to their classification. Service times to complete work tasks are also classification dependent. The number of servers needed to accomplish work tasks will vary from task to task. Before a task is started, all of the needed craftsmen must be available, and all craftsmen will complete service together. Fig. 2 shows a graphical model of this system.

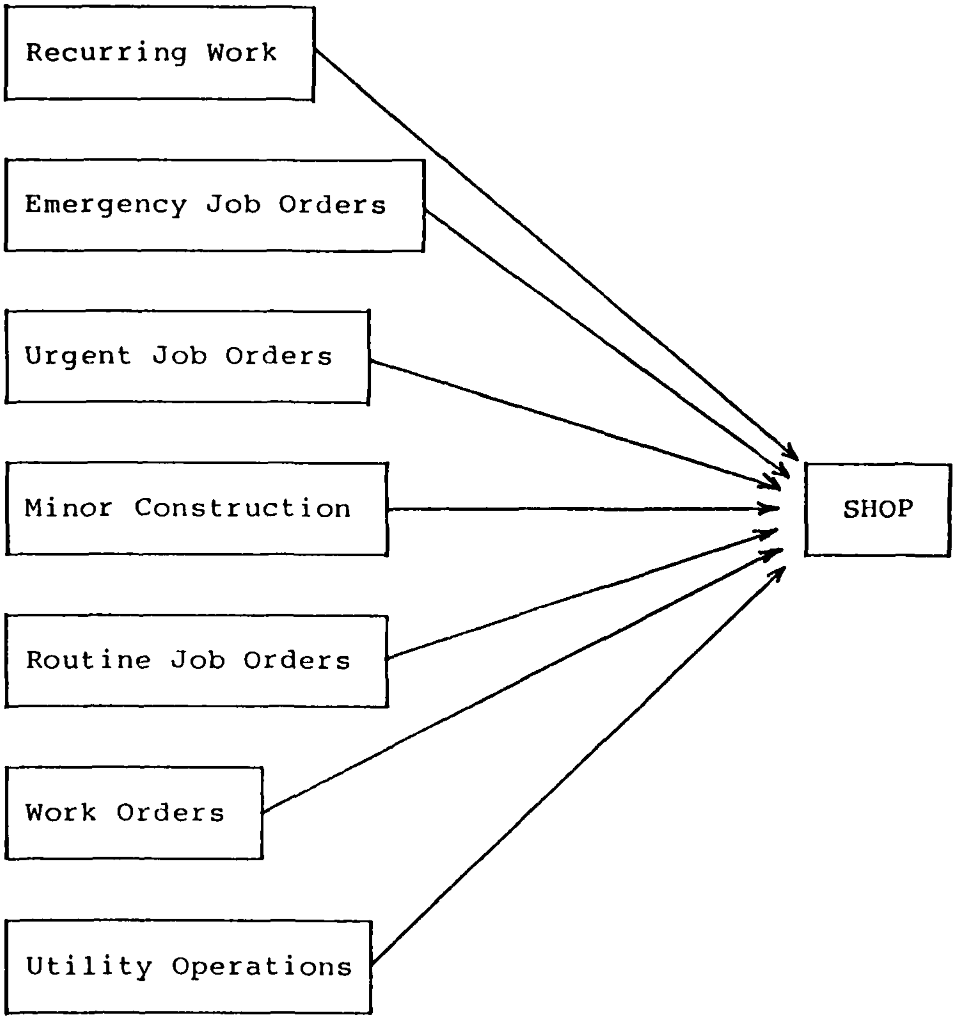


Fig. 2: CE Shop Queueing System

In modeling and analyzing queueing systems, two general classes of modeling techniques exist. The classes are simulation models and analytical models. There are advantages and disadvantages to applying either approach to CE.

Advantages of using a simulation model include the real world duplication ability and parameter testing ability of the model. Any arrival and service completion distributions can be modeled in a simulation. The need to make simplifying assumptions is eliminated by using a simulation model. Changes to arrival and service time distributions and their effect on a system can be tested easily in a simulation. The parameters that cause the most change in the desired operating characteristics of a queueing system can be analyzed.

A major disadvantage of using a simulation, especially as it applies to CE is the nonavailability of software. The current software proposal for the WIMS does not include a simulation package. It is not foreseen that the Air Force leadership will decide to include a simulation package for each mini-computer system installation.

An advantage of using an analytical model includes the ease of application computationally. The model can be fit into the WIMS easily without taking much memory. A program to do the necessary calculations can be written and loaded into the computer by users of the system. It can be made available to the CE programmer.

A disadvantage is that assumptions must be made about the actual system to use the analytical model. The assumptions may have no effect on the accuracy of results, or it could have a major distorting effect. Another disadvantage is that distributions of arrivals and service times are restricted. The model may require distributions that are different from the real world situation.

Since the end product of this analysis is a product to be used on the WIMS system, the examination is limited to analytical models. The search through the literature has sought a model to handle a varying number of servers per customer as a key prerequisite. Green [8],[9] has developed a model that deals with queueing systems requiring a random number of servers. In this model, servers must begin service simultaneously, but can complete service independently, resulting in different service times for each server. Green calls this an independent-server system. What is specifically needed by CE is a system allowing for a random number of servers that will end service together, i.e., all servers have equal service times on each job. Green calls this system a joint-service system.

According to Green [9], a solution technique for the general, n-server, joint-service system other than simulation has not been developed. The independent-server system can be used to approximate the joint-service system by determining a lower <u>or</u> upper bound on the joint-service system. If the customers have service times distributed as the maximum of the completion times of the individual servers involved, the expected waiting time in queue will be bounded from below by the expected waiting time in a system with servers that free independently. Conversely, if the customers have service times distributed as the minimum of the completion times of the individual servers involved, the expected waiting time in queue will be bounded from above by the expected waiting time in a system with independent servers. Using Green's method will result in a one-sided bound of the actual system.

## Summary

This chapter has explained the concepts of direct hours and the availability rate used in CE. A discussion of the current procedures of tracking work along with the work tracking procedures to be used in the near future have been explained to show data availability for use in a queueing model. The chapter concludes with a discussion of the queueing system of CE and an overview of an analytical model is examined for use by CE.

What follows is an analysis of Green's method as applied to CE. Green's method will be explained, and data from the WIMS system at Wright-Patterson AFB is used to test the applicability of Green's method.

# CHAPTER III

# DESCRIPTION AND APPLICATION OF GREEN'S METHOD

## Introduction

This chapter begins with a discussion of Green's method for systems requiring a random number of servers. The next section contains the actual data collected and an analysis of the data. The concern is whether or not the data distributions fit Green's assumptions for arrival and service distributions. The last section presents a comparitive application of Green's method using the available data.

## Green's Method

Green [8],[9] developed a model for a multiserver queueing system in which customers require a random number of identical servers that must start service together, but can leave the customer separately. She calls this type of system an independent server system. A characteristic of this system is that a customer cannot start service until all required servers are available. This means the system is not a member of the class of batch arrival models and that servers may be idle even when customers are waiting to enter service. Some examples of this type of service model are seen in firefighting, jury selection, and emergency surgery.

In this model, customers arrive according to a Poisson process with a rate $\lambda$. Each customer requests simultaneous service from i servers with probability $c_i$, $1 \leq i \leq s$. The number of servers requested by successive customers is independent. Once in queue, customers follow the queue discipline of first-in, first-out.

Green's method assumes that there are s identical and independent servers with service completion times that are exponentially distributed with mean $1/\mu$. Since individual server completion times are independent, the actual service time of a single customer is not exponentially distributed. Let $B_s$ represent a customer's service time. $B_s$ is distributed as the maximum of a random number of exponentially distributed random variables. $B_s(t)$, the cumulative distribution function for $B_s$, is given by

$$B_s(t) = \sum_{i=1}^{s} (1 - e^{-\mu t})^i c_i \tag{3}$$

Some additional random variables are defined at this point and are illustrated in fig. 3.

A queueing period, denoted by Q, is defined as the period of time beginning when a customer arrives to an empty queue and must wait for service, and ends when the queue next becomes empty. A non-queue period, $\overline{Q}$, is defined as beginning when the preceding queueing period ends, and ending when a queue next forms.

Let $t_n$, n=1,2,... be defined as the times when the customers in a queueing period enter service, and define $B_{n+1} = t_{n+1} - t_n$, $n \geq 1$. $B_n$ is called the interservice time of the $n^{th}$ customer in the queueing period. The interservice time is the time it takes the customer to enter service after becoming first in the queue. These times are independent and identically distributed random variables, so they are henceforth referred to without a subscript.

Since B only applies to arrivals during a queueing period, define the initial delay random variable, D, as the delay encountered by the customer that initiates a queueing period. If the customer arrives to an empty queue at time $t_0$ and enters service at time $t_1$, then $D = t_1 - t_0$.

Let X(t) represent the distribution function for the random variable X and E(X) be its expected value. X*(s) will represent the Laplace Transform defined as

$$X^*(s) = \mathcal{L}(X(t)) = \int_0^\infty e^{-st} dX(t) = \int_0^\infty e^{-st} x(t) dt \qquad (4)$$

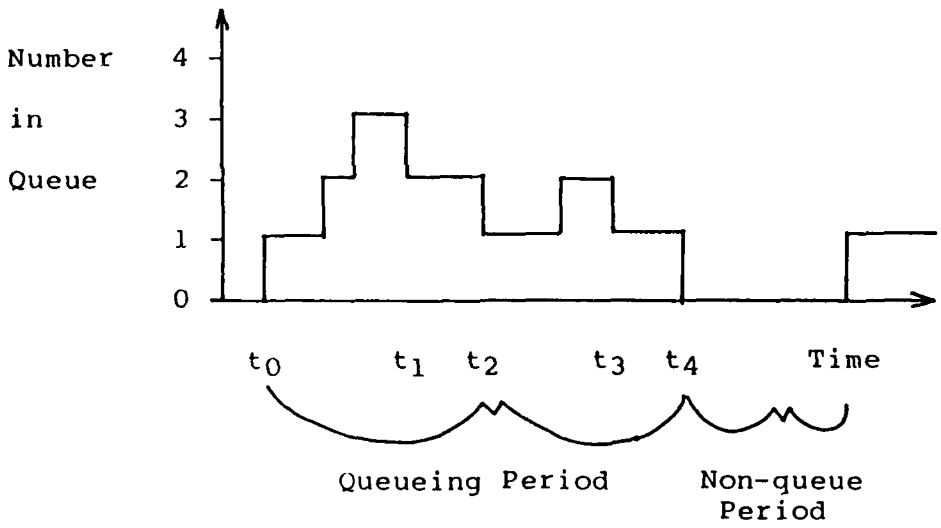


Fig. 3: The Queueing Cycle

Green's model of the independent server system is a renewal process. The renewals occur at the beginning of each queueing cycle if the system has achieved a steady-state condition. A queueing cycle will consist of a queueing period and a non-queue period. If the length of the queueing cycle is finite, a renewal will occur.

The operating characteristics of primary interest found by using Green's method are the expected wait time in queue, WQ, and the expected system wait time, W. The technique to find WQ(t), the distribution of WQ, makes use of a modification to this queueing system to take advantage of an imbedded M/G/1 queue. The modification ignores the actual service provided by the craftsmen and makes the time a customer spends waiting in the first position of the queue the new service element (see fig. 4).

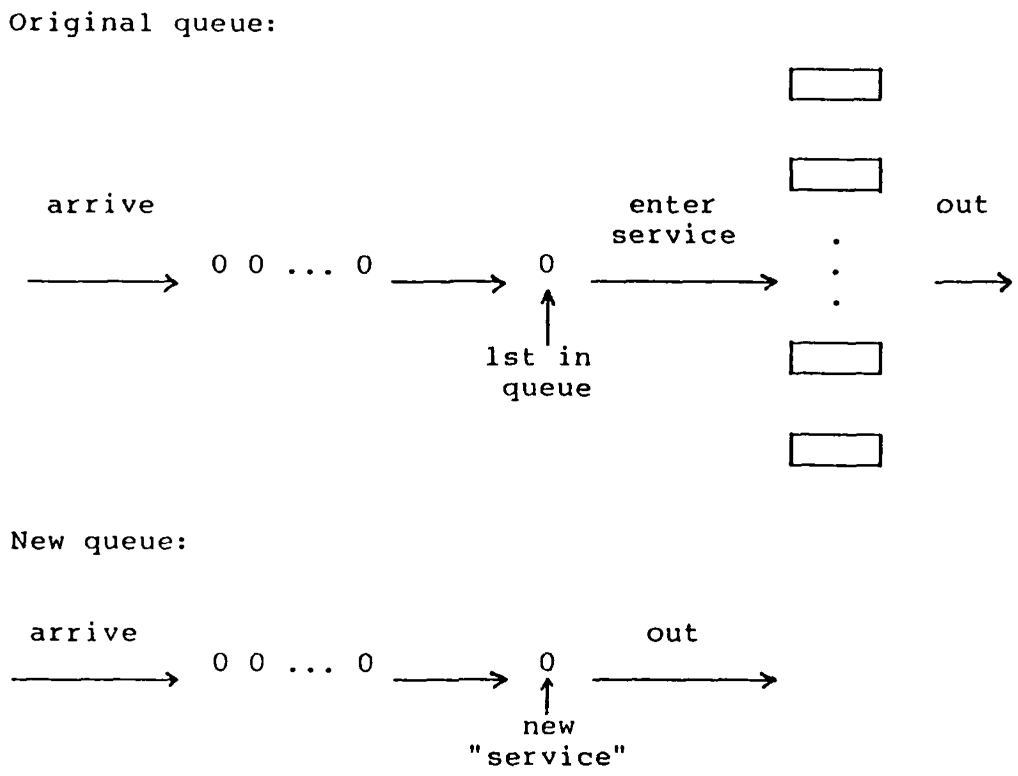


Fig. 4: Representation of Original and New Queue

The new queue is an M/G/1 system. B(t), the distribution function for the interservice random variable B, becomes the service distribution. The traffic intensity of an M/G/1 system is defined as the probability that the queue is busy, or equivalently, the probability that a customer will have to wait in queue. Let $p_q$ represent the probability that a queue exists in the original system. Then, $p_q$ is the traffic intensity of the M/G/1 system imbedded in the original system.

This holds for customers that arrive during a queueing period. The customer that initiates the queueing period experiences a delay according to D(t), the distribution function for the initial delay random variable, D. A study of M/G/1 queues in which the first customer of each busy period requires exceptional service has been accomplished by Welch (1964). The exceptional service required by the customer that initiates a queueing period is a result of the number of servers busy. To understand this, look at the difference between B and D.

Both random variables can be defined as the time it takes from the moment a customer becomes first in the queue until the customer enters service. The crucial difference between the two is that D is defined for a customer who arrives to an empty queue, while B is defined for a customer who joins a queue upon arrival. The customer that arrives during a queueing period sees all s servers busy at the moment he becomes first in the queue. In contrast to this, the customer that arrives to an empty queue and must wait until the j servers he needs are available, may see from s-j+1 to s servers busy. This causes the distribution functions B(t) and D(t) to be different.

Define $F_{ki}(t)$ as the probability that k or more servers become free in the interval $(t_0, t_0+t)$ given that i servers are busy at $t_0$. Since the probability of a server becoming free in an interval t is the distribution function of the occupation time of each individual server, namely $1-e^{-\mu t}$, the probability that k out of i servers will become free is binomially distributed. Therefore,

$$F_{ki}(t) = \sum_{j=k}^{i} \binom{i}{j}(1 - e^{-\mu t})^{j}(e^{-\mu t})^{i-j}, \quad k \leq i \qquad (5)$$

Since all servers are busy just after an interservice time begins,

$$B(t) = \sum_{k=1}^{s} F_{ks}(t)c_k \qquad (6)$$

To obtain D(t), the number of busy servers found by the arriving customer and the number of servers required by the customer must be considered. To accomplish this, define H(i,j) as the joint probability that a customer arriving during a non-queue period finds i busy servers when he arrives and needs j servers. Then,

$$H(i,j) = \begin{cases} \overline{q}_i c_j / p_d & i > s-j \\ 0 & i \leq s-j \end{cases} \qquad (7)$$

where $\overline{q}_i$ is the probability that i servers are busy when a customer arrives during a non-queue period, and $p_d$ is the probability that a customer arriving during a non-queue period is delayed. Therefore,

$$D(t) = \sum_{i=1}^{s} \sum_{k=1}^{i} F_{ki}(t)\bar{q}_i c_{s-i+k} \;/\; p_d \tag{8}$$

The equation given by Green to determine WQ(t) and expressed as a Laplace Transform is:

$$WQ^*(s) = (1-p_q)(1-p_d) + (1-p_q)D^*(s)p_d + \frac{p_q[1-D^*(s)]}{[s-\lambda+\lambda B^*(s)]E(Q)} B^*(s) \tag{9}$$

where E(Q) is the expected length of a queueing period. WS(t), the waiting time distribution in the system, is found by convolving WQ(t) and $B_s(t)$. The resulting equation expressed as a Laplace Transform is:

$$WS^*(s) = WQ^*(s)B_s^*(s) \tag{10}$$

$W_q$ is found by evaluating the first moment of WQ(t). This can be accomplished by taking the first derivative of WQ*(s) with s=0, or

$$W_q = (-1)\frac{d}{ds} WQ^*(s)\Big|_{s=0} \tag{11}$$

Finding $W_q$ with equation (9) is computationally difficult. However, Green has given an equivalent means of expressing WQ*(s) which does allow the generation of moments more easily. It is

$$WQ^*(s) = (1-p_q)(1-p_d) + (1-p_q)p_d D^*(s) + p_q[1-\lambda E(B)]D_e^*(s)B^*(s) \sum_{n=0}^{\infty} [\lambda E(B)B_e^*(s)]^n \qquad (12)$$

$B_e(t)$ and $D_e(t)$ are the equilibrium excess distributions for the interservice times and initial delay times given by

$$B_e(t) = \int_0^t [1-B(u)]\ du/E(B) \qquad (13)$$

and

$$D_e(t) = \int_0^t [1-D(u)]\ du/E(D) \qquad (14)$$

Using this version of $WQ^*(s)$ in equation (11) will result in $W_q$.

$W_q$ can also be found by a direct calculation. This equation is:

$$W_q = \frac{E(R)}{1 - \lambda E(B)} \qquad (15)$$

where $E(R)$ is the expected value of the residual interservice time of the first person in the queue if a queue exists, or the delay encountered if there is no queue. This is given by

$$E(R) = (1-p_q) \sum_{i=1}^{s} \sum_{j=s-i+1}^{s} \left[\frac{1}{i\mu} + \frac{1}{(i+1)\mu} + \ldots + \frac{1}{(s-j+1)\mu}\right] c_j \bar{q}_j$$

$$+ p_q \sum_{i=1}^{s} \sum_{j=s-i+1}^{s} \left[\frac{1}{i\mu} + \ldots + \frac{1}{(s-j+1)\mu}\right] \frac{c_j}{\sum_{k=s-i+1}^{s} c_k} q_i \qquad (16)$$

where $q_i$ is the probability that a customer arriving during a queueing period sees i busy servers upon arrival. The intermediate calculations necessary to find $W_q$ are detailed in Appendix B for both the Laplace Transform approach and the direct calculation approach.

W can be found by calculating the first moment of WS(t). This is done by finding the first derivative of WS*(s) given by equation (10). Then

$$W = (-1)\,[-W_q - E(B_s)] \qquad (17)$$

where $E(B_s)$ is most easily calculated from the Laplace Transform of $B_s(t)$ given in equation (3).

As previously mentioned, a steady-state condition will exist if the length of a queueing cycle is finite. A non-queue period will be finite since it is developed using a nonsingular matrix (see Appendix B). If the queueing period is finite, then sufficient conditions exist for a steady-state evaluation.

The length of a queueing cycle, E(Q), can be calculated by

$$E(Q) = \frac{E(D)}{1 - \lambda E(B)} \tag{18}$$

Since E(D) is finite, E(Q) is finite if $\lambda E(B) < 1$. E(B) can be found directly by

$$E(B) = \sum_{k=1}^{s} \sum_{j=0}^{k-1} \frac{c_k}{(s-j)\mu} \tag{19}$$

Define $\rho$ as the traffic intensity of this system.
If $\rho = \lambda E(B)$ is less than 1, then a steady-state condition can exist. Or

$$\rho = \frac{\lambda}{\mu} \sum_{k=1}^{s} \sum_{j=0}^{k-1} \frac{c_k}{s-j} \tag{20}$$

## Modeling Compromises Introduced

In order to employ Green's method, a verification of actual arrival rates of work requests and craftsmen service times is needed. Since the method uses Poisson distributed arrivals and exponential service times, data collected is tested to determine if it fits the respective distributions.

The data, as currently extractable from WIMS, is most easily collected by individual work types. For this reason, the testing of the arrival and service distributions for fit is initially performed on the individual work types. The data is then consolidated and analyzed for fit with the Poisson and exponential assumptions.

It is known at the outset that the analysis results cannot be compared to actual wait times. Due to the current programming of WIMS, this type of comparison is not available. To compensate for the inability to compare test results with actual data, this analysis takes two directions. One is an analysis of the individual work types as independent entities. The other analyzes consolidated data.

Both types represent a modeling compromise over the actual system. Dealing with the work types as independent entities should result in longer expected wait times. In order to follow the pattern of independent entities, the craftsmen will be divided into dedicated crews for each work type. Since the actual shop allows craftsmen to work on any work type, this approach restricts the flexibility inherent in the shop.

The consolidated data should not present as large a compromise. Because the data from the individual types is consolidated, the results are dependent only upon the consolidation technique.

Any other compromises made affect both models. Restrictions, such as the exclusion of Recurring Work tasks because it is known to not fit the arrival and service distributions are done for both types of analyses. These restrictions and their effects are examined throughout the remainder of this chapter.

## Data Analysis

Since labor is recorded in terms of hours, hours are used as the standard time unit. Job order arrivals are recorded in WIMS by date and time based on a 24 hour clock. The Production Control Unit operates from 0700 hrs until 1600 hrs Monday through Friday as a normal duty week. Since this function is manned for the entire period, 1 day equals 9 hours, and 1 week equals 5 days or 45 hours for arrivals. December 3, 1984 at 0700 is arbitrarily established as time 0 for job orders. Data for Routine Job Orders collected for two weeks results in a sample of 95 arrivals. Urgent Job Orders collected for one week results in 44 arrivals. Emergency Job Orders collected for two weeks results in a sample of 62 arrivals.

Work Orders and Minor Construction tasks do not arrive in as large a volume as job orders. To get an adequate sample, a six month sample is used. The initial analysis is done in terms of days. After testing the hypothesis that arrivals occur in a Poisson fashion, sample means are converted to hours. March 19, 1984 is arbitrarily selected as day 0. Data collected for Work Orders results in a sample of 52 arrivals. Data collected for Minor

Construction results in a sample of 45 arrivals.

Service times are collected for each arrival in each work class. The service times are in terms of hours for all work tasks. Since all of the craftsmen in the shop take an hour lunch break during a normal duty day, 1 day equals 8 hours for service times.

The last bit of data needed is the number of craftsmen in the shop. The Structures Shop is authorized 74 craftsmen. For this analysis, it is assumed that all 74 craftsmen are assigned to the shop and are available to work. It is also assumed that the craftsmen are independent and identical entities, as is the case in the service function of Green's method.

To this point, the data collection effort is tailored to the independent work types analysis. Ideally, to form the consolidated analysis, it is necessary to combine the arrival and service rates of the individual work types since the data to form the consolidated analysis is not collected at the same time as the independent work types.

