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Availability analysis of flexible manufacturing system

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NOMENCLATURE

Latin symbols

A steady state availability

A(t) instantaneous availability: probability that the system will be operating at time t

A(0,t) interval availability

DOUT the desired system output

E system effectiveness

F maximum number of failed components to maintain constant production rate

f number of failed components in each group

$\underline{H}$ row vector with elements (1 0 0 ... 0)

$\underline{I}$ row vector with elements of initial operating condition

K matrix to determine the row vector of steady state probability

k_{ac} constant that corresponds to the ath row and the cth column in the transition matrix M.

L number of series and parallel groups in the system

M transition matrix

N number of failure modes

$\underline{P}$ row vector with elements of steady state probability

$\underline{P}(s)$ Laplace transform of the transition probability vector

$\underline{P}(t)$ transition probability vector

PRATE constant representing system production rate

PRATE(t) expected production rate at time t of a system

Q set of all system-states

q number of system-states

q_a general element of Q, can either be operating or failing state

Q_f set of failed system-states

Q_o set of operating system-states

q_o number of operating system-states

t implies time-point t; $t \geq 0$

U fraction utilization

w constant representing production rate

X_1 number of components in group 1

y Group of states No.

Z_1 subset of failure modes for components in group 1

$$Z_1 = [f_1, f_2, \ldots, f_N] \quad \text{such that} \quad \sum_{n=1}^{N} (f_n) \leq X$$

e.g. $Z_2 = [3,0,1]$ shows that four components in group 2 are down, three components of failure mode 1, 0 of failure mode 2, and 1 of failure mode 3.

Greek Symbols

$\tau_1(f)$ production rate distribution for parallel components in group 1

λ_{ni} failure rate of the nth failure mode of the ith component in series

λ_{rn} failure rate of the nth failure mode of parallel components during regular operation

λ_{hn} failure rate of the nth failure mode of parallel components during heavy operation

μ_{ni} repair rate of the nth failure mode of the ith component in series

μ_n repair rate of the nth failure mode of parallel components in either heavy or regular operation

SUBSCRIPTS

c index for combined system

i index for component number in series

h implies heavy operation

jl index for number of components in parallel group l

k implies state No. k; k=1,2,...,q

l implies group No. l; l=1,2,...,L

n implies failure mode No. n; n=1,2,...,N

p index for parallel components

S index for series components

INTRODUCTION AND LITERATURE REVIEW

Introduction

The term "FMS", Flexible Manufacturing System, is used in different ways in industry. However, according to Kearney and Trecker (Hall,17), a major U.S. supplier of FMSs: FMS combines the existing technology of Numerical Control (NC) machine tool, automated material handling, and computer hardware and computer software to produce mid-volume and mid-variety of discrete parts.

The classification of a particular FMS results basically from its mode of operation as well as the properties of the three components above. According to the extent of use of the term "flexible", FMS can be classified into the following basic types (7):

(1) Flexible Machining Cell (FMC): it consists of one CNC machine tool, interfaced with automated material handling. An articulated arm, robot or pallet changer is sometimes used to load and unload the machine tool.

(2) Flexible Machining Systems (FMS): it is highly routing-flexible and product-flexible. It allows several routes for parts, with small volume production of each and consists of FMCs of different types of general purpose machine tools. Within FMS, the various kinds of material handling provide a wide range of flexibility.

(3) Flexible Transfer Line (FTL): it is less process-flexible and less capable of automatically handling breakdowns. The layout of this

type is process-driven and the material handling is usually a carousel or conveyor.

The fields of application of FMC, FMS and FTL depend on the production quantity and other features of the parts to be produced. The performance of an FMS is frequently distorted by irregularities caused by components breakdowns. Breakdowns can result from one or a combination of five broad classes of failure in the system: mechanical, electrical, hydraulic, computer hardware and computer software.

The appropriate Markov model to study the availability of FMS is that describing the system as a discrete-state continuous-time Markov process. Numerical values of the appropriate availability are obtained by studying the different failure modes entered by the manufacturing system, as it evolves in time, and setting up and solving the mathematical models described in Chapter 2.

While the concept of availability is well known, the performance measures, such as production rate with lapse of time, are not so well determined. The formulas presented in Chapter 3, are developed by which the expected production rate can be determined after solving the system-state transition matrix.

Due to the numerical complexity of the method, a program in BASIC is designed to determine the transition matrix, steady-state availability and expected production rate. The transient behavior of the state probabilıties and the performance measures are determined by a FORTRAN program which is executed under control of the BASIC code.

Problem Definition

The ideal performance measures in an FMS tend to be distorted by irregularities caused by machine breakdowns, tool failure, preventive maintenance, raw material quality and a variety of other short term interruptions. This is a significant problem since it affects the true productive capacity of the FMS.