Combining the arrival rates can be accomplished by finding the distribution that results from the convolution of the different work type arrival distributions. This is also known as finding the sum of random variables. This can be done with relative ease using transform techniques illustrated by Giffin [7]. If this new distribution is a Poisson distribution, the mean can be determined and used as the arrival rate for the application of Green's method.

Since the Poisson is a discrete probability distribution, a geometric transform is used. Giffin shows that using Borel's Theorem gives

$$T(g(y)) = T(f_1(x))T(f_2(x)) \tag{21}$$

where T is any discrete transform operator. Using the tables developed by Giffin, the geometric transform of a Poisson distribution is given by:

$$G\left(\frac{\lambda^t e^{-\lambda}}{t!}\right) = e^{-\lambda(1-z)} \tag{22}$$

The mean of a Poisson distribution equals $\lambda$. Let g(y) represent the combined distribution that is given as:

$$g(y) = f_1(t) * f_2(t) * f_3(t) * f_4(t) * f_5(t) \tag{23}$$

where $f_i(t)$, i=1,2,3,4,5 is the distribution representing the arrival rate of the individual work types, and * represents the convolution operator. The addition follows:

$$G(g(y)) = G(f_1(t))G(f_2(t))G(f_3(t))G(f_4(t))G(f_5(t))$$

$$= (e^{-\lambda_1(1-z)})(e^{-\lambda_2(1-z)})(e^{-\lambda_3(1-z)})(e^{-\lambda_4(1-z)})(e^{-\lambda_5(1-z)})$$

$$= e^{-(1-z)(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5)}$$

Taking the inverse transform results in

$$g(y) = \frac{(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5)^t \, e^{-(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5)}}{t!}$$

which is a Poisson distribution. Therefore, the consolidated mean arrival rate is merely the sum of the individual mean arrival rates if the individual arrival processes are Poisson distributed.

The consolidation of the service rates is much more difficult. It is not an additive process. Schemes using differing service rates for tasks involve priority queues or multi-vector queueing analysis. Neither of these schemes apply to this analysis.

To develop a consolidated model that can use Green's method, a sampling plan that resamples from the individual work type data is used. The mean arrival rates of the individual work types are used to normalize the consolidated arrival rate. This normalization allows samples to be taken in the same volume as indicated by the individual arrival processes. Table 2 gives the range of values used in the normalizing process for selecting a data point from the various work types.

Using random number tables from Duncan [5], a random sample can be taken from the respective individual work type data. For example, if the number from Duncan's table is 74, then a sample data point is drawn from the Routine

TABLE 2
NORMALIZING PERCENTAGES FOR THE RANDOM SELECTION PROCESS

| Work Type | Norm. % | Range of Values |
|---|---|---|
| Emergency Job Order | 25 | 0 - 24 |
| Urgent Job Order | 37 | 25 - 61 |
| Minor Construction | 1 | 62 |
| Routine Job Order | 37 | 63 - 99 |

Source: Author's Calculations With WIMS Data

Job Order data.

Using another random number table, the specific data point to be drawn is determined. For each work type, a range of values to identify a specific data point is determined based on the number of data points per work type and the fact that the table gives random numbers between 0 and 99, inclusive.

This process uses two random numbers drawn from the tables to determine a single data point. The first number identifies the work type. The second number identifies the specific data point to be used in the consolidated model. Both the arrival rate and service rate are used to build the sample for the consolidated model. In all, 75 samples are taken.

To test the arrival data for the individual work types, a normal test from Giffin [6] that tests the hypothesis that the arrival processes are Poisson distributed with a constant rate parameter is used. The test is based on observing a Poisson process for a fixed time length T. If r events occur in [0,T] at times $t_1 \leq t_2 \ldots t_r \leq T$, then these times are considered to be r independent observations on a random variable uniformly distributed over [0,T]. The test invokes the central limit theorem to argue that the sum of the observed arrival times will be appoximately normally distributed. In Giffin's notation, for the predetermined time interval T, the sample statistic, S,

$$S = \sum_{i=1}^{r} t_i \tag{24}$$

will be approximately normally distributed with

$$\mu = rT/2 \tag{25}$$

and

$$\sigma^2 = rT^2/12 \tag{26}$$

For the consolidated data, a predetermined number of events is used since the predetermined time interval does not apply because of the consolidation technique. The test can still be used with modified equations for S, $\mu$, and $\sigma^2$. Again, using Giffin's notation, the equations are

$$S = \sum_{i=1}^{r-1} t_i \tag{27}$$

$$\mu = (r-1)(t_r)/2 \tag{28}$$

$$\sigma^2 = (r-1)(t_r)^2/12 \tag{29}$$

For the consolidated data, r = 75. Standard tables for the normal distribution are used to test the hypothesis with a 95 percent confidence interval.

The observations and details of the analysis for each work type are given in Appendix C. The sample statistic S and the acceptance range for each work type are listed in table 3.

TABLE 3
RESULTS OF THE NORMAL TEST ON ARRIVALS OF WORK REQUESTS

| Work Type | S | 95% Confidence Interval |
|---|---|---|
| Emergency Job Order | 2462.75 | (2389,3191) |
| Urgent Job Order | 894.04 | (821,1159) |
| Minor Construction | 3041.48 | (2336,3296) |
| Routine Job Order | 4571.46 | (3779,4771) |
| Work Order | 4200.20 | (2806,3850) |
| Consolidated Data | 4665.75 | (4450,5799) |

Source: Author's Calculations With WIMS Data

From these results, all but Work Orders fail to reject the hypothesis that the underlying distribution is Poisson. Because of the results of the individual work types, Work Orders are not included in the Consolidated Data.

In the case of the service time distribution a graphical analysis discussed by Giffin is used. The analysis first tests the hypothesis of the existence of randomness about the median using tables in Duncan [5].

The second phase of the analysis plots the actual data against a theoretical curve with the same mean as the data. The theoretical curve is developed using the cumulative distribution for an exponential distribution,

$$F(t) = 1 - e^{-\lambda t}, \qquad t \geq 0 \tag{30}$$

Using logarithms allows development of a straight line slope. From (30)

$$y = \ln\left[\frac{1}{1 - F(t)}\right] = \lambda t \tag{31}$$

Plotting y against t should result in a slope of $\lambda = 1/E(t)$. The sample estimate for F(t) is given by

$$F(t_i) = \frac{i}{n+1} \tag{32}$$

where n is the number of service times and $t_i$ is the length of the $i^{th}$ longest service time. If the data falls reasonably close to a straight line passing through the origin with slope $\hat{\lambda} = 1/\hat{\tau}$, $\hat{\tau}$ being the sample mean of the data, an exponential service time distribution is assumed. The details of this analysis for the work types is given in Appendix D. The resulting plots are given in figs. 5, 6, 7, 8, and 9.

The results of the graphical analysis show that only the service times for the Routine Job Orders may be assumed exponential. Rather than eliminating the use of Green's

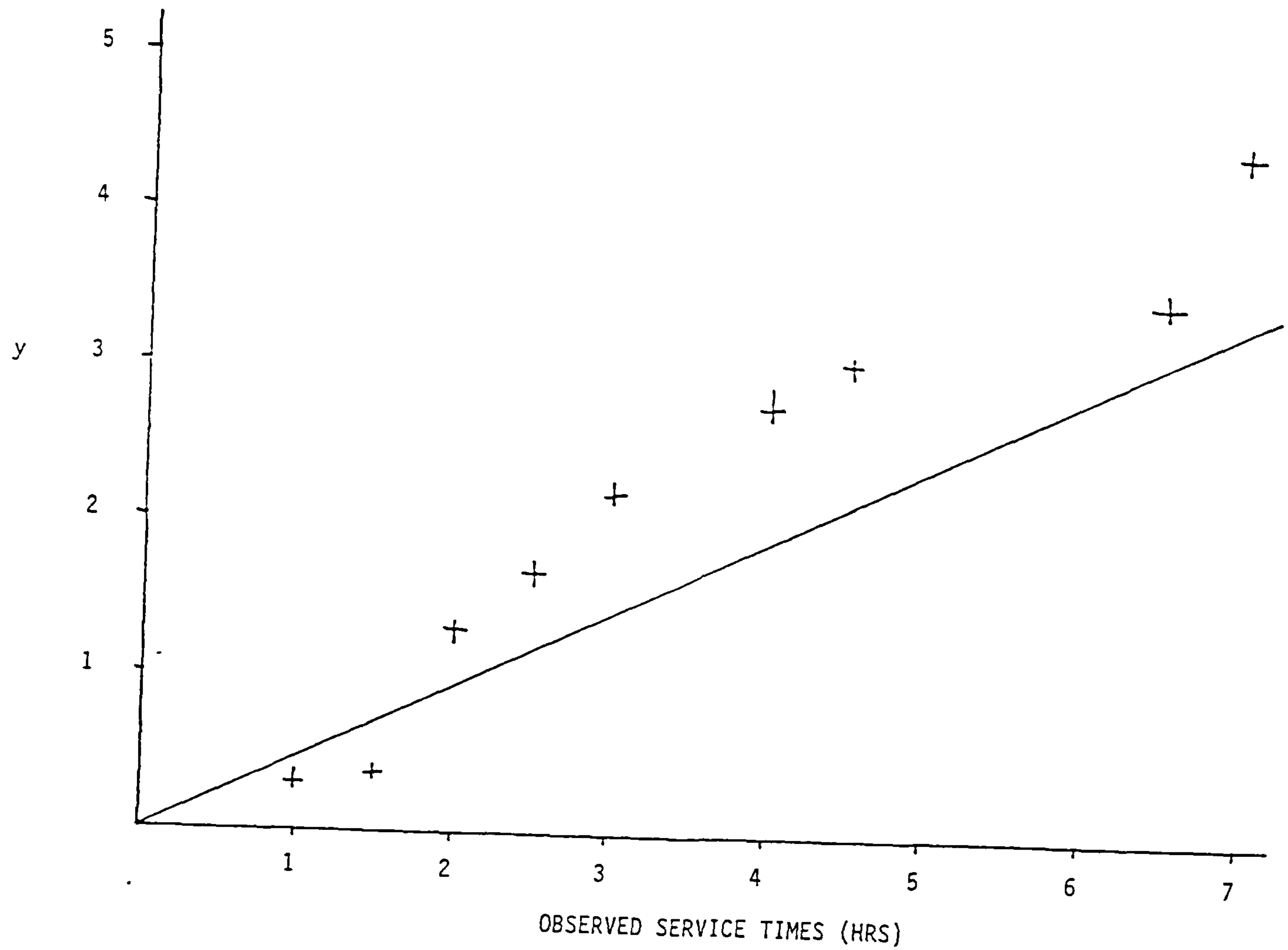


Fig. 5: Emergenc, Job Order Results Plot

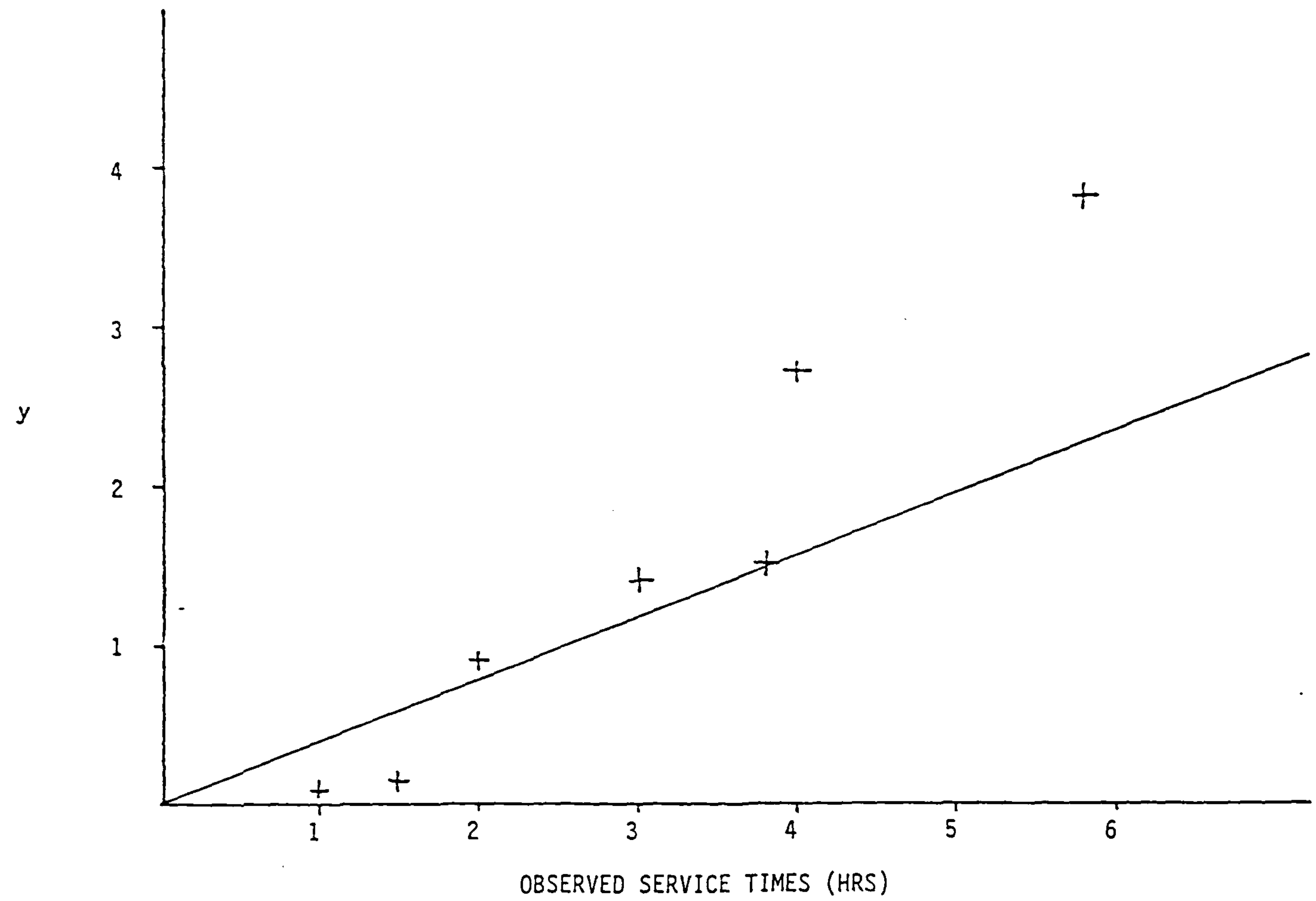


Fig 6: Urgent Job Order Results Plot

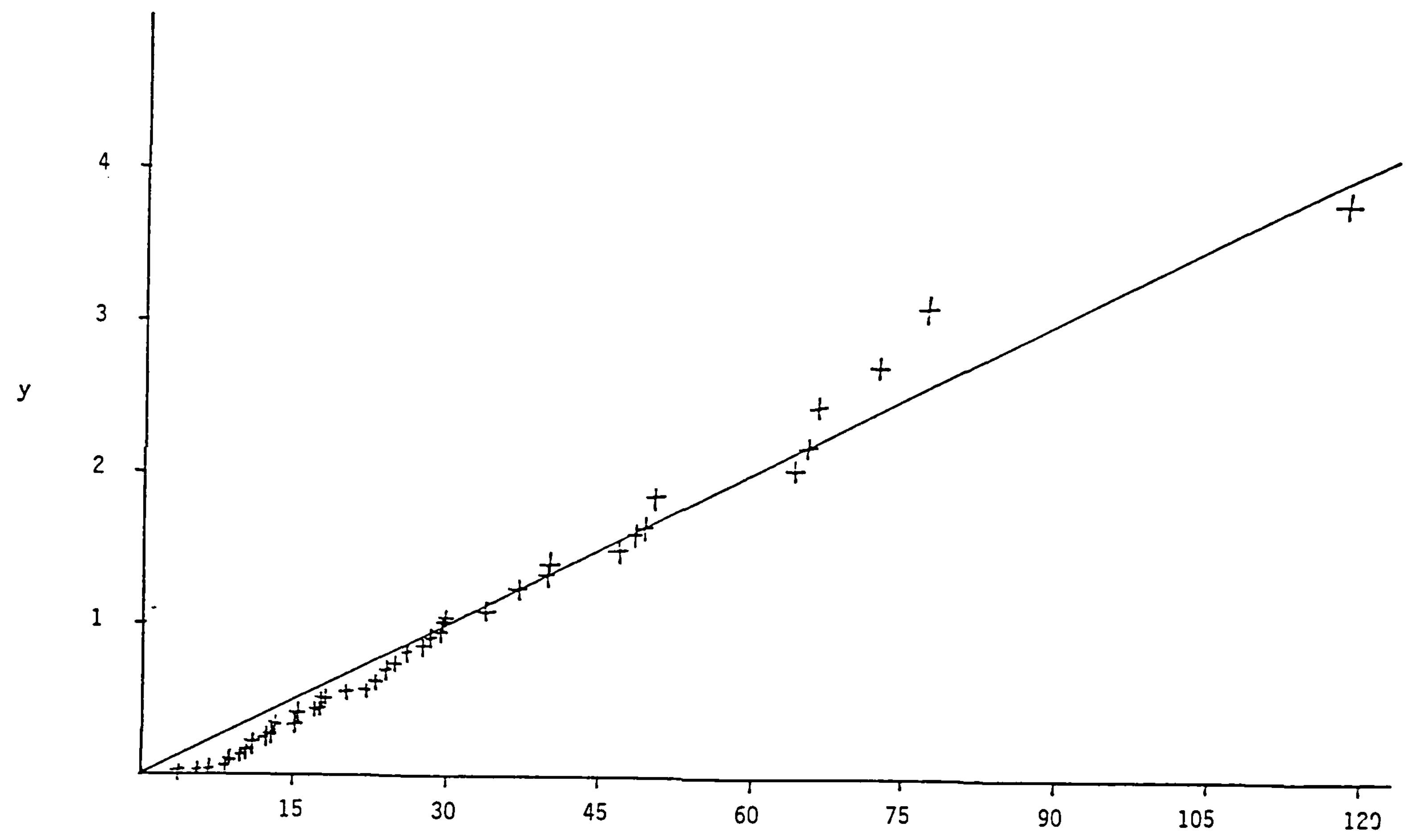


Fig 7: Minor Construction Results Plot

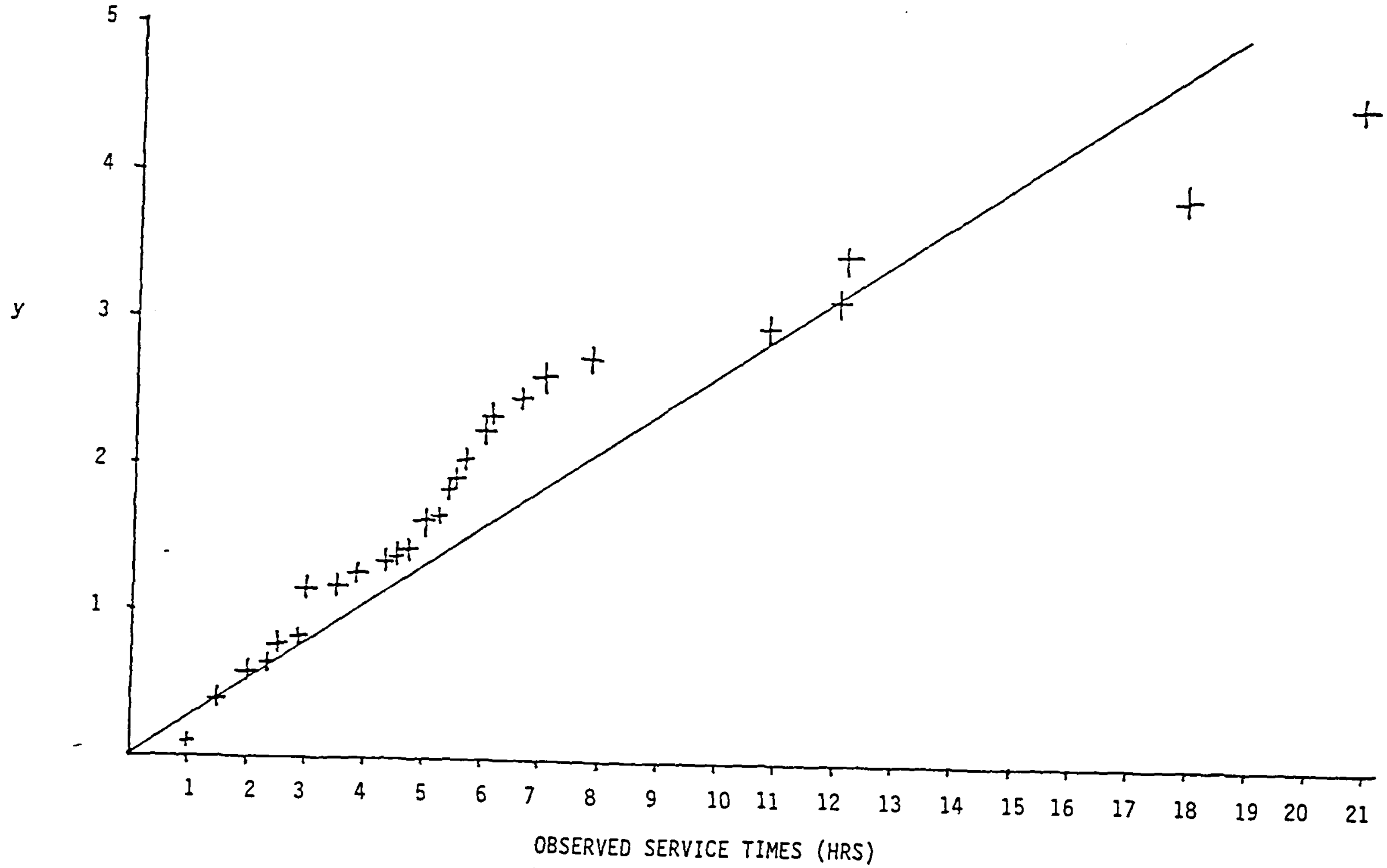


Fig 8: Routine Job Order Results Plot

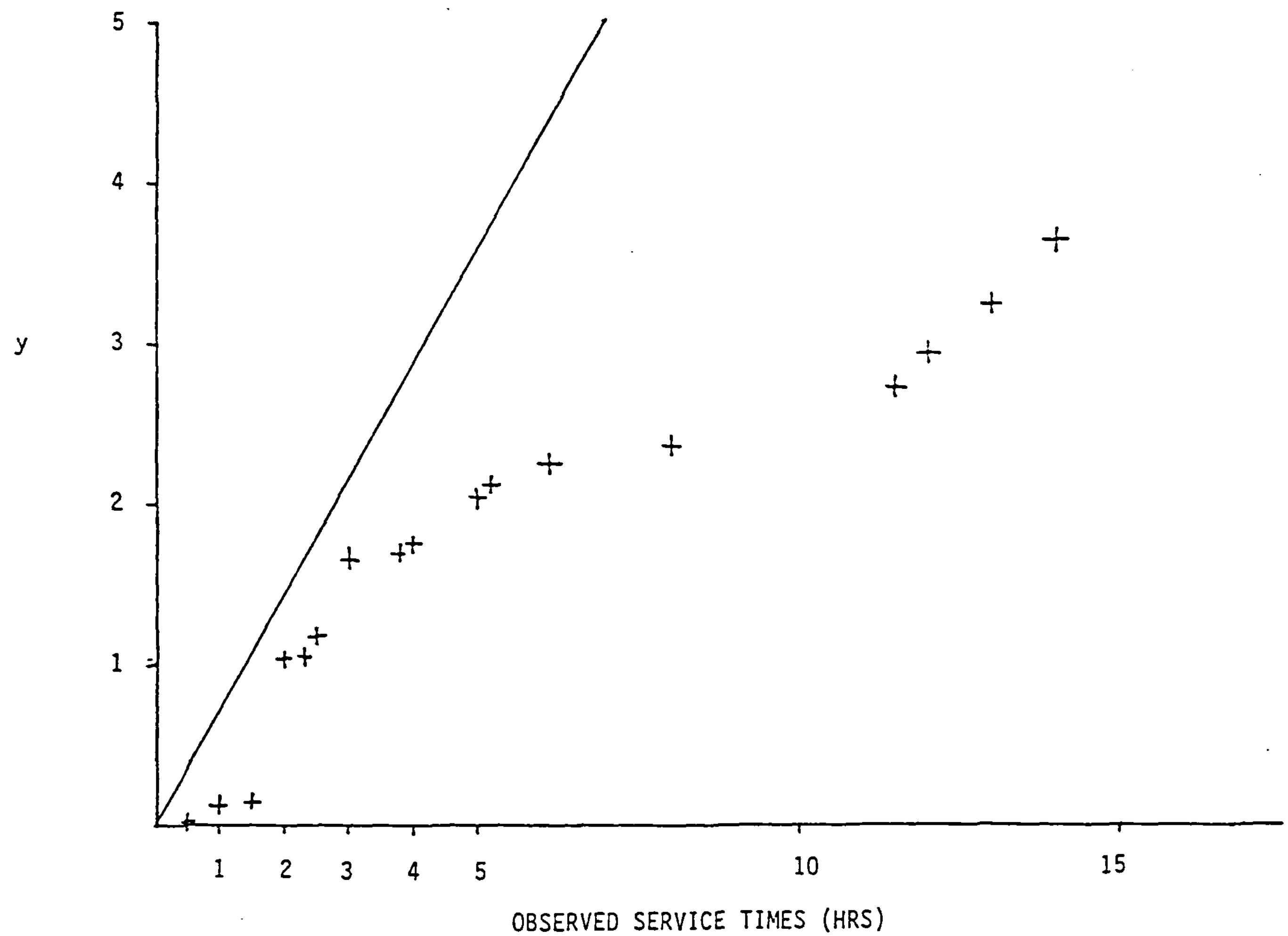


Fig 9: Consolidated Results Plot

method because the remaining service distributions are not exponentially distributed, and noting that the coefficient of variance for the work type and consolidated distributions are all less than 1, modelling the service distributions as exponential should not cause major difficulties. According to Giffin,

> "If one examines the expected waiting times for alternative choices of service distribution, the exponential will lead to a larger wait than for any other distribution whose coefficient of variation is less than unity. This includes the family of gamma distributions often used to describe service operations. The point is that design decisions made under the assumption that service is exponential, even when it obviously is not, will err on the safe side in terms of predicted line lengths and waiting times." [6]

Mean arrival times and mean service times calculated from this analysis are listed in table 4.