Performance models of manufacturing systems subject to failures are basic tools to understand and predict accurately the behavior of the system to aid decision making. One of the most practical application of these models is in production schedule planning. Thus, optimum capacity planning can be determined as a result of the modeling. In addition, the time period that the predictive maintenance analyst is concerned with is the time between planned maintenance shutdowns during which components are cleaned, lubricated and adjusted so that the system will continue to remain in the random failure period (constant hazard failures) the rest of its life. The system availability predicts the actual running time with respect to the scheduled operating time.

The Markovian models and the computer program presented in this research have been developed to analyze different types of FMS and to investigate realistic performance measures. Moreover, effects of desired system output on other system performance are analyzed.

Stochastic processes are used to define the Markovian models and the resulting probabilities are used to evaluate the system availability and consequently the system effectiveness. Table 1 (22) summarizes some of the common expressions of the time dependent and steady-state availabilities of systems consisting of one, two, or three identical units that operate either in active parallel, or in standby without failures. Calculation of the general solution for time dependent availability can be quite complicated even when the number of states is only moderately large. Method of calculating the availability using a Markov approach was developed by decomposing the system into subsystem technique (1). In many cases, where instantaneous availability is not needed, the steady state availability and the mean time to failure were used to model a parallel system (8,18), and a group of series components (14).

Summary of Previous Research

Much of the previous published research concerning FMS has taken two basic directions: first, most of the recorded work attempts to apply models to evaluate FMS performance without considering the failure concepts. These models can be divided into five classes:

1. Static allocation models

This type of model simply adds up the total amount of work distributed or assigned to each resource, and estimates the performance. It is static and simple. It ignores all dynamics, all interactions and all uncertainties.

2. Queueing network models

These models tend to give reasonable estimates of performance. Although, they require relatively little input data, the output measures

Table 1. Availability of systems comprised of identical units

No. of Identical components	Type of system	Instantaneous Availability $A(t)$
1	-	$\mu/(\mu+\lambda) + \lambda/(\mu+\lambda)\, e^{s_1 t}$
2	Standby	$(2\mu^2 + 2\mu\lambda)/(2\mu^2 + 2\mu\lambda+\lambda^2)$ $-\lambda^2(s_2 e^{s_1 t} - s_1 e^{s_2 t})/s_1 s_2(s_1 - s_2)$
	Active-parallel	$(\mu^2 + 2\mu\lambda)/(2\mu^2 + 2\mu\lambda+\lambda^2)$ $-\lambda^2(s_2 e^{s_1 t} - s_1 e^{s_2 t})/s_1 s_2(s_1 - s_2)$
3	Standby	$(6\mu^3+6\mu^2\lambda+3\mu\lambda^2)/(6\mu^3+6\mu^2\lambda+3\mu^2\lambda+\lambda^2)$ $+[\lambda 3(s_2 s_3(s_2-s_3)e^{s_1 t} - s_1 s_3(s_1-s_3)e^{s_2 t} + s_1 s_2(s_1-s_2)e^{s_3 t}]$ $/s_1 s_2 s_3(s_1-s_2)(s_1-s_3)(s_2-s_3)$
	Active-parallel	$(\mu^3+3\mu^2\lambda+3\mu\lambda^2)/(\mu+\lambda)^3$ $+[6\lambda^3(s_2 s_3(s_2-s_3)e^{s_1 t} - s_1 s_3(s_1-s_3)e^{s_2 t} + s_1 s_2(s_1-s_2)e^{s_3 t}]$ $/s_1 s_2 s_3(s_1-s_2)(s_1-s_3)(s_2-s_3)$

TABLE 1. Continued

Eigenvalues other than $s_0=0$	$A(\infty)$
$s_1 = -(\lambda+\mu)$	$\mu/(\mu+\lambda)$
$s_1 = -\frac{1}{2}\,[2\lambda+3\mu] + (\mu^2+4\mu\lambda)^{\frac{1}{2}}$ $s_2 = -\frac{1}{2}\,[2\lambda+3\mu] - (\mu^2+4\mu\lambda)^{\frac{1}{2}}$	$(2\mu^2+2\mu\lambda)/(2\mu^2+2\mu\lambda+\lambda^2)$
$s_1 = -2(\lambda+\mu)$ $s_2 = -(\lambda+\mu)$	$(2\mu^2+2\mu\lambda)/(2\mu^2+2\mu\lambda+\lambda^2)$
s_1, s_2 and s_3 correspond to the three roots of $s^3+s^2(3\lambda+6\mu) + s(3\lambda^2+9\mu\lambda+11\mu^2) + (\lambda^3+3\mu\lambda^2+6\mu^2\lambda+6\mu^2)$	$(6\mu^3+6\mu^2\lambda+3\mu\lambda^2)/(6\mu^2+6\mu^2+3\mu\lambda^2+\lambda^2)$
s_1, s_2 and s_3 correspond to the three roots of $s^3+s^2(6\lambda+6\mu) + s[11(\mu+\lambda)^2] + 6(\mu+\lambda)^3$	$(\mu^3+3\mu^2\lambda+3\mu\lambda^2)/(\mu^3+3\mu^2\lambda+3\mu\lambda^2+\lambda^3)$

are average values, which assumes a steady state operation of the system. The earliest queueing network model of FMS was CAN-Q (32). The most recent developments in this area are priority mean value analysis (PMVA), (28), and mean value analysis of queues (MVAQ), (35). Some studies (31,33), proposed the use of the closed network of queues models. Other models of FMS (9) included the open queueing networks.

3. Discrete event simulation

Simulation is perhaps the most widely used computer-based performance evaluation tool for FMS. GPSS, SLAM and MAP/1 (27) are the main languages used in the simulation models. Although these models can be made very accurate, they cost too much in terms of programming time, input time to generate detailed data sets and computer running time. Thus, it is recommended to use queueing network models prior to conducting the more expensive simulation studies.

4. Perturbation analysis P/A

Perturbation is the observation of the detailed behavior of the system for one set of decision parameters. It is a new technique which has potential applications to both simulation and real-time operation of FMS. The modeling assumptions required by P/A are minimal, since it can work directly off real data. The main disadvantage of P/A is that it cannot predict accurately the effect of "large" changes in decisions (19).

5. Petri Nets

While in the past the main use of Petri Nets was to answer qualitative questions, recent advances in Petri Nets applied to FMS permit a dynamic, deterministic model of the system. However, there are still some questions about the efficiency of such models. Also, current models do not incorporate any uncertainty (13).

The second major direction is to evaluate the performance measures of an FMS with multiple components that are subject to failure and modeled as closed network of queues. A small number of studies have been carried out. These studies can be divided into academic and industrial.

Academic Studies

Some examples of the more recent practical studies are:

1. Vinod and John (40) investigated an FMS with two stage repair facility and presented a mathematical model that integrates queueing theory and integer programming to determine optimal capacities for repair facilities subject to preset availability requirements of the resources.

2. Vinod and Solberg (41) dealt with the approximate analysis and application of a closed queueing network to model the performance of multistage FMS with multiple server (machine) resources that are subject to resource failure.

3. Hitomi et al. (18) considered a manufacturing system in which two machines are arranged in parallel and investigated the variation of reliability and failure rate of cutting tools with lapse of time.

4. El Sayed and Turley (14) considered a two-stage transfer line with buffer storage where each stage has two failure modes, and presented the equilibrium probability equations for three repair policies.

Industrial Studies

A high proportion of availability studies performed in the manufacturing systems made use of reliability simulation. A study performed at IBM Federal System Division (16) developed a method of process generation that requires no event calendar under the assumptions of exponential independent failures and N-stage Erlang server. This method is implemented in Fortran code. Several measures of system effectiveness are evaluated, including reliability, availability, and mean time between failures.

Objectives of Research

This research presents a methodology that determines the time-dependent availability of flexible manufacturing systems. It provides performance models of manufacturing systems subject to failure and develops a methodology for assessing performance of these systems.

Because of the applied nature of this problem, every attempt has been made to investigate the problem within a realistic framework by taking into account various technological considerations through a computer program that will help the industrial user to improve the performance of the manufacturing system.

The following objectives were established to meet the above requirements:

1. To study the FMS from the stand point of availability approach.
2. To determine the major critical component to system operation.
3. To develop a general Markovian model that describes different failure modes for the availability analysis of FMS.
4. To develop a computer program to carry out the above analyses and to evaluate system availability, component utilization, average production rate and system effectiveness.
5. To evaluate the effects of desired system output on other performance measures.
6. To examine the behavior of the system state probabilities under transient conditions over specified time interval.
7. To conduct sensitivity analysis on the results of the computer program and determine the optimum system capacity.

MATHEMATICAL MODEL AND ASSUMPTIONS

Introduction

For the availability modeling of FMS with many components and different failure modes, it is helpful to consider the system to be a collection of separate components and to study the random sequence of states entered by the manufacturing system, as it evolves in time. Movement between these states will be modeled using continuous time Markov chain models.

The use of Markov processes to model manufacturing systems imposes a few restrictions and limitations. One assumption is the independence of the different failure mechanisms. Another assumption is that the times to failure and the times to repair follow exponential distributions. Thus, the probability that a working unit will become nonoperational in a specified interval is independent of how it has been functioning (12).

The sensitivity of performance modeling of manufacturing systems to the assumption of exponentiality has been studied by several authors. Based on these studies, the following tentative conclusions can be drawn:

1. The assumption of exponentiality produces consistent results that are sufficiently accurate for practical applications. Particularly the results, demonstrated in the paper by Suri (34), have validated this approximation.

2. The exponential approximation overestimates the actual

throughput (15).