TABLE 4
MEAN ARRIVAL AND SERVICE RATES

| Work Type | Mean Arrival Rate ($\lambda$) tasks/hr | Mean Service Rate ($1/\mu$) hrs/task |
|---|---|---|
| Emergency Job Order | 0.73 | 2.129 |
| Urgent Job Order | 1.05 | 2.566 |
| Minor Construction | 0.04 | 30.220 |
| Routine Job Order | 1.05 | 3.757 |
| Consolidated Data | 0.54 | 3.380 |

Source: Author's Calculations With WIMS Data

Work orders, recurring work, and utility operations have not been forgotten. Their effects on the analysis will be handled separately in the application of Green's method, and this will be discussed in the next section.

The last bit of information needed as an input to Green's method is the probability of a customer needing i servers ($c_i$). Table 5 lists these percentages extracted from the data.

TABLE 5
VALUES OF $c_i$ FROM DATA

| | Probability of Needing i Servers | | | | |
|---|---|---|---|---|---|
| Work Type i = | 1 | 2 | 3 | 4 | 5 |
| Emergency Job Order | .95 | .05 | 0 | 0 | 0 |
| Urgent Job Order | .84 | .16 | 0 | 0 | 0 |
| Minor Construction | 0 | .20 | .25 | .40 | .15 |
| Routine Job Order | .49 | .32 | .08 | .11 | 0 |
| Consolidated Data | .57 | .18 | .08 | .13 | .04 |

Source: Author's Calculations With WIMS Data

Method Application

In the original concept of developing an aid for the programmers, the total effort of work was to be considered. Utility operations have been discounted because no work of this type is done in the Structures Shop. There is no data in WIMS referencing Recurring Work. It is known that one task is scheduled each week with an estimated completion time of 40 hours. But this arrival rate is known to be constant and therefore does not fit the Poisson arrival distribution needed to apply Green's method. Arrivals of work orders analyzed also do not fit a Poisson distribution.

To allow for testing Green's method, the availability rate information and direct hour percentages available on the BCE Monthly Labor Analysis Report are used. The availability rate aids in limiting the number of craftsmen used in the analysis. For example, an availability rate of 100% would indicate that all 74 assigned craftsmen should be used when applying Green's method (s = 74), while an availability rate of 50% indicates that 37 craftsmen should be used (s = 37).

The direct hour percentages are used to further reduce s to compensate for the workhours spent accomplishing recurring work and work orders. For example, assume an availability rate of 80%, resulting in s = 59. If recurring work accounts for 2% and work orders for 10% of the total direct work effort, then s can be reduced by an additional 12%, or s = 52. Table 6 lists the direct hour percentages for Fiscal Year (FY) 1984 and December 1984 as extracted from the October 1984 and January 1985 BCE Monthly Labor Analysis Reports used in this analysis.The availability rates from the same reports are 56.5% and 54.4%, respectively.

The operating characteristics to be found by Green's method are $W_q$ and W. In addition to these, L, the expected number of tasks in the system, including those tasks in service, and $L_q$, the expected number of tasks in

TABLE 6
DIRECT LABOR PERCENTAGES

| Work Type | FY 1984 (%) | December 1984 (%) |
|---|---|---|
| Recurring Work | 2.7 | 2.7 |
| Emergency Job Order | 6.9 | 5.2 |
| Urgent Job Order | 13.1 | 16.8 |
| Minor Construction | 18.3 | 17.3 |
| Routine Job Order | 31.4 | 37.9 |
| Work Order | 27.6 | 20.0 |
| Utility Operations | 0 | 0 |

Source: BCE Monthly Labor Analysis Reports

the queue, excluding the tasks being served, are found. These can be found by applying Little's formula given as

$$L = \lambda W \tag{33}$$

and

$$L_q = \lambda W_q \tag{34}$$

$W_q$ is calculated by the direct calculation method. An interactive computer program in Fortran 77 for use on a WANG VS-100 system has been developed to perform the necessary calculations. A copy of this program is included in Appendix E. W will be calculated by (17). L and $L_q$ can then be calculated using (33) and (34). The specific calculations for W, L, and $L_q$ are done manually.

At this point, it is time to apply Green's method to the CE model. As previously discussed, recurring work, work orders, and utility operations have been removed from the analysis using the direct calculation program. Fig. 10 illustrates the consolidated model.

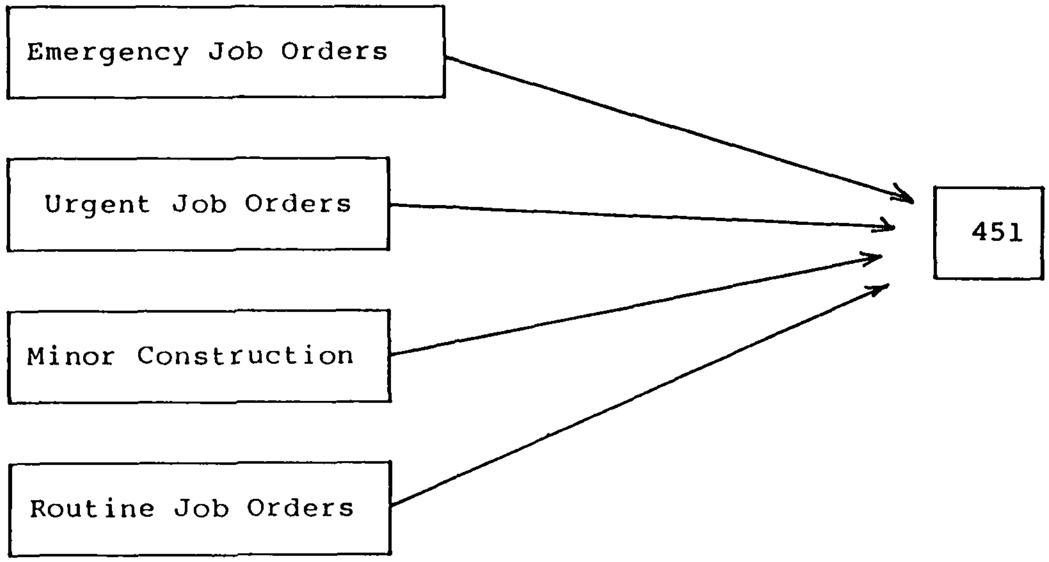


Fig. 10: Consolidated Model to Apply Green's Method

By removing a number of craftsmen from the workforce normally available to compensate for the workload generated by the recurring work and work order tasks, the results of W, $W_q$, L, and $L_q$ should be overestimates. Since a shop foreman has the latitude to assign craftsmen to complete work tasks, regardless of the work type, waiting times in the real system should be less than what will result by applying Green's method with, in effect, a group of craftsmen dedicated to completing only recurring work or work order tasks. This is a major modeling compromise introduced by using Green's method.

To analyze the independent work type model, the percentages of direct labor are used to set up multi-shops. Since the servers are independent, the craftsmen are separated based on the historical percentage of direct labor. This new model is shown in fig. 11.

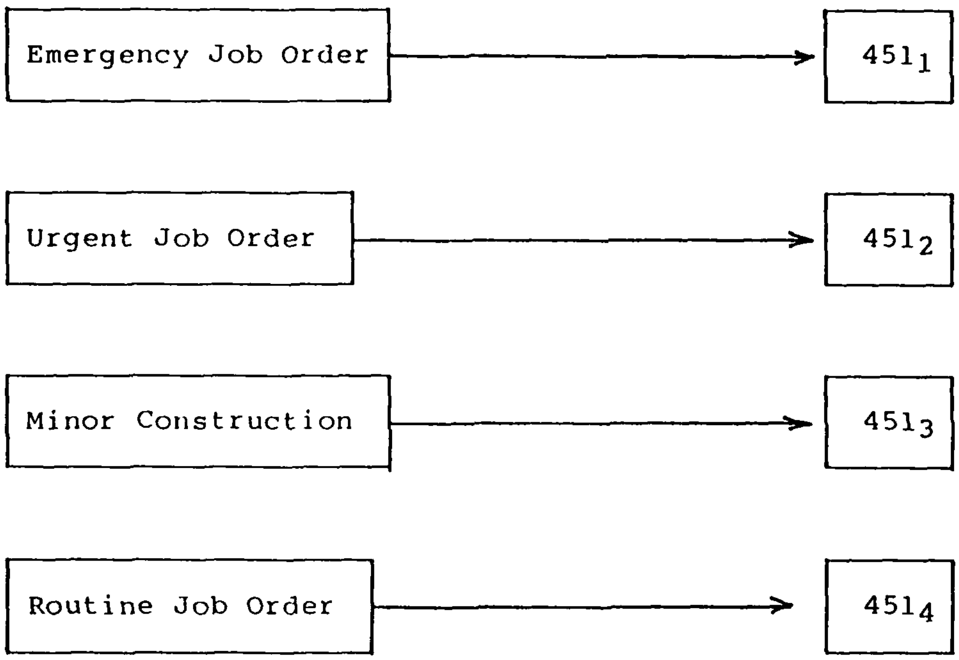


Fig. 11: Independent Task Model

Using these models, Green's method is applied. The resulting expected waiting times, expected number of tasks in the system and the queue, and the number of servers per task using the FY 1984 and December 1984 Labor Analysis Report data are listed in table 7. The program using Green's method also gives the number of craftsmen used to perform work tasks based on the direct labor percentages.

TABLE 7
RESULTS OF APPLYING GREEN'S METHOD

| Work Type | $W_q$ (hrs) | $L_q$ | W (hrs) | L | s |
|---|---|---|---|---|---|
| FY 1984 Data | | | | | |
| Emergency Job Order | 0.5593 | 0.4 | 2.7424 | 2.0 | 3 |
| Urgent Job Order | 0.5784 | 0.6 | 3.3447 | 3.5 | 5 |
| Minor Construction | 15.4802 | 0.6 | 74.0982 | 3.0 | 8 |
| Routine Job Order | 0.1714 | 0.2 | 5.2317 | 5.5 | 13 |
| Consolidated Data | <.0001 | <.001 | <.3990 | <.2 | 29 |
| December 1984 Data | | | | | |
| Emergency Job Order | 6.8705 | 5.0 | 9.0534 | 6.6 | 2 |
| Urgent Job Order | 0.0559 | 0.1 | 2.8222 | 3.0 | 7 |
| Minor Construction | 45.5841 | 1.8 | 104.2021 | 4.2 | 7 |
| Routine Job Order | 0.0489 | 0.1 | 5.1092 | 5.4 | 15 |
| Consolidated Data | <.0001 | <.001 | <.3990 | <.2 | 31 |

Source: Author's Calculations Using Green's Method

For the FY 1984 data, 1 craftsman is identified for recurring work and 12 craftsmen are identified for work orders. For the December 1984 data, 1 craftsman for recurring work and 8 craftsmen for work orders are identified.

The results of applying Green's Method clearly indicate that the expected wait times for the consolidated model are less than those for the independent model. This is not surprising. Since the craftsmen in the consolidated model can work any work type, the expected wait times should be less.

The degree that the expected wait times are different is on the order of 100 for the expected system wait times, and on the order of 1000 for the expected queue wait times. This large a difference shows how important the flexibility to work different work types is to a shop. Since this flexibility results in a quicker response time as seen by a customer, it helps improve the customer service provided by CE.

The application of the procedure allows for varying the number of craftsmen per task to analyze the effect. As expected, when the number of craftsmen used decreases, the expected waiting times increase. These results by work types are given in table 8.

Varying the number of servers has little effect on the consolidated model. Varying the number of servers in the independent model gives an indication of the minimum number of craftsmen needed to keep the backlog of that work type under control.

This does not indicate that specific craftsmen should be dedicated to the various work types. It does give the programmer and shop foreman some idea of how many craftsmen will be available to provide the flexibility needed to improve responsiveness. This is a real world consideration not covered explicitely in the models. If a programmer or foreman is directed to accomplish a given work type ahead of the others, this could be used as a guideline to determine how many craftsmen could be dedicated to that work type and still be able to prevent the backlog of other

TABLE 8
RESULTS OF VARYING THE NUMBER OF CRAFTSMEN

| s | $W_q$ | $L_q$ | W | L |
|---|---|---|---|---|
| Emergency Job Orders | | | | |
| 1 | | No Steady-state Solution | | |
| 2 | 6.8703 | 5.0 | 9.0534 | 6.6 |
| 3 | 0.5593 | 0.4 | 2.7424 | 2.0 |
| 4 | 0.1108 | 0.1 | 2.2939 | 1.7 |
| Urgent Job Orders | | | | |
| 3 | | No Steady-state Solution | | |
| 4 | 2.8079 | 2.9 | 5.5742 | 5.9 |
| 5 | 0.5784 | 0.6 | 3.3447 | 3.5 |
| 6 | 0.1726 | 0.2 | 2.9389 | 3.1 |
| 7 | 0.0559 | 0.1 | 2.8222 | 3.0 |
| Minor Construction | | | | |
| 6 | 6749.4210 | 270.0 | 6808.0390 | 272.3 |
| 7 | 45.5841 | 1.8 | 104.2021 | 4.2 |
| 8 | 15.4802 | 0.6 | 74.0982 | 3.0 |
| 9 | 6.9917 | 0.3 | 65.6097 | 2.6 |
| 10 | 3.5152 | 0.1 | 62.1332 | 2.5 |
| Routine Job Orders | | | | |
| 7 | | No Steady-state Solution | | |
| 8 | 118.3420 | 124.3 | 123.4023 | 129.6 |
| 9 | 4.2073 | 4.4 | 9.2676 | 9.7 |
| 10 | 1.4670 | 1.5 | 6.5273 | 6.9 |
| 11 | 0.6618 | 0.7 | 5.7221 | 6.0 |
| 12 | 0.3292 | 0.3 | 5.3895 | 5.7 |
| 13 | 0.1714 | 0.2 | 5.2317 | 5.5 |
| 14 | 0.0912 | 0.1 | 5.1515 | 5.4 |
| 15 | 0.0489 | 0.1 | 5.1092 | 5.4 |
| Consolidated Data | | | | |
| 5 | 33.2054 | 17.9 | 33.6044 | 18.1 |
| 6 | 2.6578 | 1.4 | 3.0568 | 1.6 |
| 7 | 0.8296 | 0.4 | 1.2286 | 0.7 |
| 8 | 0.3322 | 0.2 | 0.7312 | 0.4 |
| 9 | 0.1466 | 0.1 | 0.5456 | 0.3 |
| 10 | 0.0676 | 0.04 | 0.4666 | 0.3 |
| 11 | 0.0318 | 0.02 | 0.4308 | 0.2 |
| 12 | 0.0151 | 0.008 | 0.4141 | 0.2 |
| 15 | 0.0016 | 0.001 | 0.4006 | 0.2 |
| 19 | 0.0001 | $<$ .001 | 0.3991 | 0.2 |

Source: Author's Calculations Using Green's Method work types from becoming too large. The price paid by this type of management decision would be increasing the expected wait times, as indicated in the comparison of the consolidated and independent models previously discussed.

Summary

This chapter discusses three items. The first section is a highlight of the method developed by Green to analyze waiting times for multiserver systems that allow customers to select a random number of servers. The second section is a discussion of the analysis of data to test if it fits the distributions used in Green's method. The third section is the application of Green's method to specific model adaptations of the CE system. In the next chapter, the conclusions of this application and an examination of some avenues of possible research for use of queueing theory specific to CE are discussed.

# CHAPTER IV

## SUMMARY AND CONCLUSIONS

The results of the application of Green's method for the WIMS data are as expected. The expected waiting times for the consolidated model are significantly less than the times for the independent model.

To interpret these results as they relate to the actual CE system, use fig. 12 along with the discussion that follows.

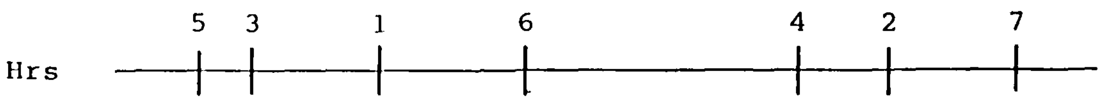


Fig. 12: Time Line Illustrating Results

Let 1 represent the positioning of the consolidated model results for the FY 1984 data. Interpreting in terms of hours, this represents a point that is less than 0.399 hours. Similarly, let 2 represent the independent model results. This is a point between 2.7424 and 74.0982 hours.

In the analysis, all service times are modeled as exponential distributions, even though none had a coefficient of variance equal to 1. Since this results in expected wait times greater than those that would result from using the true distributions, a second mark is made on the time line that indicates where the actual times might fall. 3 identifies the approximate adjusted results for the consolidated model and 4 identifies adjusted results for the independent model.

The next adjustment needed is to restore Work Orders and Recurring Work to the models. There is no impact on the independent model since each work type is treated independently. By adding more craftsmen to the consolidated model, the expected wait times are reduced further. Since more craftsmen add to the flexibility inherent in the consolidated model, it is logical to assume that taking the "independence" away from the Work Orders and Recurring Work results in lower expected wait times. This is shown on the time line by 5.

The last adjustment to make involves Green's independent-server system approximating the true joint-service model of CE. Since all craftsmen complete work together in the CE system, and since it is assumed that the longest independent server time drives the approximation that results from using Green's method, the numerical results of the analysis represent a lower bound on the actual CE system expected wait times. This leads to mark 6 for the consolidated model and mark 7 for the independent model.

At this point, it is clear that mark 6 should approximate the actual joint-service system that represents CE. Since there is no current way to validate the results, as discussed earlier, mark 6 is merely the author's best estimate of where the expected system wait times should fall in relation to the consolidated and independent model results given by using Green's method. The consolidated model results can be used as a lower bound of the true system, while the independent results might be utilized as an upper bound. Without actual expected wait time information, this assertion cannot be validated.

The analysis of the consolidated model and independent model using Green's method indicates that using the consolidated model is a viable alternative for CE programmers. The selection of the consolidated model over the independent model is made because it more truly reflects the way work tasks are processed in a CE shop. The way to check this for certain is to compare against an actual CE system. To do the actual comparison, changes need to be incorporated into the work processing programming of WIMS.

To this point in time, the ability to track the work flow process in the depth needed to perform a detailed queueing analysis has not been available. Using queueing techniques to analyze CE is new to CE managers. A means of obtaining more accurate work start times by the shop could be an interface with the labor reporting programming to allow the actual start time to be recorded in the work processing system in real time as opposed to reporting completed hours after the fact.

The analysis at the shop level is only one node in a network of work flow processing by CE. Future research using Green's method can test whether or not the method can be the terminal node for a Jackson network [10],[11]. Since the output from a node in the Jackson network enters the succeeding node in a Poisson fashion, on the surface it appears it should work. If successful, this represents a powerful programming aid in CE.

As CE acquires the mini-computers world-wide through the late 1980's, the potential for use of techniques such as Green's method is enormous. Future development of analytical queueing techniques by researchers can be used by CE managers to truly improve the efficiency and effectiveness of CE real property activities.