3. The relative throughput error decreases as the number of parts in the system increases (15,34).

4. The detailed error analysis is very useful to validate the accuracy of the exponential approximation (15,39).

However, the exponential assumption is valid for the failure events of many manufacturing problems, especially for those in which all components are properly burnt in and do not enter the wear-out region (4). Moreover, the exponential distribution is also valid for the repair time, since the manufacturing systems are designed so that those components which fail most frequently require less time to repair and vice versa (22).

Markov processes, used in this research, are stochastic processes describing movement between states of the process at times specified by the index. Each component will be in one of a discrete set of states at any point in time and so the state space of the process is discrete. Time is treated as continuous and failed states are not "absorbing"; that is, the time to repair the failed component and restore the system into an "up" state is included in the process.

There are several references (2,11,20,30) that describe methods for determining the possible states of a system, developing the system state transition matrix and solving the state equations to find the system availability. However, these methods do not describe how to use the system state transition matrix in calculating performance measures related to time interval between failures of a system required to operate continuously.

Sections 2-4 contain background material and mathematical methodology about failure mode analysis, stochastic performance and availability. Then, the three Markovian models are described in the following sections.

Stochastic Performance

The dynamic behavior of FMS can best be described by a transition diagram among states, which represents the continuous-time discrete-state Markov processes. Each state specifies all possible combination of input and output transition rates. Then, the transition-rate matrix is obtained by inspection of the transition diagram. It can be found by first determining the off-diagonal elements based on the definitions of system states which is described in the next section. After all the off diagonal elements are determined, the diagonal elements can be obtained and is equal to the negative sum of the remaining elements of the row.

Once the transition matrix is obtained, the set of differential equations relating the state probabilities of the system is found by using the state equation:

$$d\,P(t)\,/\,dt = M\,P(t) \qquad \text{for } t \geqslant 0 \tag{1}$$

The transition probability vector, P(t), has q elements and is given by,

$$P(t) = \{P_0(t)\ P_1(t)\ P_2(t)\ .....P_{q-1}(t)\} \tag{2}$$

M is an (q*q) state transition (rate) matrix which has the following properties:

* It is a square matrix
* The sum of the elements in each column equals 0
* The diagonal elements are the values that correspond to the rates out of state. These values are negative.
* The elements of M is the instantaneous transition rate between states.

The solution of the state equation is determined by solving the differential equations. This is typically done using of Laplace transforms. This method enables a first-order differential equation in terms of time to be converted into an algebraic equation in terms of Laplace transform variable s, while the inverse transform permits to convert to the opposite. Therefore, by taking the Laplace transform of the state equation, the following relation results,

$$\mathcal{L}[\, d\, P(t) \,/\, dt] = s\, P(s) - P(0) \qquad (3)$$

The solution of the above equation is

$$(sI - M)\, P(s) = P(0)$$

or

$$P(s) = (sI - M)^{-1}\, P(0) \qquad (4)$$

where P(s) is Laplace transform of the transition probability

s's are the roots of the characteristic equation given by the determinant $|sI - M| = 0$. In general, one eigenvalue must be zero and all others should be negative.

I is an identity matrix

M is the transition matrix

P(0) is the initial condition of the system

Therefore, the matrix elements in P(s) are calculated from the equation:

$$P_k(s) = \frac{[\mathrm{cof}(sI - M)^T]_{k0}}{\Pi\ (s-s_i)} \qquad (5)$$

where the k^{th} element of the (cofactor) $[\mathrm{cof}(sI - M)^T] = (-1)^k\ |M_d|$, and M_d is the matrix obtained by omitting the first column and the k^{th} row of $(sI - M)^T$.

Then, the transition probability vector, P(t), can be calculated numerically from the inverse Laplace transform. However, the Laplace transform method for a general transition matrix M is very difficult to apply by hand when the number of states exceeds four. This is because the eigenvalues are the roots of a q-degree polynomial equation. For this reason, many methods were developed to solve first-order differential equations numerically. These methods are justified in a number of texts dealing with numerical analysis (5,30).

Failure Mode Analysis

Failure mode analysis is a systematic procedure for determining, evaluating and analyzing all potential failures in a manufacturing system. The term "component" will refer to a number of types of elements used in manufacturing systems, such as machine tools, material handling equipment, robots and pallet changer, etc. The term "failure mode" refers to the manner in which a component fails to meet the design intent; thus, mechanical, electrical, electronic, hydraulic and other types of failures can be considered as failure modes. In FMS, failures may be categorized as:

1. Component failures. When the machine fails, it can detect, and display failure diagnostics. It can also give information for repair and maintenance to the operator. Component failures may be further categorized as: unexpected failures, scheduled maintenance and overload failures. This study considers both the unexpected and overload failures.

2. Operation failures. Examples of operation failures may include errors in supplying NC command data, selecting tools and specifying the cutting conditions.

A detailed description of the two categories and other possible sources of failure is illustrated in Appendix C. The results of the failure mode analysis are discussed in the case study.

The procedures for failure mode analysis, which are used in this research, are as follows:

1. Identify and list those component failures and combinations of component failure that cause any of the following to occur:

    a) Partial or complete system shutdown.

    b) Unacceptable performance of equipment.

2. Investigate each component in its potential failure modes for both regular and heavy operation described in Chapter 3.

3. Compute the frequency of each failure mode, the average failure rate and the average downtime to repair.

The results of this analysis could come from systems which used the same type of equipment under similar operating conditions. It can then be used as input data for the application of the Markovian models described in the next section.

The failure rate for a specified time interval is defined as:

$$\lambda = \frac{\text{number of failures}}{\text{total operating hours}}$$

and is expressed in terms of failures per hour. As an example, for the head indexer, 1488 hours of downtime have been experienced in 17 months. Downtime includes 209 total system interruptions, 149 caused by electrical failures, 49 for mechanical failures, and 11 for tool failures. Thus, the rates of three failure modes are 0.018, 0.006, and 0.004 failures per hour, respectively.

When one of the machines in active parallel fails, the other machines increases its production rate up to a 100 % utilization. The operation at this increased production rate is named as "heavy operation" and is described in Chapter 3.

Theoretically speaking, the failure rate for the heavy operation can be found from the mean time between failures which is given by,

$$\theta = \int_{0}^{\infty} R(t)\, dt$$

To calculate the reliability function R(t), the availability formula given in Table 1 can be used with some exception. Consider a system of two components in active parallel, the corresponding equation can be applied, except that:

1. $R(\infty) = 0$, thus the left part of the equation is eliminated.

2. The eigenvalues s_1 and s_2 are different so that

$$s_1 x s_2 = 2\ \lambda_r\ x\ \lambda_h$$

Thus, the reliability of the system is

$$R(t) = \frac{-\ s_2 x e^{s_1 t} + s_1 x e^{s_2 t}}{s_1 - s_2}$$

where $s_1 = -0.5\ [2\ \lambda_r + \lambda_h + \mu] + [(2\ \lambda_r - \lambda_h)^2 + 2\ \ (2\ \lambda_r + \lambda_h) + \mu^2]^{.5}$

$$s_2 = -0.5\ [2\ \lambda_r + \lambda_h + \mu] - [(2\ \lambda_r - \lambda_h)^2 + 2\ \ (2\ \lambda_r + \lambda_h) + \mu^2]^{.5}$$

Therefore, the time between failures is given by

$$\theta = \int_0^{\infty} R(t)\, dt = \frac{1}{s_1 - s_2}\left[\frac{s_2}{s_1} - \frac{s_1}{s_2}\right]$$

$$= \frac{-\ (s_1 + s_2)}{s_1\ x\ s_2}$$

Substituting s_1 and s_2 in the above equation, get

$$\theta = \frac{2\ \lambda_r + \lambda_h + \mu}{2 \lambda_r\ x \lambda_h}$$

For given values of θ, λ_r, and μ, λ_h can be obtained by:

$$\lambda_h = \frac{2\ \lambda_r + \mu}{2\ \theta\ \lambda_r - 1}$$

Availability

Availability may be expressed and defined in three different ways as follows:

I) Pointwise (Instantaneous) Availability. The instantaneous availability, A(t), for a given point in time, is the sum of probabilities of all the operating states at that given point in time. The system is up at time t if a state is in Q_0, which is a subset of the state space Q. On the other hand, the system is down at time t, if a state is in Q_f, which is the complement of Q_0 in Q. The subset Q_0 depends on the structure of the system.

As λ_i and μ_i are, respectively, the failure rates and the repair rates of components, they are positive quantities. Assuming there enough repair crews, the availability of systems, comprised of single, series or parallel components, are derived and given in Table 2. Due to the difficulty of applying Laplace transform theory to a large number of states, the derivation of instantaneous availability was limited to two components for the parallel structure. A numerical comparison of the instantaneous availability is presented in Chapter 3.

II) Interval Availability

The interval availability, A(0,T), is the expected proportion of the time interval from system initiation (time = 0) to time t during which the system is working. Once the transition matrix is set up, the interval availability, which is:

$$A(0,T) = 1/T \int_{0}^{T} A(t)\, dt$$

TABLE 2. Availability of systems comprised of single, series or parallel components