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APPENDIX A

WORK PROCESSING FLOW CHARTS

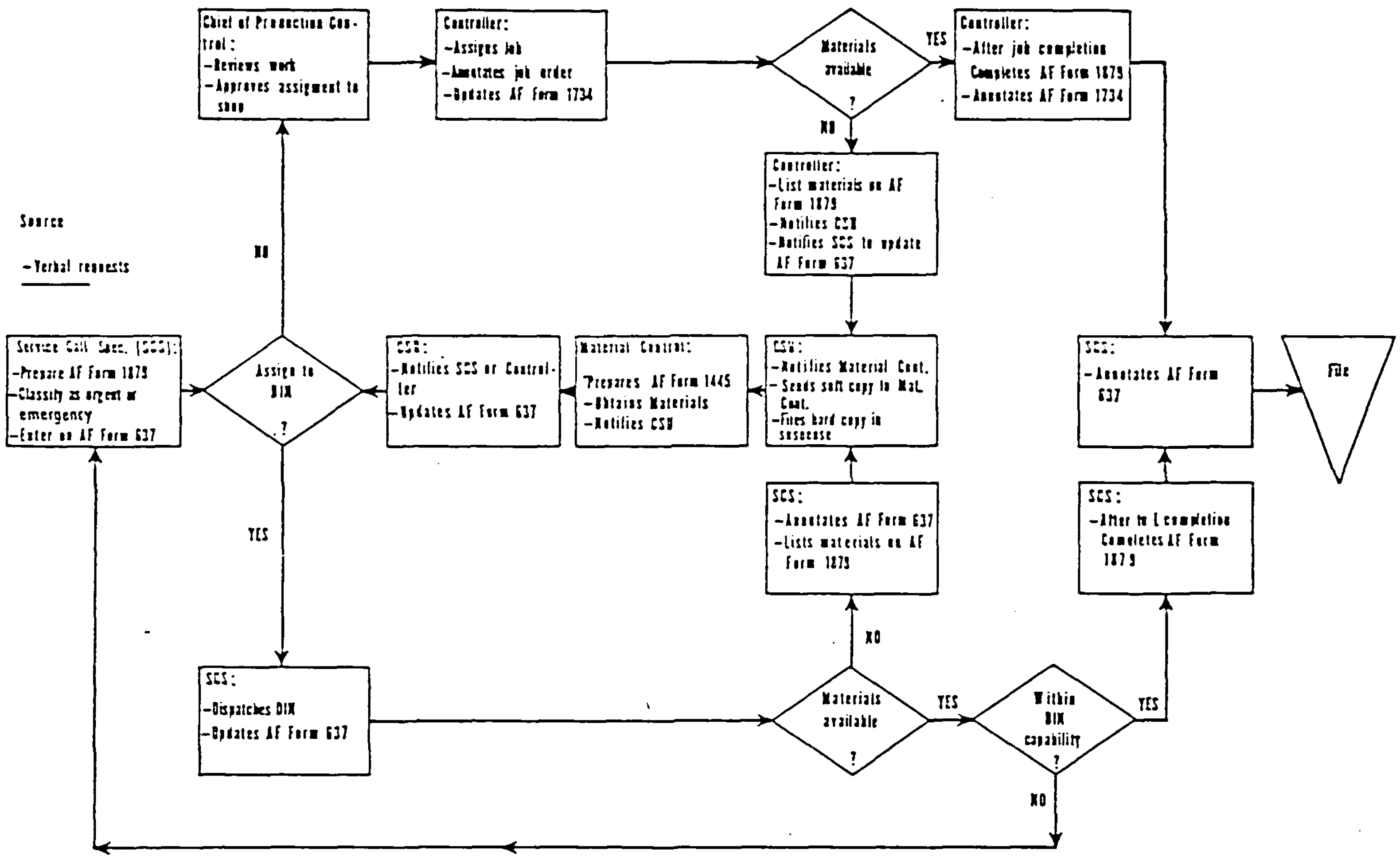


Fig. 13: Emergency or Urgent Job Order Flow Chart

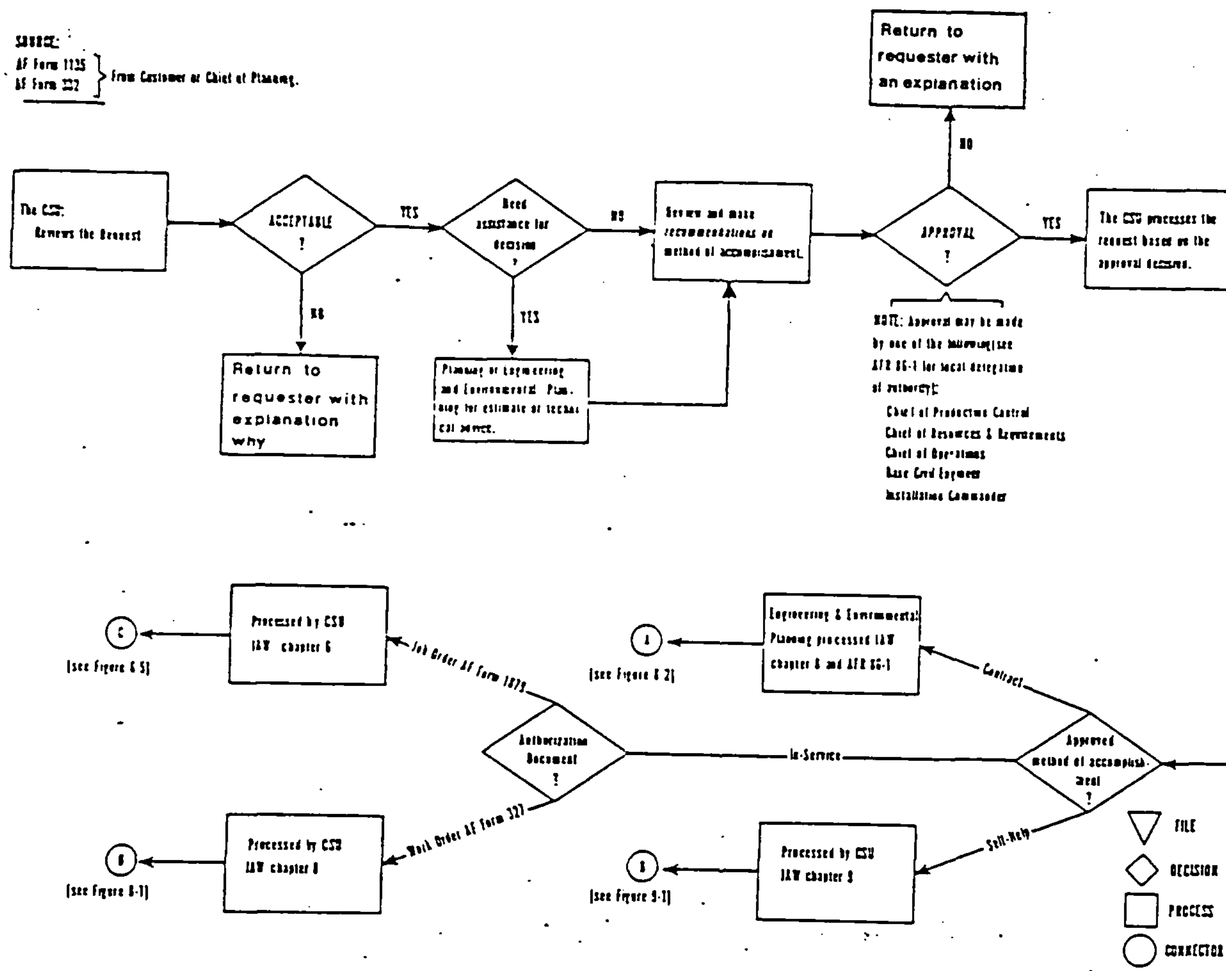


Fig. 14: Written Work Request Flow Chart

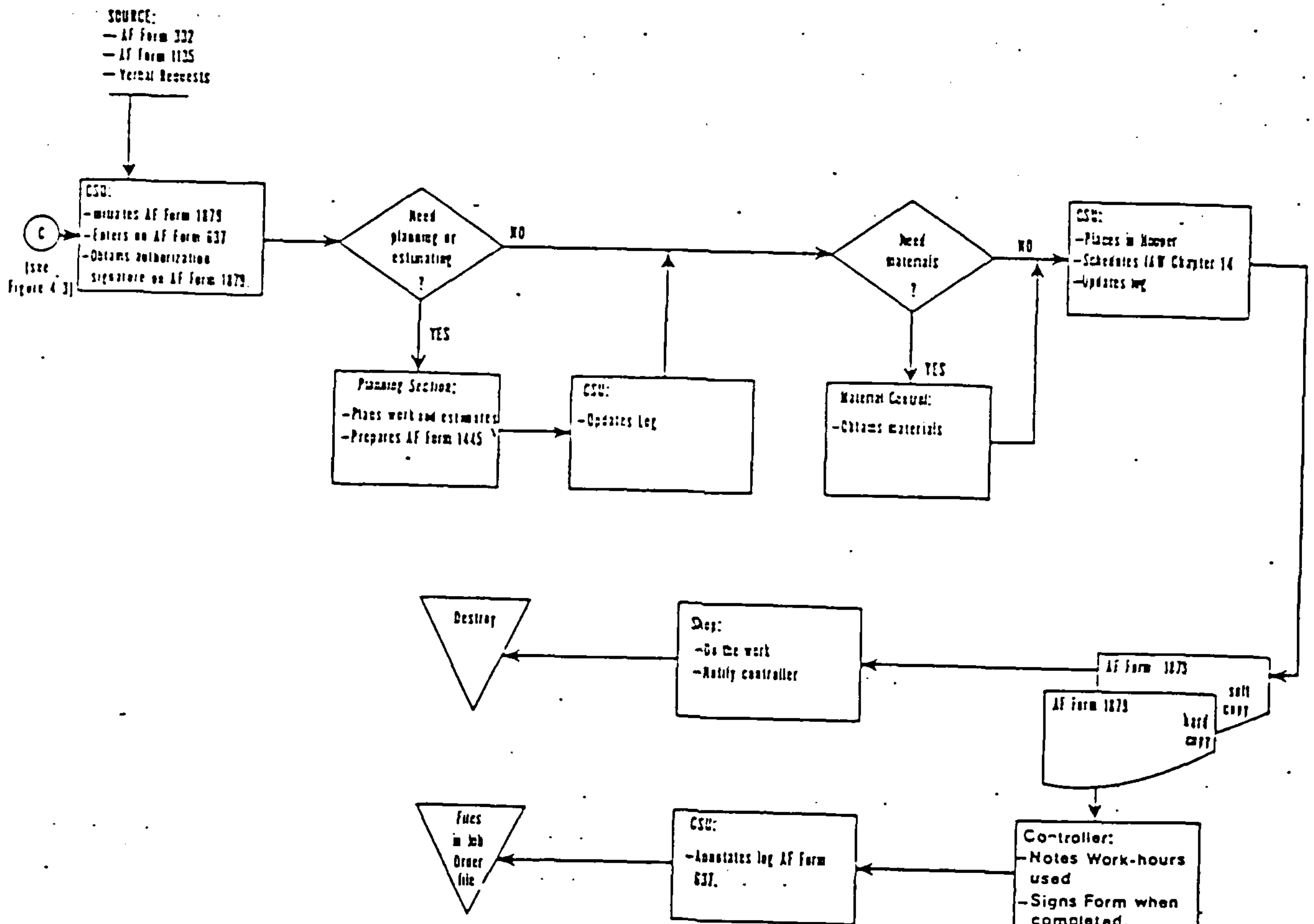


Fig. 15: Routine Job Order Flow Chart

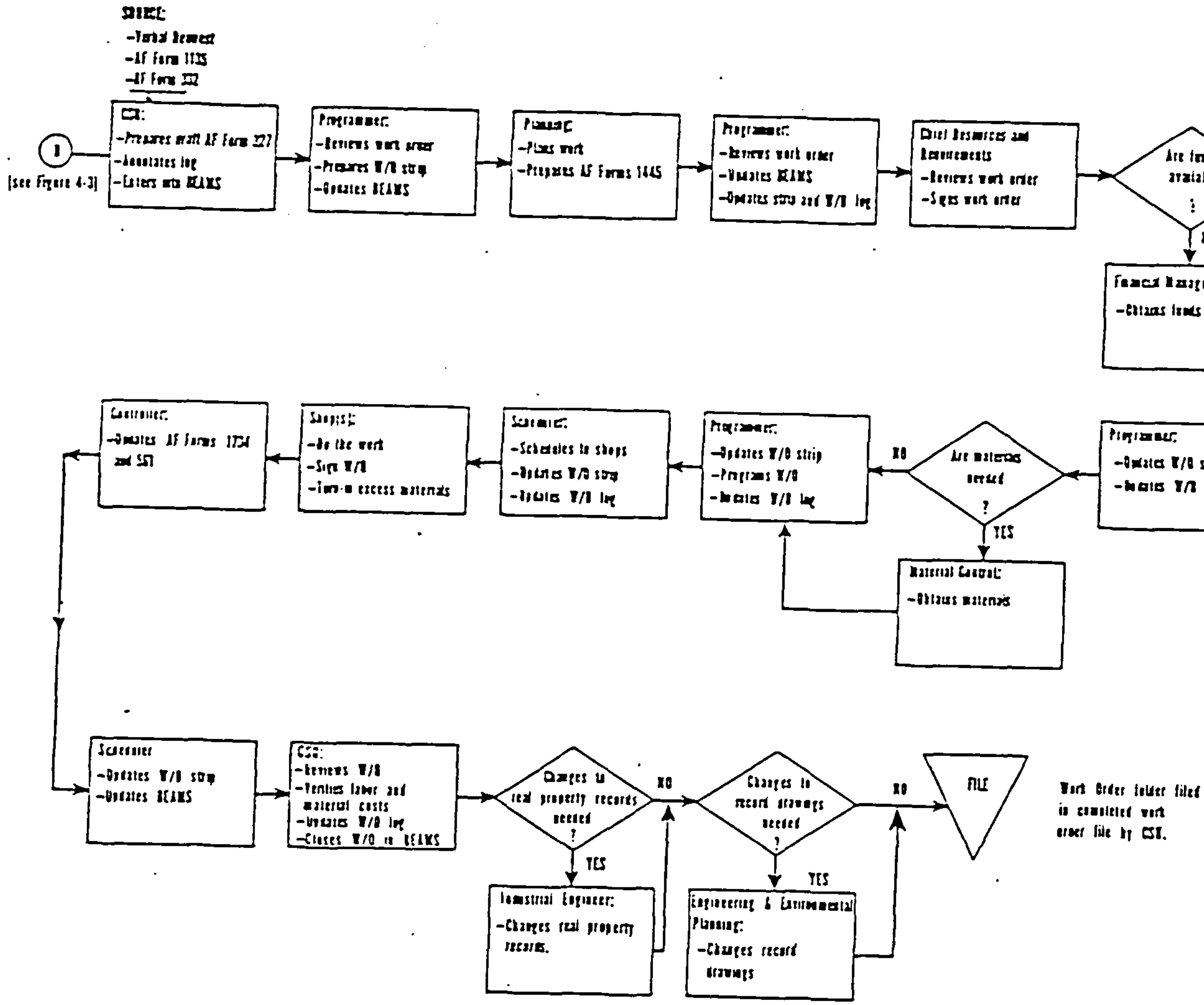


Fig. 16: Inservice Work Order Flow Chart

# APPENDIX B

# INTERIM CALCULATIONS FOR USING GREEN'S METHOD

This appendix gives the equations necessary to apply Green's method of calculating the expected waiting times for independent server system.

$P_B$ is the transition matrix for the Markov chain embedded in the system.

$$P_B = \begin{array}{cc} & \begin{array}{cccccc} 0 & 1 & 2 & & s & s+1 \end{array} \\ \begin{array}{c} 0 \\ 1 \\ 2 \\ \vdots \\ s \\ s+1 \end{array} & \begin{bmatrix} 0 & c_1 & c_2 & \cdots & c_s & 0 \\ \frac{\mu}{\lambda+\mu} & 0 & \frac{c_1\lambda}{\lambda+\mu} & \cdots & \frac{c_{s-1}\lambda}{\lambda+\mu} & \frac{c_s\lambda}{\lambda+\mu} \\ 0 & \frac{2\mu}{\lambda+2\mu} & 0 & \cdots & \frac{c_{s-2}\lambda}{\lambda+2\mu} & \frac{(c_{s-1}+c_s)\lambda}{\lambda+2\mu} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & \frac{\lambda}{\lambda+s\mu} \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \end{array}$$

where s is the number of busy servers, and s+1 is the absorption state for this system. Putting $P_B$ into canonical form results in

$$P_B = \left[\begin{array}{c|c} 1 & 0 \ldots 0 \\ \hline & \\ A & T \\ & \end{array}\right].$$

T is the transition matrix for the transient states, A is the matrix of absorption probabilities, and the single element 1 corresponds to the ergodic state, s+1. Kemeny and Snell [12] have proven that the matrix $(V_{ij})$ which gives the expected number of visits to transient state j starting in transient state i before absorption is given by

$$V = (I - T)^{-1} \tag{35}$$

I is the identity matrix. T is found as follows:

$$T = \begin{array}{cc} & \begin{array}{ccccc} 0 & 1 & 2 & \cdots & s \end{array} \\ \begin{array}{c} 0 \\ 1 \\ 2 \\ \vdots \\ s \end{array} & \begin{bmatrix} 0 & c_1 & c_2 & \cdots & c_s \\ \dfrac{\mu}{\lambda+\mu} & 0 & \dfrac{c_1\lambda}{\lambda+\mu} & \cdots & \dfrac{c_{s-1}\lambda}{\lambda+\mu} \\ 0 & \dfrac{2\mu}{\lambda+2\mu} & 0 & \cdots & \dfrac{c_{s-2}\lambda}{\lambda+2\mu} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & \cdots & \dfrac{\lambda}{\lambda+s\mu} \end{bmatrix} \end{array}$$

V is needed to calculate the expected value for the length of a non-queue period, $E(\bar{Q})$.

$$E(\bar{Q}) = \sum_{j=0}^{s} \frac{V_{sj}}{\lambda + j\mu} \tag{36}$$

$\bar{q}_i$ is the probability that a customer arriving during a non-queue period sees i busy servers upon arrival.

$$\bar{q}_i = \frac{V_{si}/(\lambda + i\mu)}{E(\bar{Q})} \quad , \quad i=0, \ldots , s \tag{37}$$

$E(\bar{L})$ is the expected number of arrivals during a non-queue period.

$$E(\bar{L}) = \lambda E(\bar{Q}) \tag{38}$$

$p_d$ is defined as the probability that a customer who arrives to an empty queue will experience a delay (i.e. start a queueing period).

$$p_d = \sum_{i=1}^{s} \bar{q}_i \sum_{k=1}^{i} c_{s-i+k} \tag{39}$$

E(B) and E(D), the expected value of the interservice random variable and the expected value of the initial delay random variable, respectively, can be computed directly or using Laplace Transform techniques. The direct calculation equation for E(B) is equation (19). E(D) can be found directly by

$$E(D) = \sum_{i=1}^{s} \sum_{k=1}^{i} \left[ \frac{1}{i\mu} + \frac{1}{(i-1)\mu} + \ldots + \frac{1}{(i-k+1)\mu} \right] \bar{q}_i c_{s-i+k}/p_d \tag{40}$$

To solve E(B) and E(D) using Laplace Transform techniques, B(t), given by equation (6), and D(t), given by equation (8), must first be evaluated. The resulting distributions must then be transformed to the s domain in accordance with equation (4). Once expressed as a Laplace Transform, E(B) and E(D) can be found by evaluating the first moment of the transforms, setting s=0. Therefore,

$$E(B) = (-1) \frac{d}{ds} B^*(s) \Big|_{s=0} \tag{41}$$

and

$$E(D) = (-1) \frac{d}{ds} D^*(s) \Big|_{s=0} \tag{42}$$

E(Q) is the expected length of a queueing period and is given by equation (18). $p_q$ is the probability that a queue exists.

$$p_q = \frac{E(Q)}{E(\bar{Q}) + E(Q)} \tag{43}$$

All that remains to find $W_q$ with Laplace Transforms using equations (11) and (12) is to find values for $B_e^*(s)$ and $D_e^*(s)$. These values can be found using equations (13), (14), and (4).

To continue with the direct calculation, some more terms are needed. E(L) is the expected number of arrivals during a queueing period.

$$E(L) = \frac{p_q}{p_d(1-p_q)} \quad \text{or} \quad E(L) = \lambda E(Q) \tag{44}$$

$q_i$ is the probability that a customer arriving during a queueing period sees i busy servers upon arrival.

$$q_i = [E(L) \sum_{k=s-i+1}^{s} c_k + \sum_{j=i}^{s} \bar{q}_j \sum_{k=s-i+1}^{s} c_k/p_d]/i\mu E(Q) \tag{45}$$

$q_i$ is the last variable needed to calculate E(R) given by equation (16). After calculating E(R), use equation (15) to calculate $W_q$.

To find W, L, and $L_q$, follow the procedure outlined in Chapter 3.

APPENDIX C

TABLES, CALCULATIONS, AND

FIGURES OF THE ARRIVAL ANALYSIS

TABLE 9
EMERGENCY JOB ORDER ARRIVAL TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|
| 0.43 | 21.02 | 41.70 | 58.17 |
| 1.13 | 22.45 | 42.27 | 59.32 |
| 1.78 | 25.80 | 46.02 | 59.80 |
| 1.98 | 27.97 | 46.57 | 61.03 |
| 2.25 | 28.85 | 46.82 | 63.45 |
| 2.63 | 28.87 | 47.35 | 65.47 |
| 2.68 | 29.90 | 49.07 | 66.90 |
| 3.58 | 33.12 | 49.22 | 76.02 |
| 3.73 | 33.33 | 51.32 | 76.75 |
| 4.40 | 37.23 | 52.57 | 82.23 |
| 6.62 | 37.82 | 54.58 | 82.33 |
| 6.68 | 38.03 | 55.32 | 83.10 |
| 10.08 | 38.38 | 55.95 | 83.17 |
| 18.88 | 38.52 | 56.08 | 83.38 |
| 19.17 | 38.92 | 56.33 | 84.48 |
| 20.60 | 39.15 | | |

Source: WIMS Data

Using Table 9, along with the hypothesis test explained in Chapter 3, these were the following results.

$$T = 90 \text{ hrs}, \qquad r = 62 \text{ observations}$$

$$S = \sum_{i=1}^{r} t_i = \sum_{i=1}^{62} t_i = 2462.75$$

$$\mu = rT/2 = (62)(90)/2 = 2790$$

$$\sigma^2 = rT^2/12 = (62)(90)^2/12 = 41850$$

95% acceptance interval: $S_A = 2790 \mp 1.96(205) = (2389,3190)$

Cannot reject the hypothesis of Poisson distributed.

TABLE 10
EMERGENCY JOB ORDER TIME BETWEEN ARRIVALS

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|
| 0.70 | 1.43 | 2.55 | 1.84 |
| 0.65 | 3.35 | 0.57 | 1.15 |
| 0.20 | 2.17 | 3.75 | 0.48 |
| 0.27 | 0.88 | 0.55 | 1.23 |
| 0.38 | 0.02 | 0.25 | 2.42 |
| 0.05 | 1.03 | 0.53 | 2.02 |
| 0.90 | 3.22 | 1.72 | 1.43 |
| 0.15 | 0.21 | 0.15 | 9.12 |
| 0.67 | 3.90 | 2.10 | 0.73 |
| 2.22 | 0.59 | 1.25 | 5.48 |
| 0.06 | 0.21 | 2.01 | 0.10 |
| 3.40 | 0.35 | 0.74 | 0.77 |
| 8.80 | 0.14 | 0.63 | 0.07 |
| 0.29 | 0.40 | 0.13 | 0.21 |
| 1.43 | 0.23 | 0.25 | 1.10 |
| 0.42 | | | |

Source: Calculations Using WIMS Data

Using the time between arrival data, the mean and standard deviation are calculated. The inverse of the mean is the input for Green's method.

$$\bar{X} = 1.378$$

$$S^2 = 1.820$$

$$S = 1.349$$

$$\hat{\lambda} = 1/1.378 = 0.73 \text{ arrivals/hour}$$

TABLE 11
URGENT JOB ORDER ARRIVAL TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|
| 1.17 | 11.32 | 19.88 | 29.45 |
| 2.20 | 11.35 | 21.33 | 30.22 |
| 2.95 | 11.72 | 21.83 | 31.25 |
| 6.88 | 11.90 | 22.38 | 31.33 |
| 6.98 | 11.92 | 23.63 | 33.88 |
| 7.63 | 12.57 | 23.72 | 34.50 |
| 8.18 | 17.10 | 24.88 | 37.57 |
| 8.48 | 18.85 | 25.97 | 37.63 |
| 8.55 | 19.18 | 26.67 | 38.05 |
| 9.88 | 19.30 | 27.72 | 41.47 |
| 11.12 | 19.87 | 29.33 | 42.25 |

Source: WIMS Data

Using Table 11, along with the hypothesis test explained in Chapter 3, these were the following results.

$T = 45$ hrs, $r = 44$ observations

$$S = \sum_{i=1}^{r} t_i = \sum_{i=1}^{44} t_i = \text{[illegible]}94.04$$

$$\mu = rT/2 = (44)(45)/2 = 990$$

$$\sigma^2 = rT^2/12 = (44)(45)^2/12 = 7424$$

95% acceptance interval: $S_A = 990 \mp 1.96(86.2) = (821,1159)$

Cannot reject the hypothesis of Poisson distribution.

TABLE 12
URGENT JOB ORDER TIME BETWEEN ARRIVALS

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|
| 1.03 | 0.03 | 1045 | 0.77 |
| 0.75 | 0.37 | 0.50 | 1.03 |
| 3.93 | 0.18 | 0.55 | 0.08 |
| 0.10 | 0.02 | 1.25 | 2.55 |
| 0.65 | 0.65 | 0.09 | 0.62 |
| 0.55 | 4.53 | 1.16 | 3.07 |
| 0.30 | 1.75 | 1.09 | 0.06 |
| 0.07 | 0.33 | 0.70 | 0.42 |
| 1.33 | 0.12 | 1.05 | 3.42 |
| 1.24 | 0.57 | 1.61 | 0.78 |
| 0.20 | 0.01 | 0.12 | |

Source: Calculations Using WIMS Data

Using the time between arrival data, the mean and standard deviation are calculated. The inverse of the mean is the input for Green's method.

$\overline{X} = 0.955$

$S^2 = 1.069$

$S = 1.034$

$\hat{\lambda} = 1/0.955 = 1.05$ arrivals/hour

TABLE 13
MINOR CONSTRUCTION ARRIVAL TIMES

| Time(dys) | Time(dys) | Time(dys) | Time(dys) | Time(dys) |
|---|---|---|---|---|
| 2.22 | 40.35 | 60.95 | 79.36 | 102.77 |
| 5.17 | 41.87 | 61.06 | 83.59 | 107.32 |
| 10.65 | 42.02 | 63.58 | 85.46 | 112.09 |
| 10.68 | 48.22 | 65.24 | 87.13 | 112.77 |
| 15.84 | 48.57 | 68.82 | 93.37 | 113.85 |
| 19.68 | 49.51 | 72.23 | 93.79 | 117.05 |
| 24.95 | 49.61 | 77.47 | 93.93 | 117.52 |
| 25.23 | 51.09 | 79.19 | 97.55 | 118.30 |
| 36.92 | 54.43 | 79.27 | 99.39 | 121.62 |

Using Table 13, along with the hypothesis test explained in Chapter 3, these were the following results.

$$S = \sum_{i=1}^{r} t_i = \sum_{i=1}^{44} t_i = 3041.48$$

$$\mu = rT/2 = (44)(128)/2 = 2816$$

$$\sigma^2 = rT^2/12 = (44)(128)^2/12 = 60,074$$

95% acceptance interval: $S_A = 2816 \mp 1.96(245) = (2336,3296)$

Cannot reject the hypothesis of Poisson distributed.

TABLE 14
MINOR CONSTRUCTION TIME BETWEEN ARRIVALS

| Time(dys) | Time(dys) | Time(dys) | Time(dys) | Time(dys) |
|---|---|---|---|---|
| 2.95 | 1.52 | 0.11 | 4.23 | 4.55 |
| 5.48 | 0.15 | 2.52 | 1.87 | 4.77 |
| 0.03 | 6.20 | 1.66 | 1.67 | 0.68 |
| 5.16 | 0.35 | 3.58 | 6.24 | 1.08 |
| 3.84 | 3.21 | 5.44 | 0.42 | 3.20 |
| 5.27 | 0.94 | 5.44 | 0.14 | 0.47 |
| 0.28 | 0.10 | 1.72 | 3.62 | 0.78 |
| 11.69 | 1.48 | 0.08 | 1.84 | 3.32 |
| 3.43 | 3.34 | 0.09 | 3.38 | |

Source: Calculations Using WIMS Data

Using the time between arrival data, the mean and standard deviation are calculated. The inverse of the mean is the input for Green's method.

$\bar{X} = 2.714$

$S^2 = 2.427$

$S = 1.558$

$\hat{\lambda} = 1/2.714 = .368$ arrivals/day $= 0.041$ arrivals/hour

TABLE 15
ROUTINE JOB ORDER ARRIVAL TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|---|
| 0.10 | 22.32 | 41.92 | 55.90 | 79.35 |
| 0.23 | 22.75 | 42.23 | 56.13 | 80.25 |
| 1.02 | 23.22 | 42.38 | 56.82 | 80.47 |
| 1.75 | 24.58 | 45.38 | 57.62 | 80.52 |
| 2.25 | 26.55 | 45.50 | 58.83 | 80.75 |
| 2.60 | 27.83 | 45.60 | 61.95 | 81.25 |
| 3.62 | 29.63 | 45.70 | 64.30 | 81.55 |
| 3.98 | 30.00 | 45.77 | 65.55 | 81.80 |
| 6.25 | 30.05 | 46.38 | 65.68 | 81.82 |
| 6.63 | 31.37 | 46.60 | 66.17 | 81.92 |
| 7.52 | 31.82 | 46.65 | 69.33 | 82.78 |
| 14.50 | 33.28 | 52.68 | 69.47 | 83.13 |
| 16.60 | 34.53 | 54.72 | 70.38 | 83.83 |
| 16.77 | 34.60 | 54.82 | 71.23 | 84.72 |
| 16.92 | 38.10 | 54.92 | 73.67 | 86.78 |
| 17.68 | 38.12 | 55.10 | 76.47 | 88.72 |
| 19.28 | 38.48 | 55.17 | 78.05 | 88.75 |
| 19.80 | 39.77 | 55.30 | 78.35 | 89.05 |
| 22.18 | 41.38 | 55.42 | 78.47 | 89.35 |

Source: WIMS Data

Using Table 15, along with the hypothesis test explained in Chapter 3, these were the following results.

$T = 90$ hrs, $r = 95$ observations

$$S = \sum_{i=1}^{r} t_i = \sum_{i=1}^{95} t_i = 4571.46$$

$$\mu = rT/2 = (95)(90)/2 = 4275$$

$$\sigma^2 = rT^2/12 = (95)(90)^2/12 = 64,125$$

95% acceptance interval: $S_A = 4275 \mp 1.96(253) = (3779,4771)$

Cannot reject the hypothesis of Poisson distributed.

TABLE 16
ROUTINE JOB ORDER TIME BETWEEN ARRIVALS

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|---|
| 0.13 | 0.43 | 0.31 | 0.23 | 0.90 |
| 0.79 | 0.47 | 0.15 | 0.69 | 0.22 |
| 0.73 | 1.36 | 3.00 | 0.80 | 0.05 |
| 0.50 | 1.97 | 0.12 | 1.21 | 0.23 |
| 0.35 | 1.28 | 0.10 | 3.12 | 0.50 |
| 1.02 | 1.80 | 0.10 | 2.35 | 0.30 |
| 0.36 | 0.37 | 0.07 | 1.25 | 0.25 |
| 2.27 | 0.05 | 0.61 | 0.13 | 0.02 |
| 0.38 | 1.32 | 0.22 | 0.49 | 0.10 |
| 0.89 | 0.45 | 0.05 | 3.16 | 0.86 |
| 6.98 | 1.46 | 6.03 | 0.14 | 0.35 |
| 2.10 | 1.25 | 2.04 | 0.91 | 0.70 |
| 0.17 | 0.07 | 0.10 | 0.85 | 0.89 |
| 0.15 | 3.50 | 0.10 | 2.44 | 2.06 |
| 0.76 | 0.02 | 0.18 | 2.80 | 1.94 |
| 1.60 | 0.36 | 0.07 | 1.58 | 0.03 |
| 0.52 | 1.29 | 0.13 | 0.30 | 0.30 |
| 2.38 | 1.61 | 0.12 | 0.12 | 0.30 |
| 0.14 | 0.54 | 0.48 | 0.88 | |

Source: Calculations Using WIMS Data

Using the time between arrival data, the mean and standard deviation are calculated. The inverse of the mean is the input for Green's method.

$\bar{X} = 0.949$

$S^2 = 1.185$

$S = 1.089$

$\hat{\lambda} = 1/0.949 = 1.05$ arrivals/hour

TABLE 17
WORK ORDER ARRIVAL TIMES

| Time(dys) | Time(dys) | Time(dys) | Time(dys) |
|---|---|---|---|
| 5.10 | 57.82 | 86.41 | 113.56 |
| 8.27 | 62.98 | 87.50 | 114.39 |
| 10.53 | 68.04 | 93.61 | 117.65 |
| 11.96 | 70.14 | 93.88 | 117.71 |
| 16.23 | 71.12 | 100.64 | 118.09 |
| 25.71 | 72.09 | 102.85 | 118.62 |
| 30.50 | 72.15 | 103.27 | 118.94 |
| 36.54 | 73.26 | 105.18 | 120.62 |
| 40.23 | 73.78 | 105.20 | 120.76 |
| 40.36 | 76.25 | 106.83 | 121.11 |
| 47.54 | 76.47 | 112.36 | 124.89 |
| 51.31 | 80.47 | 113.05 | 125.34 |
| 56.04 | 83.28 | 113.36 | 126.21 |

Source: WIMS Data

Using Table 17, along with the hypothesis test explained in Chapter 3, these were the following results.

$$T = 128 \text{ days}, \qquad r = 52 \text{ observations}$$

$$S = \sum_{i=1}^{r} t_i = \sum_{i=1}^{52} t_i = 4200.2$$

$$\mu = rT/2 = (52)(128)/2 = 3328$$

$$\sigma^2 = rT^2/12 = (52)(128)^2/12 = 70{,}997.3$$

95% acceptance interval: $S_A = 3328 \mp 1.96(266) = (2806, 3850)$

Reject the hypothesis of Poisson distributed.

TABLE 18
WORK ORDER TIME BETWEEN ARRIVALS

| Time(dys) | Time(dys) | Time(dys) | Time(dys) |
|---|---|---|---|
| 3.17 | 5.16 | 1.09 | 0.83 |
| 2.26 | 5.06 | 6.11 | 3.26 |
| 1.43 | 2.10 | 0.27 | 0.06 |
| 4.27 | 0.98 | 6.76 | 0.38 |
| 9.48 | 0.97 | 2.21 | 0.53 |
| 4.79 | 0.06 | 0.42 | 0.32 |
| 6.04 | 1.11 | 1.91 | 1.68 |
| 3.69 | 0.52 | 0.02 | 0.14 |
| 0.13 | 2.47 | 1.63 | 0.35 |
| 7.18 | 0.22 | 5.53 | 3.78 |
| 3.77 | 4.00 | 0.69 | 0.45 |
| 4.73 | 2.81 | 0.31 | 0.87 |
| 1.78 | 3.13 | 0.20 | |

Source: Calculations Using WIMS Data

Using the time between arrival data, the mean and standard deviation are calculated. The inverse of the mean is the input for Green's method.

$\bar{X} = 2.375$

$S^2 = 2.275$

$S = 1.508$

$\hat{\lambda} = 1.0/2.375 = 0.421$ arrivals/day $= 0.047$ arrivals/hour

TABLE 19
CONSOLIDATED DATA ARRIVAL TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|---|
| 0.05 | 19.74 | 32.38 | 80.27 | 125.55 |
| 1.48 | 20.41 | 32.88 | 83.07 | 127.72 |
| 3.52 | 21.06 | 33.25 | 83.16 | 128.37 |
| 5.46 | 21.21 | 34.58 | 117.72 | 128.74 |
| 6.82 | 21.26 | 34.65 | 117.82 | 129.04 |
| 9.98 | 21.46 | 37.20 | 117.84 | 129.24 |
| 10.20 | 21.94 | 37.22 | 118.27 | 131.21 |
| 13.95 | 23.22 | 37.87 | 118.86 | 133.22 |
| 13.97 | 23.36 | 38.22 | 119.11 | 134.27 |
| 15.21 | 23.93 | 38.77 | 119.90 | 134.63 |
| 15.31 | 25.36 | 40.38 | 120.11 | 136.65 |
| 17.48 | 27.11 | 41.43 | 120.18 | 137.75 |
| 18.13 | 27.12 | 42.68 | 120.70 | 137.76 |
| 18.21 | 27.21 | 42.78 | 124.12 | 138.38 |
| 18.99 | 30.28 | 79.85 | 124.52 | 138.50 |

Source: Calculations Using Random Selection of WIMS Data

Using Table 19, along with the hypothesis test explained in Chapter 3, these were the following results.

$r = 75$ observations

$$S = \sum_{i=1}^{r-1} t_i = \sum_{i=1}^{74} t_i = 4665.75$$

$$\mu = (r-1)(t_r)/2 = (74)(138.50)/2 = 5124.50$$

$$\sigma^2 = (r-1)(t_r)^2/12 = (74)(138.50)^2/12 = 118{,}290.54$$

95% acceptance interval: $S_A = 5125 \mp 1.96(344) = (4450, 5799)$

Cannot reject the hypothesis of Poisson distributed.

AD-A166 621 AN ANALYSIS OF AN ANALYTICAL QUEUING TECHNIQUE FOR USE 2/2
AS A PROGRAMMING A..(U) AIR FORCE INST OF TECH
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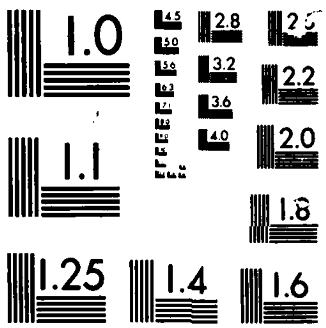


MICROCOPY CHART

TABLE 20
CONSOLIDATED DATA TIME BETWEEN ARRIVALS

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|---|
| 0.05 | 0.75 | 2.10 | 0.42 | 1.03 |
| 1.43 | 0.67 | 0.50 | 2.80 | 2.17 |
| 2.04 | 0.65 | 0.37 | 0.09 | 0.65 |
| 1.94 | 0.15 | 1.33 | 34.56 | 0.37 |
| 1.36 | 0.05 | 0.07 | 0.10 | 0.30 |
| 3.16 | 0.20 | 2.55 | 0.02 | 0.20 |
| 0.22 | 0.48 | 0.02 | 0.43 | 1.97 |
| 3.75 | 1.28 | 0.65 | 0.59 | 2.01 |
| 0.02 | 0.14 | 0.35 | 0.25 | 1.05 |
| 1.24 | 0.57 | 0.55 | 0.79 | 0.36 |
| 0.10 | 1.43 | 1.61 | 0.21 | 2.02 |
| 2.17 | 1.75 | 1.05 | 0.07 | 1.10 |
| 0.65 | 0.01 | 1.25 | 0.52 | 0.01 |
| 0.08 | 0.09 | 0.10 | 3.42 | 0.62 |
| 0.78 | 3.07 | 38.07 | 0.40 | 0.12 |

Source: Random Selection of WIMS Data

Using the time between arrival data, the mean and standard deviation are calculated. The inverse of the mean is the input for Green's method.

$\bar{X} = 1.86$

$S^2 = 5.82$

$S = 2.41$

$\hat{\lambda} = 1.0/1.86 = 0.538$ arrivals/hour

APPENDIX D

TABLES, CALCULATIONS AND

FIGURES OF THE SERVICE ANALYSIS

TABLE 21
EMERGENCY JOB ORDER SERVICE TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|
| 1.0 | 2.5 | 2.0 | 3.0 |
| 2.0 | 2.0 | 2.0 | 1.0 |
| 1.0 | 1.0 | 7.0 | 1.5 |
| 3.0 | 2.0 | 2.5 | 1.0 |
| 2.0 | 2.0 | 1.0 | 2.0 |
| 2.0 | 2.0 | 2.0 | 1.5 |
| 1.0 | 4.0 | 2.0 | 4.5 |
| 2.0 | 2.0 | 1.0 | 1.0 |
| 3.0 | 2.0 | 2.0 | 1.0 |
| 1.0 | 2.0 | 2.0 | 2.5 |
| 2.0 | 2.0 | 1.0 | 6.5 |
| 2.0 | 1.0 | 1.0 | 4.0 |
| 2.0 | 1.0 | 4.0 | 1.5 |
| 2.0 | 2.0 | 2.0 | 3.0 |
| 3.0 | 2.0 | 2.5 | 2.5 |
| 1.0 | 2.0 | | |

Source: WIMS Data

Using the service time data, the mean and standard deviation are calculated. The mean is the input for Green's method.

$\bar{\tau} = 2.129$

$S^2 = 1.184$

$S = 1.089$

From the data, 59 tasks used 1 server and 3 used 2 servers. Dividing each by 62 results in the percentages used for $c_i$. The coefficient of variation for this data is 0.512.

The first test run is a check for randomness proposed by Giffin [6] using tables in Duncan [5]. Fig. 18 is a graph showing the spread on both sides of the median of the service time data. The results of the hypothesis test of randomness are:

| Runs above the median | | Runs below the median | |
|---|---|---|---|
| Runs of 1 | = 15 | Runs of 1 | = 15 |
| " " 2 | = 5 | " " 2 | = 5 |
| " " 3 | = 2 | " " 3 | = 2 |
| Total Runs | = 22 | Total Runs | = 22 |
| Number of points above | = 31 | Number of points below | = 31 |

According to the tables in Duncan, for the number of points above and below the median, there must be less than 21 runs above and below the median for a probability of less than 0.005 that the values could have been produced by a random process. Since the total is 44 runs, the hypothesis that these values are created by a random process cannot be rejected.

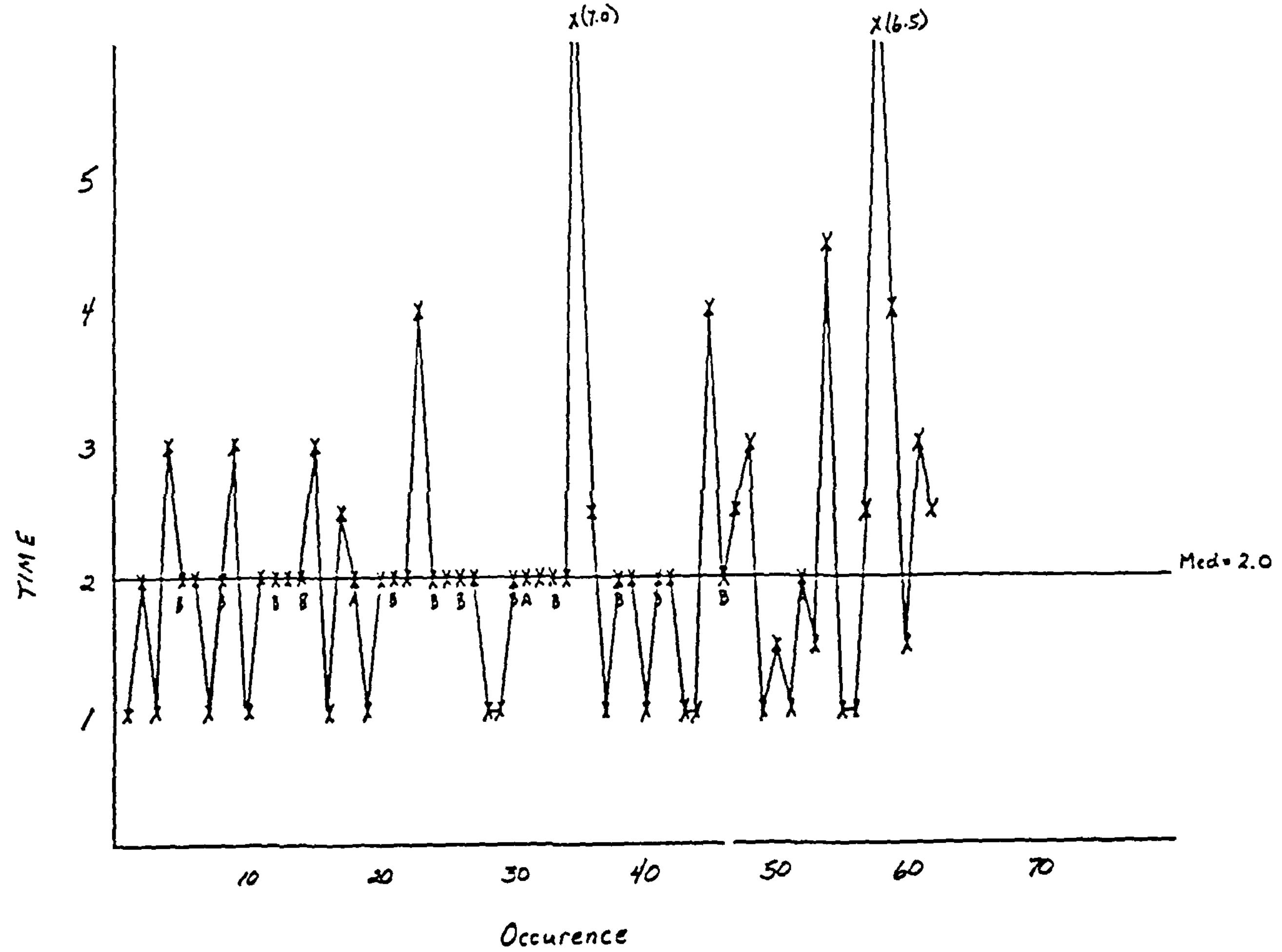


Fig. 17: Emergency Job Order Randomness Test

TABLE 22
EMERGENCY JOB ORDER CUMULATIVE DISTRIBUTION

| i | $t_i$ | $F(t_i)$ | y | i | $t_i$ | $F(t_i)$ | y |
|---|---|---|---|---|---|---|---|
| 1 | 1.0 | .016 | .016 | 32 | 2.0 | .508 | .709 |
| 2 | 1.0 | .032 | .032 | 33 | 2.0 | .524 | .742 |
| 3 | 1.0 | .048 | .049 | 34 | 2.0 | .540 | .776 |
| 4 | 1.0 | .063 | .066 | 35 | 2.0 | .556 | .811 |
| 5 | 1.0 | .079 | .083 | 36 | 2.0 | .571 | .847 |
| 6 | 1.0 | .095 | .100 | 37 | 2.0 | .587 | .885 |
| 7 | 1.0 | .111 | .118 | 38 | 2.0 | .603 | .924 |
| 8 | 1.0 | .127 | .136 | 39 | 2.0 | .619 | .965 |
| 9 | 1.0 | .143 | .154 | 40 | 2.0 | .635 | 1.008 |
| 10 | 1.0 | .159 | .173 | 41 | 2.0 | .651 | 1.052 |
| 11 | 1.0 | .175 | .192 | 42 | 2.0 | .667 | 1.099 |
| 12 | 1.0 | .190 | .211 | 43 | 2.0 | .683 | 1.147 |
| 13 | 1.0 | .206 | .231 | 44 | 2.0 | .698 | 1.199 |
| 14 | 1.0 | .222 | .251 | 45 | 2.0 | .714 | 1.253 |
| 15 | 1.0 | .238 | .272 | 46 | 2.0 | .730 | 1.310 |
| 16 | 1.0 | .254 | .293 | 47 | 2.5 | .746 | 1.371 |
| 17 | 1.5 | .270 | .314 | 48 | 2.5 | .762 | 1.435 |
| 18 | 1.5 | .286 | .336 | 49 | 2.5 | .778 | 1.504 |
| 19 | 1.5 | .302 | .359 | 50 | 2.5 | .794 | 1.578 |
| 20 | 2.0 | .317 | .382 | 51 | 2.5 | .810 | 1.658 |
| 21 | 2.0 | .333 | .405 | 52 | 3.0 | .825 | 1.745 |
| 22 | 2.0 | .349 | .430 | 53 | 3.0 | .841 | 1.841 |
| 23 | 2.0 | .365 | .454 | 54 | 3.0 | .857 | 1.946 |
| 24 | 2.0 | .381 | .480 | 55 | 3.0 | .873 | 2.064 |
| 25 | 2.0 | .397 | .506 | 56 | 3.0 | .889 | 2.197 |
| 26 | 2.0 | .413 | .532 | 57 | 4.0 | .905 | 2.351 |
| 27 | 2.0 | .429 | .560 | 58 | 4.0 | .921 | 2.534 |
| 28 | 2.0 | .444 | .588 | 59 | 4.0 | .937 | 2.757 |
| 29 | 2.0 | .460 | .617 | 60 | 4.5 | .952 | 3.045 |
| 30 | 2.0 | .476 | .647 | 61 | 6.5 | .968 | 3.450 |
| 31 | 2.0 | .492 | .677 | 62 | 7.0 | .984 | 4.143 |

Source: Calculations Using WIMS Data

Table 22 is used to prepare Fig. 5.