NO. of Compo-nents	Conditions: type of system	Conditions: No. of failure modes	A(t)
1	single	1	$(\mu/\mu+\lambda) + (\lambda e^{s_1 t})/(\mu+\lambda)$
1	single	2	$(\mu_1+\mu_2)/s_1 s_2 + (s_1+\mu_1)(s_2+\mu_2) e^{s_1 t}/s_1(s_1-s_2) + (s_2+\mu_1)(s_2+\mu_2) e^{s_2 t}/s_2(s_2-s_1)$
1	single	N	$\prod_{i=1}^{N} \mu_i/s_i + 1/s_1 \times [\prod_{i=1}^{N} (s_1+\mu_i) e^{s_1 t}) / \prod_{i=1}^{N} (s_1-s_i)]$ $\ldots\ldots + 1/s_N \times [\prod_{i=1}^{N} (s_N+\mu_i) e^{s_N t}) / \prod_{i=1}^{N} (s_N-s_i)$
2	series	1	$(\mu_1\mu_2/s_1 s_2) + (s_1+\mu_1)(s_1+\mu_2) e^{s_1 t}/s_1(s_1-s_2) + (s_2+\mu_1)(s_2+\mu_2) e^{s_2 t}/s_2(s_2-s_1)$
2	series	2	$\prod_{i=1}^{4} \mu_i/s_i + \sum_{j=1}^{4} [\prod_{i=1}^{4} (s_j+\mu_i) e^{s_j t}/\prod_{i=j} (s_j-s_i)]$
Y	series	$N_1 \ldots N_Y$	$\prod_{i=1}^{q} \mu_i/s_i + \sum_{j=1}^{q} 1/s_j \times (\prod_{i=1}^{q} (s_j+\mu)] e^{s_j t}/\prod_{i=j}^{q} (s_j-s)\})$
2	parallel	1	$(\mu^2+2\mu\lambda)/(\mu^2+2\mu\lambda-2\lambda^2) - [2\lambda^2 (s_2 e^{s_1 t} - s_1 e^{s_2 t})/ s_1 s_2 (s_1-s_2)]$

EigenValues	$A(\infty)$
$s_1, s_2 = -.5[(\lambda_1+\lambda_2+\mu_1+\mu_2) \pm \sqrt{(\lambda_1+\lambda_2+\mu_1+\mu_2)^2 - 4(\lambda_1\mu_2+\lambda_2\mu_1+\mu_1\mu_2)}$	$(\mu/\mu+\lambda)$
$s_1 \ldots, s_N$ correspond to the roots of the N-degree polynomial equation	$(\mu_1\mu_2) / (\lambda_1\mu_2+\lambda_2\mu_1+\mu_1\mu_2)$
$s_1, s_2 = -.5[(\lambda_1+\lambda_2+\mu_1+\mu_2) \pm \sqrt{(\lambda_1+\lambda_2+\mu_1+\mu_2)^2 - 4(\lambda_1\mu_2+\lambda_2\mu_1+\mu_1\mu_2)}$	$\prod_{i=1}^{N} \mu_i/s_i$
$s_1, \ldots, s_4$ correspond to the roots of the 4-degree polynomial equation	$\prod_{i=1}^{4} \mu_i/s_i$
$s_1, \ldots, s_q$ correspond to the roots of the q-degree polynomial equation	$\prod_{i=1}^{q} \mu_i/s_i$
$s_1 = -2(\mu+\lambda)$, $s_2 = -(\mu+\lambda)$	$(\mu^2+2\mu\lambda)/(\mu^2+2\mu\lambda+2\lambda^2)$

or by approximation,

$$A(0,T) = 1/T \sum_{g=0}^{G} A(t \times g) \tag{6}$$

can be obtained simply by summing the solutions of the pointwise availability model for incremental value of t. The number of increments G depends on the accuracy of the solution desired.

III) Steady-State Availability

The steady-state availability, A, is the long term average fraction of time that a system will be in an "up" state performing its intended function (37). The steady state availability index is the limit of the pointwise availability as t goes to infinity, i.e., A is defined as,

$$A = \lim_{t \to 0} A(t) \tag{7}$$

Although the transition matrix M for the steady-state availability is identical to that for the pointwise availability, three factors should be considered:

1. The probabilities, P_i, are constants; therefore, their first derivatives, $P_i'(t)$, are equal to 0.
2. The elements of the vector P(0), which indicates the initial condition can be eliminated, since the steady state availability is affected by the initial condition of the system.
3. The sum of the transition probabilities at each interval of time is always equal to 1.

Thus, the state equation becomes:

$$\underline{H} = K \times \underline{P} \qquad \text{or} \qquad \underline{P} = K^{-1} \times \underline{H}$$

where $\underline{P}$ is the column vector of the state probabilities.

K is the matrix obtained by omitting the last state in the matrix M and adding a unit vector at the first row of the matrix. The probability of this state is equal to:

$$1 - \sum_{i=0}^{q-1} P_i$$

The corresponding equation to the row which was omitted can always be used as a check of the correctness of the algebra once the P_i are all calculated, by comparing the above value and the exact solution of the state equation including this state.

$\underline{H}$ is a column vector equal to (1 0 . . . 0).

The steady-state availability is then equal to the sum of the probabilities of the corresponding operating states;

$$A = \sum_{i \in Q_o} P_i \qquad (9)$$

where Q_o is the set of operating states.

Accordingly, the Markovian models described in the following section can be applied directly to systems that are physically in series, parallel, or a combination of the two, and indirectly to more complex systems provided that these systems are first decomposed into parallel/series arrangements.

The Markovian Models

Scope of basic model

The basic function of an FMS is to manufacture different families of parts (4-100 part numbers), each part requiring multiple (1-10) fixtured holdings or sequences and numerous operations per sequence. Thus, an FMS is conceptualized as in Figure 1. This configuration shows an FMS with one family of parts and two types of machining modules. It represents the physical relationship among the main components in FMS: load/unload stations, machine tools, material handling equipment that are controlled by a computer. The first sequence for this family of parts is scheduled for a system of one parallel group of machine type 1. The second sequence consists of two groups of parallel components. One group has two machines of type 1 and the other group has three machines of type 2.

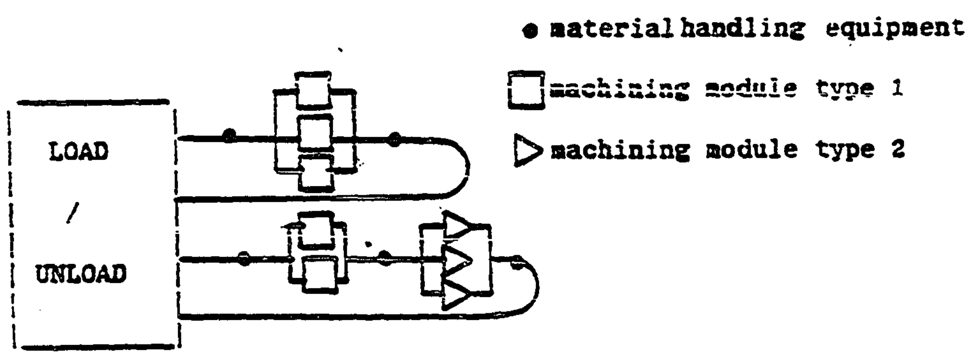

FIGURE 1. A schematic diagram of FMS

Based on the above description, the FMS configuration can be represented by one of the three Markovian models, which are developed and described in the following section. In each model, the system state is defined in terms of the failure modes affecting the availability of the system. Each state, q_a, is an L-tuple $\{Z_1, Z_2, \ldots, Z_L\}$ where Z_l denotes the subset of failure modes in group l. Each subset, Z_l, is ordered into:

$$Z_l = [f_1, f_2, \ldots, f_N]$$

where f_n denotes the number of components failed by the n^{th} failure mode.

The three basic models to be considered are:

Model A: This model represents one or more flexible manufacturing cells connected in series, where the transfer of parts is performed by the worker between them. Associated with each component and its different failure modes, there are both a constant failure rate and a constant repair rate.

Model B: This Model represents a manufacturing system with one group of identical components, operating in parallel and having the same operating conditions and consequently, the same types of failure. Associated with each failure mode, there is a constant failure and repair rate.

Model C: This model represents a typical FMS where groups of parallel machines are linked with the material handling equipment. By consequence, it is a combined case of models A and B.

Model A: Series system with one or more components

This model describes a system that has S series components, each of which has N_i different number of failure modes. For specified integer values of S and N_i (or N if all N_i's are equal), the system represented by this case has q states;

$$q = 1 + \sum_{i=1}^{S} N_i \tag{10}$$

where N is the number of failure modes.

Each component represents a group, i.e., L=S. A system state is represented by the unions of the subset of failure modes, i.e.,

$$q_a = \{Z_1 u Z_2 u \ldots u Z_L\} \tag{11}$$

and each Z_l is represented by the subvectors:

$$Z_l = [f_1, f_2, \ldots f_N]_l \tag{12}$$

where

$$f_n = \begin{cases} 1 & \text{if a component is down} \\ 0 & \text{if a component is up} \end{cases}$$

The system is down if one of the components fails by one of its failure modes. Thus, only a "1" shows in all subset and the remaining elements are 0. So, the system states are described as follows. State 0, corresponds to the case where all series components are running. States $\{(1,0,\ldots,0)_1,(0,1,0,\ldots,0)_1,\ldots,(0,0,\ldots,1)_S\}$ correspond to the case where the n^{th} failure mode of the i^{th} component occurs and causes the entire system to shut down.