TABLE 23
URGENT JOB ORDER SERVICE TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|
| 4.0 | 3.0 | 3.0 | 2.0 |
| 2.0 | 3.0 | 2.0 | 1.0 |
| 1.0 | 1.0 | 2.0 | 5.8 |
| 2.0 | 2.0 | 2.0 | 4.0 |
| 2.0 | 1.5 | 2.0 | 3.0 |
| 4.0 | 2.0 | 3.0 | 4.0 |
| 2.0 | 2.0 | 3.8 | 4.0 |
| 3.0 | 4.0 | 2.0 | 2.0 |
| 2.0 | 1.0 | 2.0 | 2.0 |
| 2.0 | 1.0 | 5.8 | 2.0 |
| 2.0 | 2.0 | 3.0 | 4.0 |

Source: WIMS Data

Using the service time data, the mean and standard deviation are calculated. The mean is the input for Green's method.

$\bar{\tau} = 2.566$

$S^2 = 1.164$

$S = 1.079$

From the data, 37 tasks used 1 server and 7 used 2 servers. Dividing each by 44 results in the percentages used for $c_i$. The coefficient of variation for this data is 0.420.

The first test run is a check for randomness proposed by Giffin [6] using tables in Duncan [5]. Fig. 17 is a graph showing the spread on both sides of the median of the service time data. The results of the hypothesis test of randomness are:

| Runs above the median | | Runs below the median | |
|---|---|---|---|
| Runs of 1 | = 5 | Runs of 1 | = 4 |
| " " 2 | = 3 | " " 2 | = 5 |
| " " 3 | = 2 | " " 3 | = 4 |
| " " 4 | = 0 | " " 4 | = 1 |
| " " 5 | = 1 | | |
| Total Runs | = 11 | Total Runs | = 14 |
| Number of points above | = 22 | Number of points below | = 22 |

According to the tables in Duncan, for the number of points above and below the median, there must be less than 14 runs above and below the median for a probability of less than 0.005 that the values could have been produced by a random process. Since the total is 25 runs, the hypothesis that these values are created by a random process cannot be rejected.

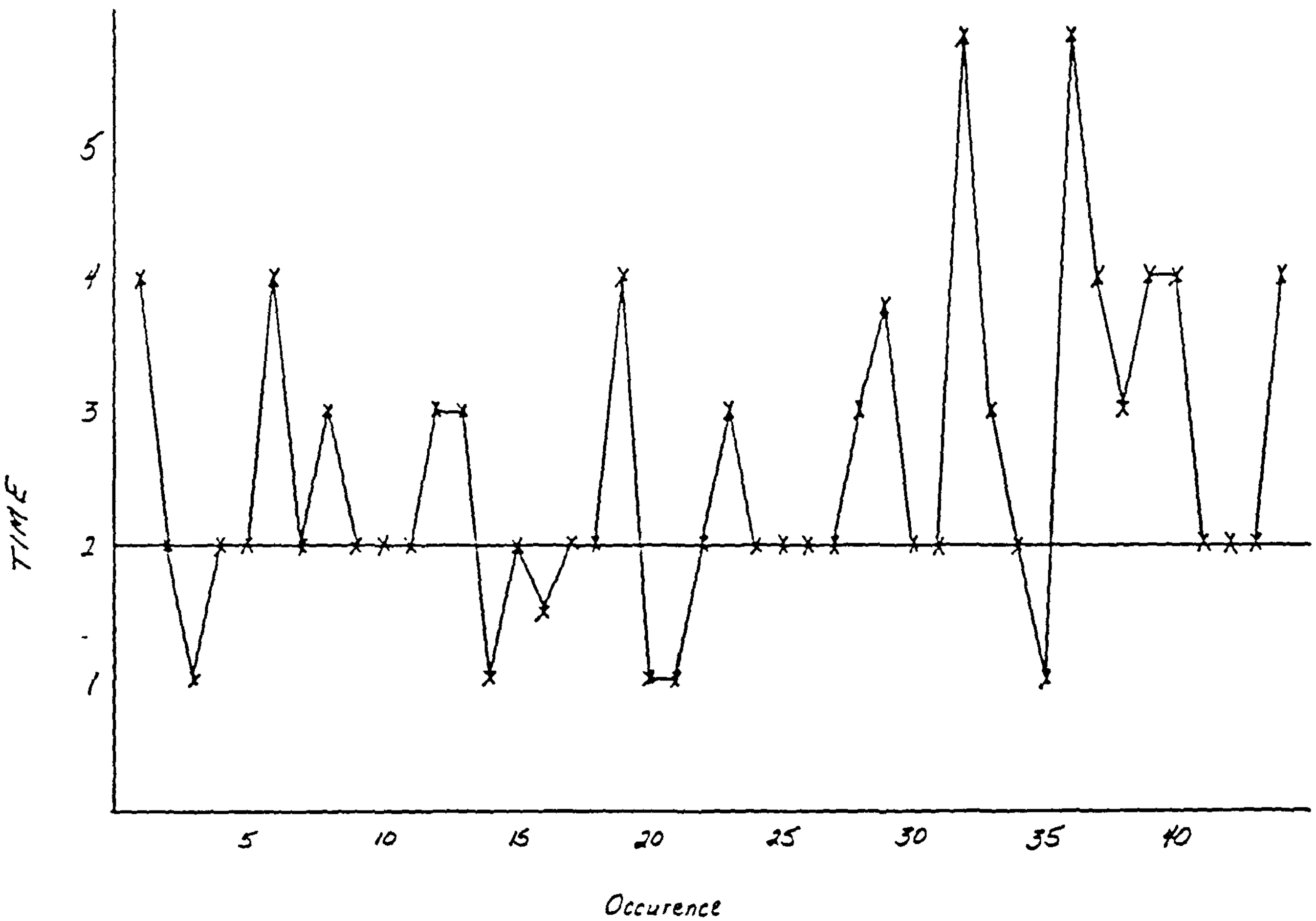


Fig. 18: Urgent Job Order Randomness Test

TABLE 24
URGENT JOB ORDER CUMULATIVE DISTRIBUTION

| i | $t_i$ | $F(t_i)$ | y | i | $t_i$ | $F(t_i)$ | y |
|---|---|---|---|---|---|---|---|
| 1 | 1.0 | .022 | .022 | 23 | 2.0 | .511 | .716 |
| 2 | 1.0 | .044 | .045 | 24 | 2.0 | .533 | .762 |
| 3 | 1.0 | .067 | .069 | 25 | 2.0 | .556 | .811 |
| 4 | 1.0 | .089 | .093 | 26 | 2.0 | .578 | .862 |
| 5 | 1.0 | .111 | .118 | 27 | 2.0 | .600 | .916 |
| 6 | 1.5 | .133 | .143 | 28 | 3.0 | .622 | .973 |
| 7 | 2.0 | .156 | .169 | 29 | 3.0 | .644 | 1.034 |
| 8 | 2.0 | .178 | .196 | 30 | 3.0 | .667 | 1.099 |
| 9 | 2.0 | .200 | .223 | 31 | 3.0 | .689 | 1.168 |
| 10 | 2.0 | .222 | .251 | 32 | 3.0 | .711 | 1.242 |
| 11 | 2.0 | .244 | .280 | 33 | 3.0 | .733 | 1.322 |
| 12 | 2.0 | .267 | .310 | 34 | 3.0 | .756 | 1.409 |
| 13 | 2.0 | .289 | .341 | 35 | 3.8 | .778 | 1.504 |
| 14 | 2.0 | .311 | .373 | 36 | 4.0 | .800 | 1.609 |
| 15 | 2.0 | .333 | .405 | 37 | 4.0 | .822 | 1.727 |
| 16 | 2.0 | .356 | .439 | 38 | 4.0 | .844 | 1.861 |
| 17 | 2.0 | .378 | .474 | 39 | 4.0 | .867 | 2.015 |
| 18 | 2.0 | .400 | .511 | 40 | 4.0 | .889 | 2.197 |
| 19 | 2.0 | .422 | .549 | 41 | 4.0 | .911 | 2.420 |
| 20 | 2.0 | .444 | .588 | 42 | 4.0 | .933 | 2.708 |
| 21 | 2.0 | .467 | .629 | 43 | 5.8 | .956 | 3.114 |
| 22 | 2.0 | .489 | .671 | 44 | 5.8 | .978 | 3.807 |

Source: Calculations Using WIMS Data

Table 24 is used to prepare Fig. 6.

TABLE 25
MINOR CONSTRUCTION SERVICE TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|
| 40.0 | 12.5 | 28.1 | 6.5 |
| 27.5 | 20.4 | 12.1 | 11.3 |
| 22.2 | 17.6 | 5.8 | 29.9 |
| 39.4 | 8.9 | 65.0 | 29.1 |
| 23.2 | 48.3 | 11.0 | 118.7 |
| 13.0 | 72.3 | 24.7 | 8.8 |
| 18.0 | 24.0 | 10.7 | 29.6 |
| 15.0 | 48.8 | 4.0 | 25.8 |
| 64.7 | 50.0 | 66.1 | 47.6 |
| 11.6 | 15.3 | 77.4 | 13.0 |
| 33.7 | 24.0 | 36.9 | 17.3 |

Source: WIMS Data

Using the service time data, the mean and standard deviation are calculated. The mean is the input for Green's method.

$$\bar{\tau} = 30.22$$

$$S^2 = 23.55$$

$$S = 4.85$$

From the data, 8 tasks used 2 servers, 11 used 3 servers, 18 used 4 servers, and 7 used 5 servers. Dividing each by 44 results in the percentages used for $c_i$. The coefficient of variation for this data is 0.160.

The first test run is a check for randomness proposed by Giffin [6] using tables in Duncan [5]. Fig. 19 is a graph showing the spread on both sides of the median of the service time data. The results of the hypothesis test of randomness are:

| Runs above the median | | Runs below the median | |
|---|---|---|---|
| Runs of 1 | = 6 | Runs of 1 | = 5 |
| " " 2 | = 1 | " " 2 | = 4 |
| " " 3 | = 3 | " " 3 | = 0 |
| " " 4 | = 1 | " " 4 | = 2 |
| Total Runs | = 11 | Total Runs | = 11 |
| Number of points above | = 21 | Number of points below | = 21 |

According to the tables in Duncan, for the number of points above and below the median, there must be less than 13 runs above and below the median for a probability of less than 0.005 that the values could have been produced by a random process. Since the total is 22 runs, the hypothesis that these values are created by a random process cannot be rejected.

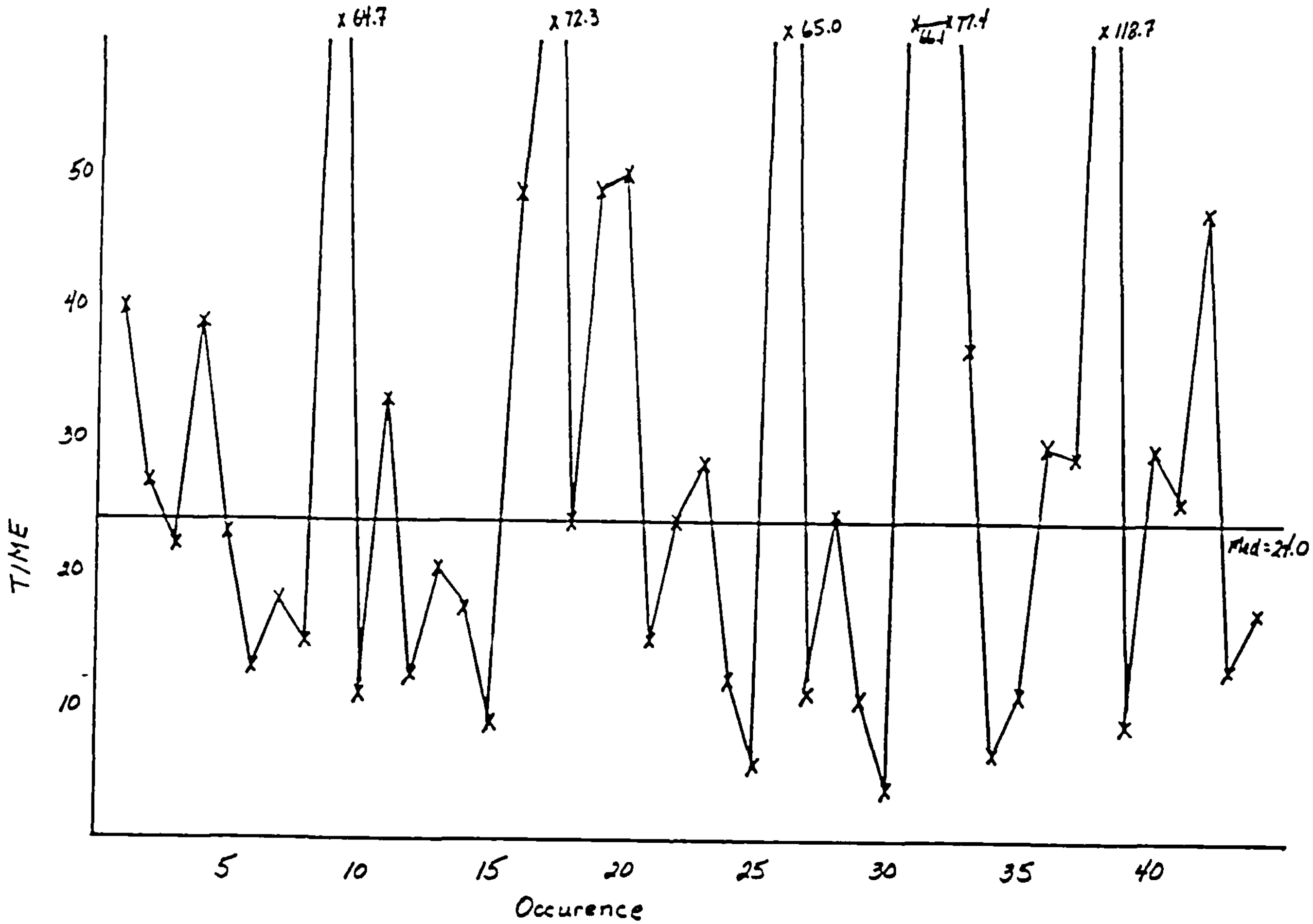


Fig.19: Minor Construction Randomness Test

TABLE 26
MINOR CONSTRUCTION CUMULATIVE DISTRIBUTION

| i | $t_i$ | $F(t_i)$ | y | i | $t_i$ | $F(t_i)$ | y |
|---|---|---|---|---|---|---|---|
| 1 | 4.0 | .022 | .022 | 23 | 24.0 | .511 | .716 |
| 2 | 5.8 | .044 | .045 | 24 | 24.7 | .533 | .762 |
| 3 | 6.5 | .067 | .069 | 25 | 25.8 | .556 | .811 |
| 4 | 8.8 | .089 | .093 | 26 | 27.5 | .579 | .862 |
| 5 | 8.9 | .111 | .118 | 27 | 28.1 | .600 | .916 |
| 6 | 10.7 | .133 | .143 | 28 | 29.1 | .622 | .973 |
| 7 | 11.0 | .156 | .169 | 29 | 29.6 | .644 | 1.034 |
| 8 | 11.3 | .178 | .196 | 30 | 29.9 | .667 | 1.099 |
| 9 | 11.6 | .200 | .223 | 31 | 33.7 | .689 | 1.168 |
| 10 | 12.1 | .222 | .251 | 32 | 36.9 | .711 | 1.242 |
| 11 | 12.5 | .244 | .280 | 33 | 39.4 | .733 | 1.322 |
| 12 | 13.0 | .267 | .310 | 34 | 40.0 | .756 | 1.409 |
| 13 | 13.0 | .289 | .341 | 35 | 47.6 | .779 | 1.504 |
| 14 | 15.0 | .311 | .373 | 36 | 48.3 | .800 | 1.609 |
| 15 | 15.3 | .333 | .405 | 37 | 48.8 | .822 | 1.727 |
| 16 | 17.3 | .356 | .439 | 38 | 50.0 | .844 | 1.861 |
| 17 | 17.6 | .379 | .474 | 39 | 64.7 | .867 | 2.015 |
| 18 | 18.0 | .400 | .511 | 40 | 65.0 | .889 | 2.197 |
| 19 | 20.4 | .422 | .549 | 41 | 66.1 | .911 | 2.420 |
| 20 | 22.2 | .444 | .588 | 42 | 72.3 | .933 | 2.708 |
| 21 | 23.2 | .467 | .629 | 43 | 77.4 | .956 | 3.114 |
| 22 | 24.0 | .489 | .671 | 44 | 118.7 | .979 | 3.807 |

Source: Calculations Using WIMS Data

Table 26 is used to prepare Fig. 7.

TABLE 27
ROUTINE JOB ORDER SERVICE TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|---|
| 20.8 | 2.0 | 1.0 | 2.8 | 1.5 |
| 2.0 | 1.5 | 2.0 | 2.5 | 2.0 |
| 1.0 | 2.0 | 3.0 | 6.6 | 2.0 |
| 2.0 | 2.0 | 2.5 | 2.0 | 3.0 |
| 2.0 | 2.0 | 4.3 | 5.7 | 3.0 |
| 3.8 | 12.1 | 2.0 | 0.5 | 2.5 |
| 2.0 | 2.0 | 1.0 | 5.3 | 2.0 |
| 4.3 | 5.0 | 5.7 | 3.0 | 2.0 |
| 6.0 | 2.5 | 3.0 | 3.0 | 2.0 |
| 1.0 | 1.0 | 5.0 | 5.0 | 7.0 |
| 2.0 | 7.8 | 3.0 | 3.0 | 3.5 |
| 17.9 | 1.0 | 3.8 | 2.0 | 5.3 |
| 10.8 | 3.0 | 2.3 | 2.0 | 5.3 |
| 2.0 | 1.0 | 2.0 | 2.0 | 3.0 |
| 2.0 | 2.5 | 1.0 | 6.1 | 0.5 |
| 1.0 | 2.3 | 2.0 | 2.5 | 6.0 |
| 12.0 | 1.0 | 2.0 | 2.0 | 1.5 |
| 3.0 | 5.2 | 1.0 | 2.5 | 4.7 |
| 5.0 | 3.0 | 5.5 | 3.0 | 4.5 |

Source: WIMS Data

Using the service time data, the mean and standard deviation are calculated. The mean is the input for Green's method.

$\bar{\tau} = 3.757$

$S^2 = 3.905$

$S = 1.976$

From the data, 47 tasks used 1 server, 30 used 2 servers, 8 used 3 servers, and 10 used 4 servers. Dividing each by 95 results in the percentages used for $c_i$. The coefficient of variation for this data is 0.526.

The first test run is a check for randomness proposed by Giffin [6] using tables in Duncan [5]. Fig. 16 is a graph showing the spread on both sides of the median of the service time data. The results of the hypothesis test of randomness are:

| Runs above the median | Runs below the median |
|---|---|
| Runs of 1 = 7 | Runs of 1 = 9 |
| " " 2 = 7 | " " 2 = 4 |
| " " 3 = 3 | " " 3 = 4 |
| " " 4 = 1 | " " 4 = 1 |
| " " 5 = 3 | " " 5 = 1 |
| | " " 6 = 1 |
| Total Runs = 21 | Total Runs = 20 |
| Number of points above = 50 | Number of points below = 45 |

According to the tables in Duncan, for the number of points above and below the median, there must be less than 33 runs above and below the median for a probability of less than 0.005 that the values could have been produced by a random process. Since the total is 41 runs, the hypothesis that these values are created by a random process cannot be rejected.

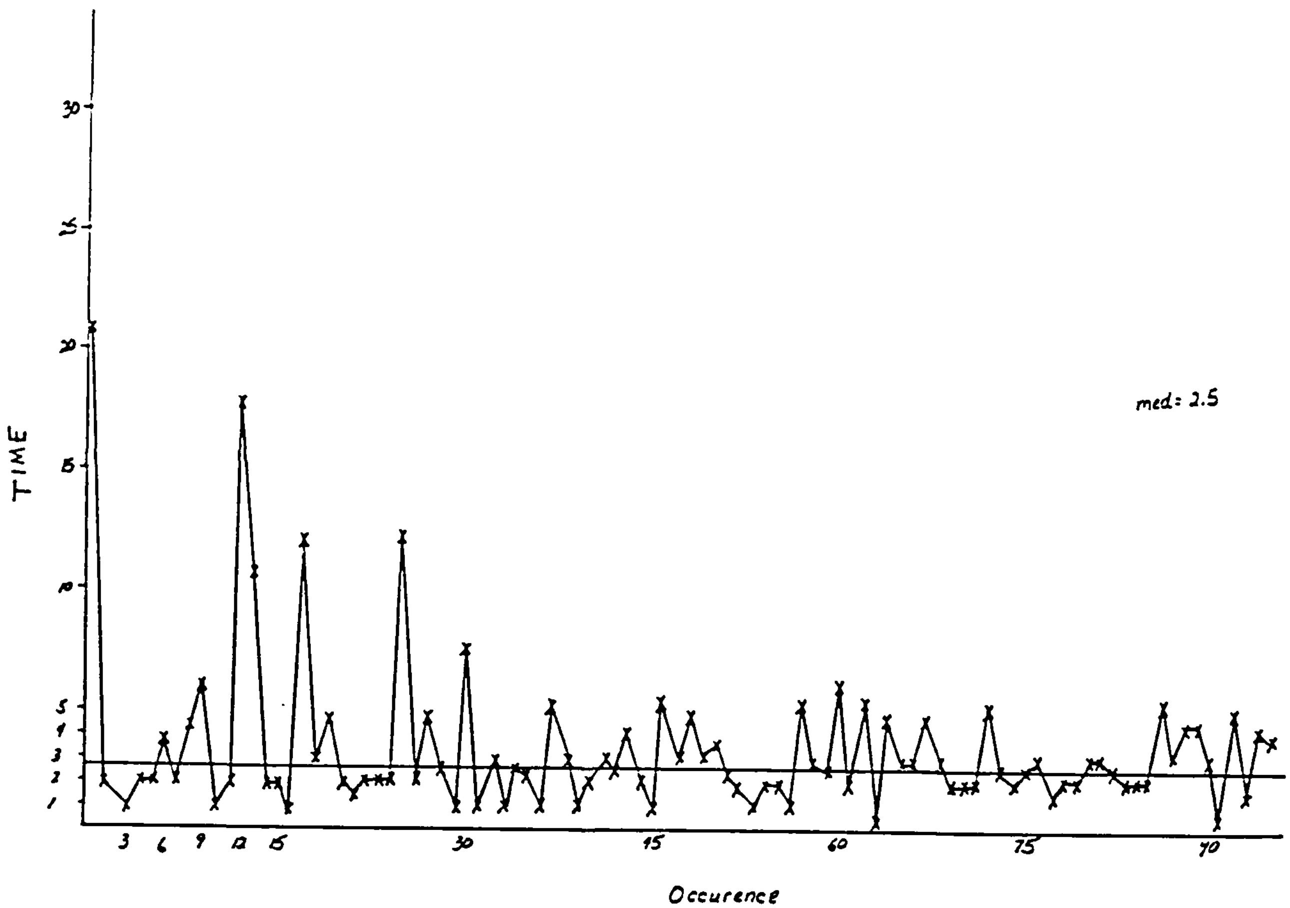


Fig. 20: Routine Job Order Randomness Test

TABLE 28
ROUTINE JOB ORDER CUMULATIVE DISTRIBUTION

| i | $t_i$ | $F(t_i)$ | y | i | $t_i$ | $F(t_i)$ | y |
|---|---|---|---|---|---|---|---|
| 1 | 0.5 | .0104 | .0105 | 45 | 2.3 | .4688 | .6325 |
| 2 | 0.5 | .0208 | .0211 | 46 | 2.5 | .4792 | .6523 |
| 3 | 1.0 | .0313 | .0317 | 47 | 2.5 | .4896 | .6725 |
| 4 | 1.0 | .0417 | .0426 | 48 | 2.5 | .5000 | .6931 |
| 5 | 1.0 | .0521 | .0535 | 49 | 2.5 | .5104 | .7142 |
| 6 | 1.0 | .0625 | .0645 | 50 | 2.5 | .5208 | .7357 |
| 7 | 1.0 | .0729 | .0757 | 51 | 2.5 | .5313 | .7577 |
| 8 | 1.0 | .0833 | .0870 | 52 | 2.5 | .5417 | .7802 |
| 9 | 1.0 | .0938 | .0984 | 53 | 2.8 | .5521 | .8031 |
| 10 | 1.0 | .1042 | .1100 | 54 | 3.0 | .5625 | .8267 |
| 11 | 1.0 | .1146 | .1217 | 55 | 3.0 | .5729 | .8508 |
| 12 | 1.0 | .1250 | .1335 | 56 | 3.0 | .5833 | .8755 |
| 13 | 1.0 | .1354 | .1455 | 57 | 3.0 | .5938 | .9008 |
| 14 | 1.5 | .1458 | .1576 | 58 | 3.0 | .6042 | .9268 |
| 15 | 1.5 | .1563 | .1699 | 59 | 3.0 | .6146 | .9534 |
| 16 | 1.5 | .1667 | .1823 | 60 | 3.0 | .6250 | .9808 |
| 17 | 2.0 | .1771 | .1949 | 61 | 3.0 | .6354 | 1.0090 |
| 18 | 2.0 | .1875 | .2076 | 62 | 3.0 | .6458 | 1.0380 |
| 19 | 2.0 | .1979 | .2205 | 63 | 3.0 | .6563 | 1.0678 |
| 20 | 2.0 | .2083 | .2336 | 64 | 3.0 | .6667 | 1.0986 |
| 21 | 2.0 | .2188 | .2469 | 65 | 3.0 | .6771 | 1.1304 |
| 22 | 2.0 | .2292 | .2603 | 66 | 3.0 | .6875 | 1.1632 |
| 23 | 2.0 | .2396 | .2739 | 67 | 3.5 | .6979 | 1.1971 |
| 24 | 2.0 | .2500 | .2877 | 68 | 3.8 | .7083 | 1.2321 |
| 25 | 2.0 | .2604 | .3017 | 69 | 3.8 | .7188 | 1.2685 |
| 26 | 2.0 | .2708 | .3159 | 70 | 4.3 | .7292 | 1.3063 |
| 27 | 2.0 | .2813 | .3302 | 71 | 4.3 | .7396 | 1.3455 |
| 28 | 2.0 | .2917 | .3448 | 72 | 4.5 | .7500 | 1.3863 |
| 29 | 2.0 | .3021 | .3597 | 73 | 4.7 | .7604 | 1.4289 |
| 30 | 2.0 | .3125 | .3747 | 74 | 5.0 | .7708 | 1.4733 |
| 31 | 2.0 | .3229 | .3900 | 75 | 5.0 | .7813 | 1.5198 |
| 32 | 2.0 | .3333 | .4055 | 76 | 5.0 | .7917 | 1.5686 |
| 33 | 2.0 | .3438 | .4212 | 77 | 5.0 | .8021 | 1.6199 |
| 34 | 2.0 | .3542 | .4372 | 78 | 5.2 | .8125 | 1.6740 |
| 35 | 2.0 | .3646 | .4535 | 79 | 5.3 | .8229 | 1.7311 |
| 36 | 2.0 | .3750 | .4700 | 80 | 5.3 | .8333 | 1.7918 |
| 37 | 2.0 | .3854 | .4868 | 81 | 5.3 | .8438 | 1.8563 |
| 38 | 2.0 | .3958 | .5039 | 82 | 5.5 | .8542 | 1.9253 |
| 39 | 2.0 | .4063 | .5213 | 83 | 5.7 | .8646 | 1.9994 |
| 40 | 2.0 | .4167 | .5390 | 84 | 5.7 | .8750 | 2.0794 |
| 41 | 2.0 | .4271 | .5570 | 85 | 6.0 | .8854 | 2.1665 |
| 42 | 2.0 | .4375 | .5754 | 86 | 6.0 | .8958 | 2.2618 |
| 43 | 2.0 | .4479 | .5941 | 87 | 6.1 | .9063 | 2.3671 |
| 44 | 2.3 | .4583 | .6131 | 88 | 6.6 | .9167 | 2.4849 |

TABLE 28 (cont)

| $i$ | $t_i$ | $F(t_i)$ | $y$ | $i$ | $t_i$ | $F(t_i)$ | $y$ |
|---|---|---|---|---|---|---|---|
| 89 | 7.0 | .9271 | 2.6184 | 93 | 12.1 | .9688 | 3.4657 |
| 90 | 7.8 | .9375 | 2.7726 | 94 | 17.9 | .9792 | 3.8712 |
| 91 | 10.8 | .9479 | 2.9549 | 95 | 20.8 | .9896 | 4.5643 |
| 92 | 12.0 | .9583 | 3.1781 | | | | |

Source: Calculations Using WIMS Data

Table 28 is used to prepare Fig. 8.

TABLE 29
CONSOLIDATED SERVICE TIMES

| Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) | Time(hrs) |
|---|---|---|---|---|
| 2.0 | 2.0 | 1.0 | 2.0 | 1.0 |
| 5.0 | 3.0 | 3.0 | 6.1 | 1.0 |
| 3.8 | 2.0 | 2.0 | 2.0 | 2.0 |
| 0.5 | 2.0 | 2.0 | 13.0 | 3.0 |
| 2.0 | 2.0 | 3.0 | 2.0 | 1.5 |
| 5.0 | 2.0 | 4.0 | 2.0 | 1.0 |
| 3.0 | 1.0 | 2.5 | 2.0 | 2.0 |
| 2.0 | 2.0 | 1.5 | 2.0 | 2.0 |
| 2.5 | 1.0 | 2.0 | 2.5 | 2.0 |
| 2.0 | 1.0 | 14.0 | 2.0 | 2.0 |
| 2.3 | 5.0 | 5.2 | 2.0 | 2.0 |
| 1.0 | 2.0 | 11.5 | 3.0 | 3.0 |
| 2.0 | 2.0 | 2.0 | 12.0 | 2.0 |
| 11.5 | 2.0 | 2.0 | 2.0 | 3.0 |
| 2.0 | 8.0 | 29.1 | 2.0 | 1.0 |

Source: WIMS Data

Using the service time data, the mean and standard deviation are calculated. The mean is the input for Green's method.

$\bar{\tau} = 3.38$

$s^2 = 4.12$

$s = 2.03$

The percentages of servers required for the consolidated tasks has been determined as explained in Chapter 3. The coefficient of variation for this data is 0.601.

The first test run is a check for randomness proposed by Giffin [6] using tables in Duncan [5]. Fig. 20 is a graph showing the spread on both sides of the median of the service time data. The results of the hypothesis test of randomness are:

| Runs above the median | | Runs below the median | |
|---|---|---|---|
| Runs of 1 | = 12 | Runs of 1 | = 12 |
| " " 2 | = 6 | " " 2 | = 8 |
| " " 3 | = 2 | " " 3 | = 3 |
| " " 4 | = 2 | | |
| Total Runs | = 22 | Total Runs | = 23 |
| Number of points above | = 38 | Number of points below | = 37 |

According to the tables in Duncan, for the number of points above and below the median, there must be less than 26 runs above and below the median for a probability of less than 0.005 that the values could have been produced by a random process. Since the total is 45 runs, the hypothesis that these values are created by a random process cannot be rejected.

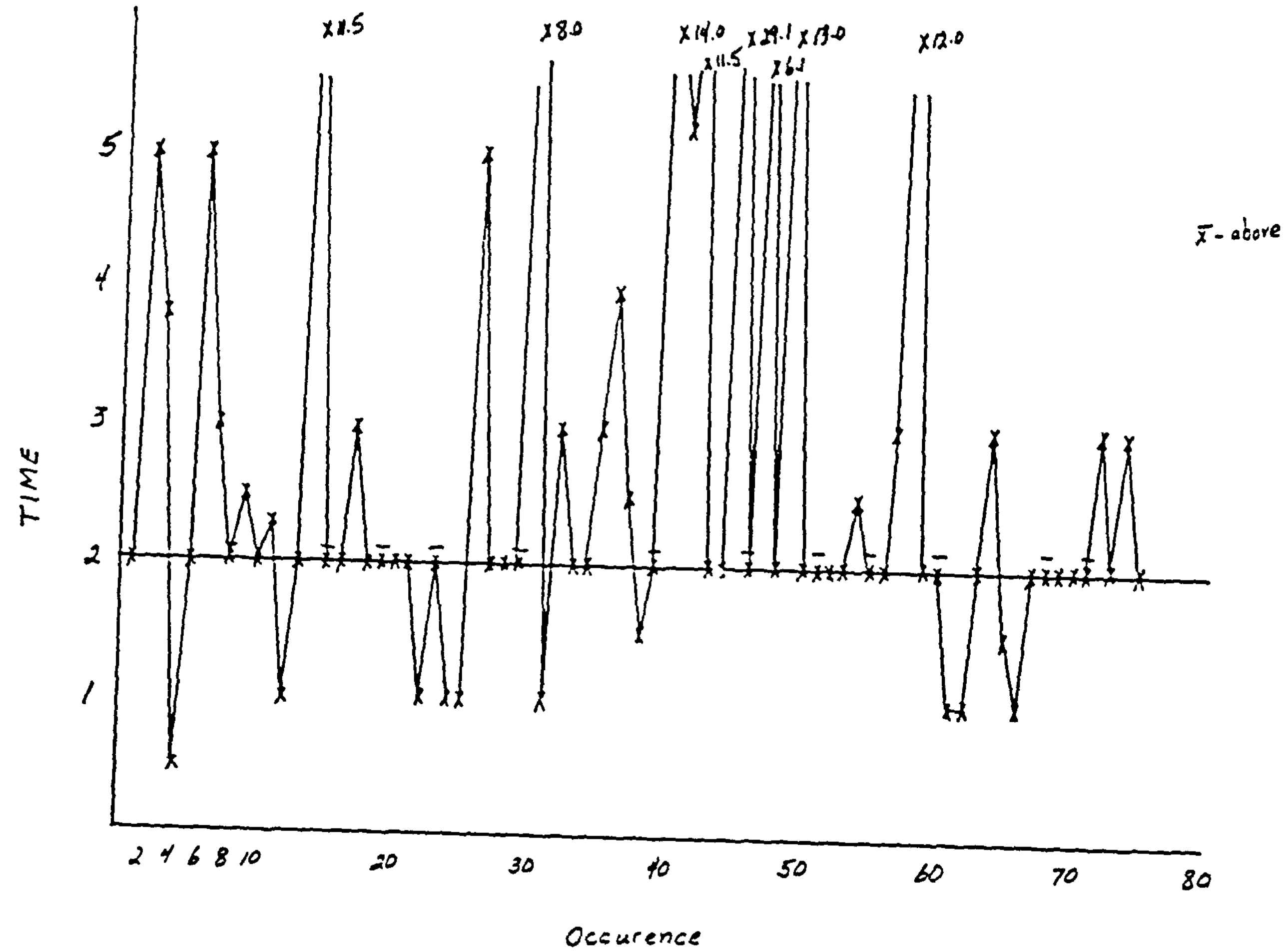


Fig. 21: Consolidated Data Randomness Test

TABLE 30
CONSOLIDATED CUMULATIVE DISTRIBUTION

| i | $t_i$ | $F(t_i)$ | y | i | $t_i$ | $F(t_i)$ | y |
|---|---|---|---|---|---|---|---|
| 1 | 0.5 | .013 | .013 | 39 | 2.0 | .513 | .720 |
| 2 | 1.0 | .026 | .027 | 40 | 2.0 | .526 | .747 |
| 3 | 1.0 | .039 | .040 | 41 | 2.0 | .539 | .775 |
| 4 | 1.0 | .053 | .054 | 42 | 2.0 | .553 | .804 |
| 5 | 1.0 | .066 | .068 | 43 | 2.0 | .566 | .834 |
| 6 | 1.0 | .079 | .082 | 44 | 2.0 | .579 | .865 |
| 7 | 1.0 | .092 | .097 | 45 | 2.0 | .592 | .897 |
| 8 | 1.0 | .105 | .111 | 46 | 2.0 | .605 | .930 |
| 9 | 1.0 | .118 | .126 | 47 | 2.0 | .618 | .963 |
| 10 | 1.0 | .132 | .141 | 48 | 2.0 | .632 | .999 |
| 11 | 1.5 | .145 | .156 | 49 | 2.0 | .648 | 1.035 |
| 12 | 1.5 | .158 | .172 | 50 | 2.3 | .658 | 1.073 |
| 13 | 2.0 | .171 | .188 | 51 | 2.5 | .671 | 1.112 |
| 14 | 2.0 | .184 | .204 | 52 | 2.5 | .684 | 1.153 |
| 15 | 2.0 | .197 | .220 | 53 | 2.5 | .697 | 1.195 |
| 16 | 2.0 | .211 | .236 | 54 | 3.0 | .711 | 1.240 |
| 17 | 2.0 | .224 | .253 | 55 | 3.0 | .724 | 1.286 |
| 18 | 2.0 | .237 | .270 | 56 | 3.0 | .737 | 1.335 |
| 19 | 2.0 | .250 | .288 | 57 | 3.0 | .750 | 1.386 |
| 20 | 2.0 | .263 | .305 | 58 | 3.0 | .763 | 1.440 |
| 21 | 2.0 | .276 | .323 | 59 | 3.0 | .776 | 1.498 |
| 22 | 2.0 | .289 | .342 | 60 | 3.0 | .789 | 1.558 |
| 23 | 2.0 | .303 | .360 | 61 | 3.0 | .803 | 1.623 |
| 24 | 2.0 | .316 | .379 | 62 | 3.8 | .816 | 1.692 |
| 25 | 2.0 | .329 | .399 | 63 | 4.0 | .829 | 1.766 |
| 26 | 2.0 | .342 | .419 | 64 | 5.0 | .842 | 1.846 |
| 27 | 2.0 | .355 | .439 | 65 | 5.0 | .855 | 1.933 |
| 28 | 2.0 | .368 | .460 | 66 | 5.0 | .868 | 2.028 |
| 29 | 2.0 | .382 | .481 | 67 | 5.2 | .882 | 2.134 |
| 30 | 2.0 | .395 | .502 | 68 | 6.1 | .895 | 2.251 |
| 31 | 2.0 | .408 | .524 | 69 | 8.0 | .908 | 2.385 |
| 32 | 2.0 | .421 | .547 | 70 | 11.5 | .921 | 2.539 |
| 33 | 2.0 | .434 | .570 | 71 | 11.5 | .921 | 2.539 |
| 34 | 2.0 | .447 | .593 | 72 | 12.0 | .947 | 2.944 |
| 35 | 2.0 | .461 | .617 | 73 | 13.0 | .961 | 3.232 |
| 36 | 2.0 | .474 | .642 | 74 | 14.0 | .974 | 3.638 |
| 37 | 2.0 | .487 | .667 | 75 | 29.1 | .987 | 4.331 |
| 38 | 2.0 | .500 | .693 | | | | |

Source: Calculations Using WIMS Data

Table 30 is used to prepare Fig. 9.

# APPENDIX E

# FORTRAN PROGRAM OF THE DIRECT CALCULATION APPLICATION OF GREEN'S METHOD

```
C
C - - - This is an interactive program designed to use an
C - - - approximation for a M/M/s multiserver queue with
C - - - the number of busy servers being selected at random
C - - - and releasing from a customer independently.
C
C
      PROGRAM MULTIQ
C
C - - - Establish arrays, matrices, and variables.
C
      DIMENSION V(90,90)
      DIMENSION C(90),PNBSQ(90), PNBSNQ(90), LW(90), MW(90)
      DIMENSION NCPT(7), PCTYPE(7), ACPT(7), DTYPE(7)
      CHARACTER ANS*1, MSG1*36, MSG2*19
      INTEGER COSTCT
      PARAMETER (MSG1=' TYPE SELECTION MUST BE FROM 1 TO 7')
      PARAMETER (MSG2=' RESPOND BY Y OR N ')
C
C - - - Read the shop number (COSTCT), the availability rate
C - - - (AVAIL), and the percentage of direct labor
C - - - utilization (PCTYPE).  NOTE:  To allow for all
C - - - servers to be utilized in evaluating one type of
C - - - work, use values of 1 for AVAIL and/or PCTYPE.
C
1     WRITE(5,10)
10    FORMAT('0Give Cost Center and Availability Rate: ')
      READ (5,20) COSTCT, AVAIL
20    FORMAT(I3, F5.1)
      AVA = AVAIL
      AVAIL = AVAIL/100
      PRINT 30, COSTCT
30    FORMAT('1THIS IS THE ANALYSIS OF COST CENTER ', I3)
      PRINT 40, AVA
40    FORMAT('0THE AVAILABILITY RATE IS ', F7.3)
      WRITE(5,40) AVA
      DO 50 I=1,7
      WRITE(5,41) I
41    FORMAT('0GIVE PERCENTAGE OF DIRECT LABOR FOR ',I1,'
     1   WHERE ',/,
     1    ' 1 = RECURRING WORK ',/,
     1    ' 2 = EMERGENCY JOB ORDERS ',/,
     1    ' 3 = URGENT JOB ORDERS ',/,
     1    ' 4 = MINOR CONSTRUCTION ',/,
     1    ' 5 = ROUTINE JOB ORDERS ',/,
     1    ' 6 = WORK ORDERS ',/,
     1    ' 7 = UTILITY OPERATIONS : ')
      READ(5,42) PCTYPE(I)
42    FORMAT(F5.1)
      DTYPE(I) = PCTYPE(I)
```

```
      PCTYPE(I) = PCTYPE(I)/100
50    CONTINUE
      PRINT 60
60    FORMAT('ODIRECT LABOR PERCENTAGES ARE: ')
      PRINT 61, DTYPE(1)
61    FORMAT(' RECURRING WORK : ',F7.3)
      PRINT 62, DTYPE(2)
62    FORMAT(' EMERGENCY JOB ORDERS : ',F7.3)
      PRINT 63, DTYPE(3)
63    FORMAT(' URGENT JOB ORDERS : ',F7.3)
      PRINT 64, DTYPE(4)
64    FORMAT(' MINOR CONSTRUCTION : ',F7.3)
      PRINT 65, DTYPE(5)
65    FORMAT(' ROUTINE JOB ORDERS : ',F7.3)
      PRINT 68, DTYPE(6)
68    FORMAT(' WORK ORDERS : ',F7.3)
      PRINT 67, DTYPE(7)
67    FORMAT(' UTILITY OPERATIONS : ',F7.3)
C
C - - - - GET THE INFORMATION CONCERNING THE NUMBER OF
C - - - - CRAFTSMEN ASSIGNED (NCRAFT) AND COMPUTE THE PORTION
C - - - - AVAILABLE FOR EACH TYPE OF WORK
C
      WRITE(5,210) COSTCT
210   FORMAT('OHOW MANY CRAFTSMEN ARE ASSIGNED TO ',I3,'?')
      READ(5,220) NCRAFT
220   FORMAT(I2)
      PRINT 230, NCRAFT
230   FORMAT('OTHE TOTAL NUMBER OF CRAFTSMEN ASSIGNED= ',I3)
C
C - - - - CALCULATE THE NUMBER OF CRAFTSMEN ASSIGNED BY TYPE
C - - - - OF WORK.
C
      PRINT 221
221   FORMAT('OCRAFTSMEN AVAILABLE BASED ON DIRECT LABOR
     PERCENTAGES',
     1   ' FOR WORK TYPE ARE : ')
      ACRAFT = NCRAFT * AVAIL
      DO 231 I=1,7
      ACPT(I) = ACRAFT * PCTYPE(I)
231   CONTINUE
      TOTAL = 0
      DO 236 I=1,7
      PRINT 234, I, ACPT(I)
      WRITE(5,234) I, ACPT(I)
234   FORMAT(5X,' ACPT(',I1,') = ', F9.4)
      TOTAL = ACPT(I) + TOTAL
236   CONTINUE
      PRINT 5, TOTAL
5     FORMAT(5X,' TOTAL   = ',F9.4)
```

```
      WRITE(5,235)
235    FORMAT('OGIVE ROUNDED VALUES FOR NUMBER OF CRAFTSMEN
FOR THE ',
     1   'TYPE OF WORK. ')
      DO 239 I=1,7
      WRITE(5,237) I, ACPT(I)
237   FORMAT(' ACPT(',I1,') = ',F9.4,'      ')
      READ(5,238) NCPT(I)
238   FORMAT(I2)
239   CONTINUE
      PRINT 222
222    FORMAT('OROUNDED VALUES OF CRAFTSMEN AVAILABLE PER
WORK TYPE: ')
      ITOT = 0
      DO 166 I=1,7
      PRINT 244, I, NCPT(I)
244   FORMAT(5X,' NCPT(',I1,') = ',I3)
      ITOT = ITOT + NCPT(I)
166   CONTINUE
      PRINT 4, ITOT
4     FORMAT(5X,' TOTAL   = ',I3)
      TOT = FLOAT(ITOT)
      CRAFT = FLOAT(NCRAFT)
      ACT = (TOT/CRAFT)*100.
      PRINT 3, ACT
3     FORMAT('OAVAILABILITY RATE BASED ON ROUNDED VALUES IS
     : ',F9.4)
C
C - - - ASSURE ALL ARRAYS AND MATRICES ARE INITIALIZED.
C
      ARR = 0.0
      A = 0.0
      SERVE = 0.0
      NCR = NCRAFT
66    DO 70 I=1,NCR
      C(I) = 0.0
      PNBSNQ(I) = 0.0
      PNBSQ(I) = 0.0
      LW(I) = 0.0
      MW(I) = 0.0
      DO 71 J=1,NCR
      V(I,J) = 0.0
71    CONTINUE
70    CONTINUE
C
C - - - GET INPUT FOR THE TYPE OF WORK (NTYPE), I.E.
C - - - THE MEAN ARRIVAL RATE (ARR), THE MEAN SERVICE RATE
C - - - (SERVE), AND THE PROBABILITIES OF ARRIVING WORK
C - - - REQUIREMENTS NEEDING I CRAFTSMEN (C(I)).
C - - - NOTE:  SINCE C(0) WILL BE STORED IN C(1), TOTAL DATA
```

```
C - - - LOCATIONS NEEDED WILL EQUAL NCRAFT + 1 FOR ARRAYS
C - - - AND MATRICES.
C
      WRITE(5,80)
80    FORMAT('1THIS PROGRAM WILL AID IN COMPUTING THE QUEUE
     ',/,
     1    ' WAITING TIME FOR VARIOUS TYPES OF WORK.  THE
     TYPES OF ',/,
     1    ' WORK THAT ARE INTENDED TO BE PROCESSED ARE ',/,
     1    5X,' (1)  RECURRING WORK ',/,
     1    5X,' (2)  EMERGENCY JOB ORDERS ',/,
     1    5X,' (3)  URGENT JOB ORDERS ',/,
     1    5X,' (4)  MINOR CONSTRUCTION ',/,
     1    5X,' (5)  ROUTINE JOB ORDERS ',/,
     1    5X,' (6)  WORK ORDERS ',/,
     1    5X,' (7)  UTILITY OPERATIONS ',/,
     1    ' PLEASE SELECT THE TYPE TO BE EVALUATED : ')
89    READ(5,90) NTYPE
90    FORMAT(I1)
91    IF (NTYPE .LT. 1 .OR. NTYPE .GT. 7) THEN
         WRITE(5,100) MSG1
100      FORMAT(1H, A)
         GO TO 89
      ELSE IF (NTYPE .EQ. 1) THEN
         PRINT 110
110      FORMAT('1',10X,' RECURRING WORK RESULTS ')
      ELSE IF (NTYPE .EQ. 2) THEN
         PRINT 120
120      FORMAT('1',10X,' EMERGENCY JOB ORDER RESULTS ')
      ELSE IF (NTYPE .EQ. 3) THEN
         PRINT 130
130      FORMAT('1',10X,' URGENT JOB ORDER RESULTS ')
      ELSE IF (NTYPE .EQ. 4) THEN
         PRINT 140
140      FORMAT('1',10X,' MINOR CONSTRUCTION RESULTS ')
      ELSE IF (NTYPE .EQ. 5) THEN
         PRINT 150
150      FORMAT('1',10X,' ROUTINE JOB ORDER RESULTS ')
      ELSE IF (NTYPE .EQ. 6) THEN
         PRINT 151
151      FORMAT('1',10X,' WORK ORDER RESULTS ')
      ELSE
         PRINT 152
152      FORMAT('1',10X,' UTILITY OPERATIONS RESULTS ')
      END IF
      IF (NCPT(NTYPE) .EQ. 0) THEN
         PRINT 205
         WRITE(5,205)
205      FORMAT('0 THIS TYPE OF WORK IS NOT DONE IN THIS
     SHOP. ')
```

```
               GO TO 620
            END IF
            IF (ARR .GT. 0.0) THEN
               PRINT 191, ARR
191         FORMAT('OTHE MEAN ARRIVAL RATE =',F10.5,'TASKS/HOUR.')
               PRINT 192, A
192         FORMAT('OTHE MEAN SERVICE RATE =',F10.5,'HOURS/TASK.')
               GO TO 201
            END IF
            WRITE(5,160)
160         FORMAT('OWHAT IS THE MEAN ARRIVAL RATE? ')
            READ(5,170) ARR
170         FORMAT(F10.5)
            PRINT 180, ARR
180         FORMAT('OTHE MEAN ARRIVAL RATE =',F10.5,'TASKS/HOUR.')
            WRITE(5,190)
190         FORMAT('OWHAT IS THE MEAN SERVICE RATE? ')
            READ(5,170) A
            SERVE = 1.0/A
            PRINT 200, A
200         FORMAT(' THE MEAN SERVICE RATE =',F10.5,'HOURS/TASK.')
201         NS = NCPT(NTYPE) + 1
            PRINT 248, NCPT(NTYPE)
            WRITE(5,248) NCPT(NTYPE)
248         FORMAT('0',I3,' CRAFTSMEN AVAILABLE FOR THIS TYPE OF
           WORK ')
            C(1) = 0.0
            IF (C(2) .GT. 0.0) THEN
               GO TO 193
            END IF
            IF (C(3) .GT. 0.0) THEN
               GO TO 193
            END IF
            DO 240 I=2,NS
            J = I - 1
            WRITE(5,232) J
232         FORMAT('OGIVE PROBABILITY OF ARRIVING TASK NEEDING
           ',I3,/,
           1    ' CRAFTSMEN : ')
            READ(5,233) C(I)
233         FORMAT(F6.4)
240         CONTINUE
193         PRINT 241
241         FORMAT('OTHE PROBABILITIES OF AN ARRIVING TASK
           NEEDING I ',
           1    'CRAFTSMEN IS : ')
            NCOL = NS/4
            DO 250 I=1,NCOL
            J=I-1
            K=(NCOL*2)-NCOL+I
```

```
      L=K-1
      M = (NCOL*3) - NCOL + I
      N=M-1
      JK = (NCOL*4) - NCOL + I
      LM = JK-1
      PRINT 242, J,C(I),L,C(K),N,C(M),LM,C(JK)
242   FORMAT('C(',I2,')=',F6.4,5X,'C(',I2,')=',F6.4,5X,'C(',
     1   I2,') = ',F6.4,5X,'C(',I2,') = ',F6.4)
250   CONTINUE
      NC = NCOL*4
      IF (NC .LT. NS) THEN
         NC=NC+1
         DO 260 I=NC,NS
         J=I-1
         PRINT 251, J,C(I)
251      FORMAT(58X,'C(',I2,') = ',F6.4)
260      CONTINUE
      ELSE
         CONTINUE
      END IF
C
C - - - TEST FOR THE EXISTENCE OF A STEADY-STATE SOLUTION.
C
      SUM = 0.0
      DO 270 K=2,NS
      I = K-2
      DO 270 J=0,I
      SUM = SUM + (C(K)/(NCPT(NTYPE) - J))
270   CONTINUE
      RO = (ARR/SERVE) * SUM
      IF (RO .LT. 1.0) THEN
         PRINT 280, RO
         WRITE(5,280) RO
280      FORMAT('0RO = ',F7.5,'.  STEADY-STATE SOLUTION
     EXISTS')
      ELSE
         PRINT 290, RO
         WRITE(5,290) RO
290    FORMAT('0RO = ',F9.5,'. NO STEADY-STATE SOLUTION.  ')
         GO TO 620
      END IF
C
C - - - SET UP MATRIX OF I - THE TRANSITION PROBABILITIES
C - - - (INVERSE OF V)
C
      DO 300 I=1,NS
      DO 293 J=1,NS
      IF (I .EQ. J) THEN
         V(I,J) = 1.0
      ELSE IF (I .LT. J .AND. I .EQ. 1) THEN
```

```
         V(I,J) = -C(J)
      ELSE IF (I .EQ. J+1) THEN
         V(I,J) = -((I-1) * SERVE/(ARR + ((I-1) * SERVE)))
      ELSE IF (I .GE. J+2) THEN
         V(I,J) = 0.0
      ELSE
         V(I,J) = -(C(J-I+1) * ARR/ (ARR + ((I-1) * SERVE)))
      END IF
293   CONTINUE
300   CONTINUE
C
C - - - INVERT THE ABOVE MATRIX V, USING IT AS THE INPUT TO
C - - - BE REPLACED BY THE INVERTED V MATRIX
C
      IF (NS .LE. 0) THEN
         PRINT 900
         WRITE(5,900)
900      FORMAT('0ORDER FOR MATRIX INVERSION IS ZERO.  ',
     1      'ERROR PRESENT')
         GO TO 620
      END IF
      S = .00000000000000001
C - - INVERT A SCALER
      IF (NS .EQ. 1) THEN
         D = V(1,1)
         V(1,1) = 1.0/D
         GO TO 306
      ELSE
C - - SEARCH FOR THE LARGEST ELEMENT
         D = 1.0
         DO 780 K=1,NS
         LW(K) = K
         MW(K) = K
         BIGV = V(K,K)
         DO 710 I=K,NS
         DO 700 J=K,NS
         IF (ABS(BIGV) .LT. ABS(V(I,J))) THEN
            BIGV = V(I,J)
            LW(K) = I
            MW(K) = J
         END IF
700      CONTINUE
710      CONTINUE
C
C - - INTERCHANGE ROWS
C
         J = LW(K)
         IF (LW(K) .GT. K) THEN
            DO 720 I=1,NS
            HOLD = -V(K,I)
```

```
            V(K,I) = V(J,I)
            V(J,I) = HOLD
720         CONTINUE
         END IF
C
C - - INTERCHANGE COLUMNS
C
         I = MW(K)
         IF (MW(K) .GT. K) THEN
            DO 730 J=1,NS
            HOLD = -V(J,K)
            V(J,K) = V(J,I)
            V(J,I) = HOLD
730         CONTINUE
         END IF
         IF (ABS(BIGV) .LE. S) THEN
            D = 0.0
            GO TO 820
         END IF
C
C - - DIVIDE COLUMNS BY MINUS PIVOT
C
         DO 740 I=1,NS
         IF (I .NE. K) THEN
            V(I,K) = V(I,K)/(-V(K,K))
         END IF
740   CONTINUE
C
C - - REDUCE MATRIX
C
         DO 760 I=1,NS
         IF (I .NE. K) THEN
            DO 750 J=1,NS
            IF (J .NE. K) THEN
               V(I,J) = V(I,K) * V(K,J) + V(I,J)
            END IF
750         CONTINUE
         END IF
760      CONTINUE
C
C - - DIVIDE ROWS BY PIVOT
C
         DO 770 J=1,NS
         IF (J .NE. K) THEN
            V(K,J) = V(K,J)/V(K,K)
         END IF
770      CONTINUE
C
C - - COMPUTE DETERMINANT
C
```

```
          D = D * V(K,K)
          IF (D .LE. S) THEN
             D = 0.0
             GO TO 820
          END IF
C
C - - REPLACE PIVOT BY RECIPROCAL
C
          V(K,K) = 1.0/V(K,K)
780       CONTINUE
       END IF
C
C - - FINAL ROW AND COLUMN INTERCHANGE
C
       K = NS
790    K = K-1
       IF (K .GT. 0) THEN
          I = LW(K)
          IF (I .GT. K) THEN
             DO 800 J=1,NS
             HOLD = V(J,K)
             V(J,K) = -V(J,I)
             V(J,I) = HOLD
800          CONTINUE
          END IF
          J = MW(K)
          IF (J .GT. K) THEN
             DO 810 I=1,NS
             HOLD = V(K,I)
             V(K,I) = -V(J,I)
             V(J,I) = HOLD
810          CONTINUE
          END IF
          GO TO 790
       END IF
C
C - - DETERMINANT IS ZERO
C
820    IF (D .EQ. 0.0) THEN
          WRITE(5,830)
          PRINT 830
830       FORMAT('ONO INVERSE EXISTS FOR THIS MATRIX.')
          GO TO 620
       END IF
306    WRITE(5,310) D
       PRINT 310, D
310    FORMAT('ODETERMINANT = ',F10.5)
C
C - - - CALCULATE THE EXPECTED VALUE FOR THE LENGTH OF A
C - - - NON-QUEUE PERIOD (EVNQ).
```

```
C
      EVNQ = 0.0
      DO 320 I=1,NS
      EVNQ = EVNQ + (V(NS,I)/(ARR + ((I-1) * SERVE)))
320   CONTINUE
      PRINT 330, EVNQ
      WRITE(5,330) EVNQ
330   FORMAT('0E(LENGTH OF NON-QUEUE PERIOD) = ', F10.4,'
     HOURS ')
C
C - - - CALCULATE THE EXPECTED NUMBER OF ARRIVALS DURING A
C - - - NON-QUEUE PERIOD (ECANQ).
C
      ECANQ = ARR * EVNQ
      PRINT 335, ECANQ
      WRITE(5,335) ECANQ
335   FORMAT('0E(NUMBER OF ARRIVALS DURING A NON-QUEUE
     PERIOD) = ',
     1   F9.4)
C
C - - - CALCULATE THE PROBABILITY DISTRIBUTION OF THE
C - - - NUMBER OF BUSY CRAFTSMEN DURING A NON-QUEUE PERIOD
C - - - (PNBSNQ).
C
      DO 340 I=1,NS
      PNBSNQ(I) = V(NS,I)/((ARR + ((I-1) * SERVE)) * EVNQ)
340   CONTINUE
      PRINT 350
350   FORMAT('0THE PROBABILITIES OF I CRAFTSMEN BUSY DURING
     1   A NON-QUEUE PERIOD ARE: ')
      NCOL = NS/3
      DO 360 I=1,NCOL
      J = I-1
      K = (NCOL * 2) - NCOL + I
      L = K-1
      M = (NCOL * 3) - NCOL + I
      N = M-1
      PRINT 351, J,PNBSNQ(I),L,PNBSNQ(K),N,PNBSNQ(M)
351   FORMAT(' PNBSNQ(',I2,') = ',F6.4,5X,'PNBSNQ(',I2,') =
     1   ',F6.4,5X,'PNBSNQ(',I2,') = ',F6.4)
360   CONTINUE
      NC = NCOL*3
      IF (NC .LT. NS) THEN
         NC = NC+1
         DO 370 I=NC,NS
         J = I-1
         PRINT 361, J,PNBSNQ(I)
361      FORMAT(49X,'PNBSNQ(',I2,') = ',F6.4)
370      CONTINUE
      ELSE
```

```
          CONTINUE
       END IF
       SUM = 0.0
       DO 380 I=1,NS
       SUM = SUM + PNBSNQ(I)
380    CONTINUE
       PRINT 390, SUM
       WRITE(5,390) SUM
390    FORMAT('OTHE SUM OF PNBSNQ(I), I=1 TO NCRAFT = ',F5.2)
C
C - - - CALCULATE THE PROBABILITY THAT A CUSTOMER WHO
C - - - ARRIVES TO AN EMPTY QUEUE EXPERIENCES A DELAY (PD)
C
       PD = 0.0
       DO 400 I=2,NS
       SUM = 0.0
       DO 395 K=2,I
       SUM = SUM + C(NS - I + K)
395    CONTINUE
       PD = PD + (PNBSNQ(I) * SUM)
400    CONTINUE
       PRINT 410, PD
       WRITE(5,410) PD
410    FORMAT('OPROBABILITY OF BEING DELAYED ARRIVING AT AN',
     1    'EMPTY QUEUE (PD) = ', F6.4)
C
C - - - CALCULATE THE EXPECTED VALUE OF THE INITIAL DELAY
C - - - DISTRIBUTION (EVD).
C
       EVD = 0.0
       DO 420 I=2,NS
       SUM = 0.0
       DO 418 J=2,I
       SUM1 = 0.0
       K = I-J+1
       L = I-1
       DO 415 M=L,K,-1
       SUM1 = SUM1 + (1/(M * SERVE))
415    CONTINUE
       SUM = SUM + (SUM1 * C(NS-I+J))
418    CONTINUE
       EVD = EVD + (SUM * PNBSNQ(I)/PD)
420    CONTINUE
       PRINT 430, EVD
       WRITE(5,430) EVD
430    FORMAT('OE(DELAY DISTRIBUTION) = ',F9.4,' HOURS ')
C
C - - - CALCULATE THE EXPECTED VALUE OF THE INTERSERVICE
C - - - TIME OF TASKS IN A QUEUEING PERIOD (EVB)
C
```

```
      EVB = 0.0
      DO 440 I=2,NS
      SUM = 0.0
      J = I-1
      DO 435 K=1,J
      SUM = SUM + (1/(SERVE * (NCPT(NTYPE) - (K-1))))
435   CONTINUE
      EVB = EVB + (SUM * C(I))
440   CONTINUE
      PRINT 450, EVB
      WRITE(5,450) EVB
450  FORMAT('OE(INTERSERVICE DISTRIBUTION) =',F9.4,'HOURS ')
C
C - CALCULATE THE EXPECTED LENGTH OF A QUEUEING PERIOD (EVQ)
C
      EVQ = EVD/(1 - (ARR * EVB))
      PRINT 460, EVQ
      WRITE(5,460) EVQ
460  FORMAT('OE(LENGTH OF QUEUEING PERIOD) =',F9.4,'HOURS ')
C
C - - - CALCULATE THE EQUILIBRIUM TIME PROBABILITY THAT
C - - - THERE EXISTS A QUEUE (PQ)
C
      PQ = EVQ/(EVNQ + EVQ)
      PRINT 470, PQ
      WRITE(5,470) PQ
470   FORMAT('OTHE PROBABILITY THAT A QUEUE EXISTS (PQ) ='
     1    ,F5.4)
C
C - - - CALCULATE THE EXPECTED NUMBER OF TASKS THAT ARRIVE
C - - - DURING A QUEUEING PERIOD (ECAQ)
C
      ECAQ = PQ/(PD * (1-PQ))
      PRINT 480, ECAQ
      WRITE(5,480) ECAQ
480   FORMAT('OE(NUMBER OF ARRIVALS DURING A QUEUEING
     1    PERIOD)=',F9.4)
C
C - - - CALCULATE THE PROBABILITY DISTRIBUTION OF THE NUMBER
C - - - OF BUSY SERVERS DURING A QUEUEING PERIOD (PNBSQ)
C
      DO 500   I=1,NCPT(NTYPE)
      SUM1 = 0.0
      J = NS-I+1
      DO 485 K=J,NS
      SUM1 = SUM1 + C(K)
485   CONTINUE
      SUM1 = SUM1 * ECAQ
      SUM2 = 0.0
      L = I+1
```

```
      DO 490 K=L,NS
      SUM2 = SUM2 + PNBSNQ(K)
490   CONTINUE
      SUM3 = 0.0
      DO 495 K=J,NS
      SUM3 = SUM3 + C(K)
495   CONTINUE
      SUM3 = SUM3/PD
      PROD = SUM3 * SUM2
      SUM4 = SUM1 + PROD
      PNBSQ(I) = SUM4/(I * SERVE * EVQ)
500   CONTINUE
      PRINT 510
510   FORMAT('0THE PROBABILITIES OF I CRAFTSMEN BUSY DURING'
     1   'A QUEUEING PERIOD ARE: ')
      NCOL = NCPT(NTYPE)/4
      DO 520 I=1,NCOL
      J = (NCOL*2) - NCOL + I
      K = (NCOL*3) - NCOL + I
      L = (NCOL*4) - NCOL + I
      PRINT 511, I,PNBSQ(I),J,PNBSQ(J),K,PNBSQ(K),L,PNBSQ(L)
511   FORMAT(' PNBSQ(',I2,') = ',F6.4,2X,'PNBSQ(',I2,') =
     1   ',F6.4,2X,'PNBSQ(',I2,') = ',F6.4,2X,
     1   'PNBSQ(',I2,') = ',F6.4)
520   CONTINUE
      NC = NCOL * 4
      IF (NC .LT. NCPT(NTYPE)) THEN
         NC = NC + 1
         DO 530 I=NC, NCPT(NTYPE)
         PRINT 521, I,PNBSQ(I)
521      FORMAT(61X,'PNBSQ(',I2,') = ',F6.4)
530      CONTINUE
      ELSE
         CONTINUE
      END IF
      SUM = 0.0
      DO 540 I=1,NCPT(NTYPE)
      SUM = SUM + PNBSQ(I)
540   CONTINUE
      PRINT 550, SUM
      WRITE(5,550) SUM
550   FORMAT('0THE SUM OF PNBSQ(I), I=1 TO NCRAFT = ', F5.2)
C
C - - - CALCULATE THE EXPECTED VALUE OF THE RESIDUAL
C - - - INTERSERVICE OF THE FIRST PERSON IN THE QUEUE, IF A
C - - - QUEUE EXISTS, OR THE DELAY ENCOUNTERED IF THERE IS
C - - - NO QUEUE (EVR)
C
      RNQ = 0.0
      DO 570 I=2,NS
```

```
      SUM = 0.0
      J = NS-I+2
      DO 560 K=J,NS
      SUM1 = 0.0
      L = NS-K+1
      M = I-1
      DO 555 N=M,L,-1
      SUM1 = SUM1 + (1/(M * SERVE))
555   CONTINUE
      SUM = SUM + (SUM1 * C(K))
560   CONTINUE
      RNQ = RNQ + (SUM * PNBSNQ(I))
570   CONTINUE
      RNQ = RNQ * (1-PQ)
      RQ = 0.0
      DO 590 I=1,NCPT(NTYPE)
      SUM = 0.0
      J = NS-I+1
      DO 585 K=J,NS
      SUM1 = 0.0
      L = NS-K+1
      DO 575 M=I,L,-1
      SUM1 = SUM1 + (1/(M * SERVE))
575   CONTINUE
      SUM2 = 0.0
      DO 580 IJ=J,NS
      SUM2 = SUM2 + C(IJ)
580   CONTINUE
      IF (SUM2 .LE. 0.) THEN
         SUM2 = 1000.
      END IF
      SUM = SUM + (SUM1 * C(K) / SUM2)
585   CONTINUE
      RQ = RQ + (SUM * PNBSQ(I))
590   CONTINUE
      RQ = RQ * PQ
      EVR = RQ + RNQ
      PRINT 600, EVR
      WRITE(5,600) EVR
600   FORMAT('OE(RESIDUAL DELAYS) = ',F9.4,' HOURS ')
C
C - - - CALCULATE THE STEADY-STATE EXPECTED WAITING TIMES
C - - - IN THE QUEUE (EVW)
C
      EVW = EVR / (1 - (ARR * EVB))
      PRINT 610, EVW
      WRITE(5,610) EVW
610   FORMAT('OE(WAIT TIME IN THE QUEUE) = ',F9.4,' HOURS ')
C
C - - - DETERMINE WHETHER OR NOT TO END THE EVALUATION
```

```
C - - - WITHIN THIS AVAILABILITY RATE AND COST CENTER
C
620   WRITE(5,611)
611   FORMAT(' DO YOU WISH TO CHANGE THE NUMBER OF
     1    CRAFTSMEN USED? ')
615   READ(5,612) ANS
612   FORMAT(10A1)
      IF (ANS .EQ. 'Y') THEN
         WRITE(5,613) NCPT(NTYPE)
613      FORMAT(1X,I2,' WAS THE LAST NUMBER OF CRAFTSMEN',
     1      'USED.  WHAT NUMBER WOULD YOU LIKE TO TRY? ')
         READ(5,614) NCPT(NTYPE)
614      FORMAT(I3)
         GO TO 91
      ELSE IF (ANS .EQ. 'N') THEN
         GO TO 625
      ELSE
         WRITE(5,616) MSG2
616      FORMAT(1H, A)
         GO TO 615
      END IF
625   WRITE(5,630)
630  FORMAT(' IS THE ANALYSIS OF ALL WORK TYPES FINISHED? ')
635   READ(5,640) ANS
640   FORMAT(10A1)
      IF (ANS .EQ. 'Y') THEN
         GO TO 840
      ELSE IF (ANS .EQ. 'N') THEN
         ARR = 0.0
         GO TO 66
      ELSE
         WRITE(5,660) MSG2
660      FORMAT(1H, A)
         GO TO 635
      END IF
C
C - - - ANALYZE NEW SHOP
C
840   WRITE(5,850)
850   FORMAT(' IS THE ANALYSIS FINISHED? ')
860   READ(5,870) ANS
870   FORMAT(10A1)
      IF (ANS .EQ. 'Y') THEN
         WRITE(5,880)
880      FORMAT(' - HAVE A NICE DAY ')
         STOP
      ELSE IF (ANS .EQ. 'N') THEN
         GO TO 1
      ELSE
```

```
          WRITE(5,890) MSG2
890       FORMAT(1H, A)
          GO TO 860
       END IF
       END
```

END
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