The transition matrix, M, for model A is of dimension (qxq). The partitioning of the matrix, is shown in Figure 2. The information

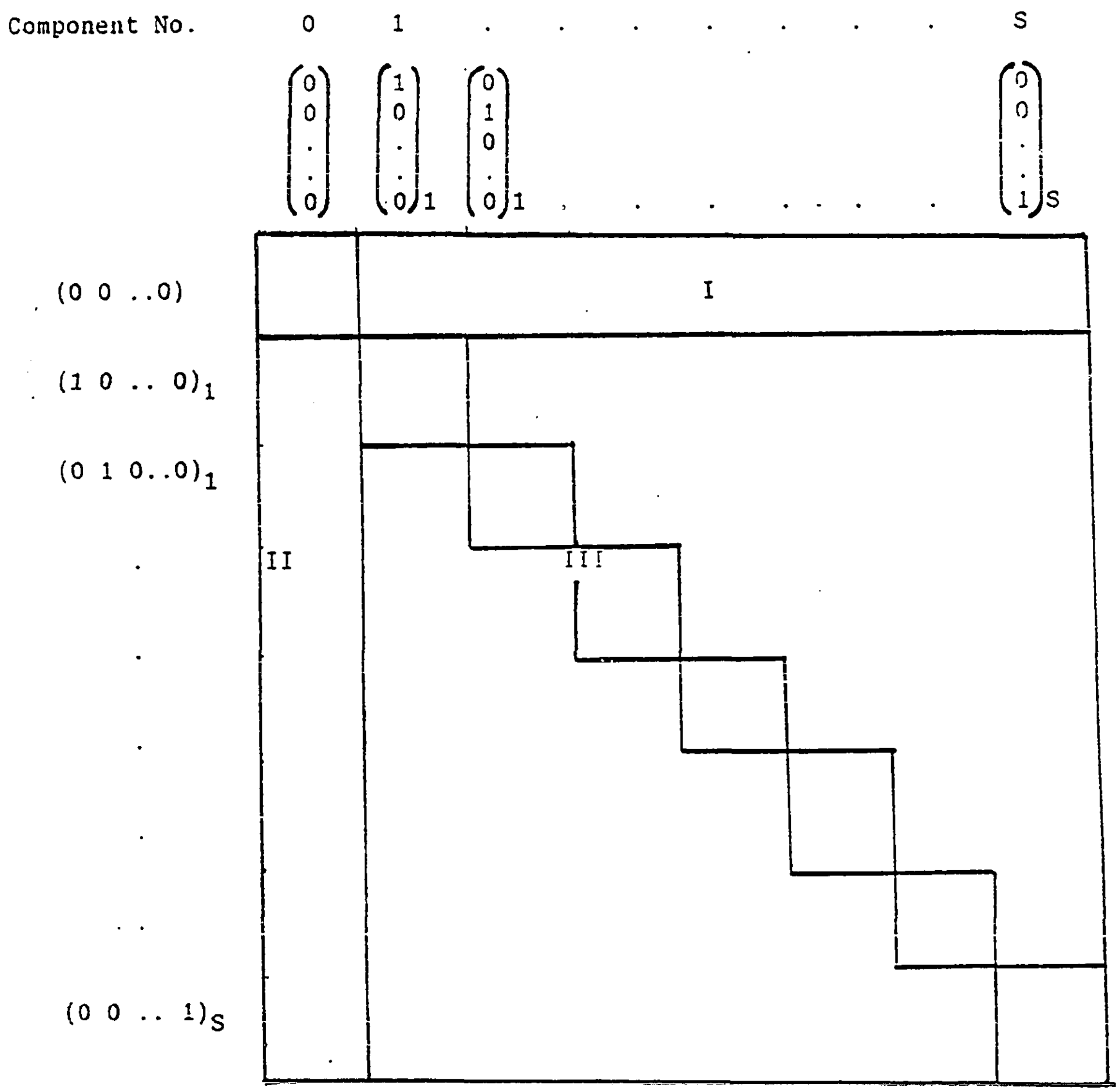

FIGURE 2. Partitioning of the transition matrix of model A.

needed to construct the matrix, particularly the constant k_{ac}, is summarized in Table 3.

TABLE 3. Variable information for Model A.

Area	Description	a	c	k_{ac}
I	repair of 1 component	0	$(1,0,..,0)_1$-$(0,0,..,1)_S$	$\mu_{11}..\mu_{SN}$
II	failure of 1 component	$(1,0,..,0)_1$-$(0,0,..,1)_S$	0	$\lambda_{11}..\lambda_{SN}$
III	diagonal elements	a = c		$-\sum_{\substack{a=0 \\ a\neq c}}^{q-1} K_{ac}$

The table contains values of a,c and K_{ac} for the areas I, II and III. Each area has been defined in terms of the corresponding ranges for a and c. Area III corresponds to the diagonal elelments of the transition matrix, i.e., a=c. For example, the variables information, shown in Table 2 have been applied to a series system with three components. Each of the first and third component has 3 failure modes and the second component has 2 failure modes, Figure 3. The transition diagram is shown in Figure 4 and the resulting transition matrix is shown in Figure 5.

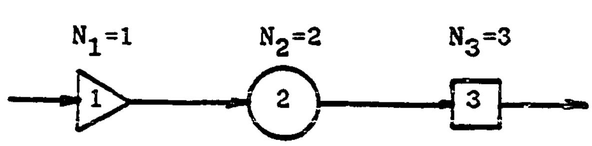

FIGURE 3. A schematic pattern of a series system.

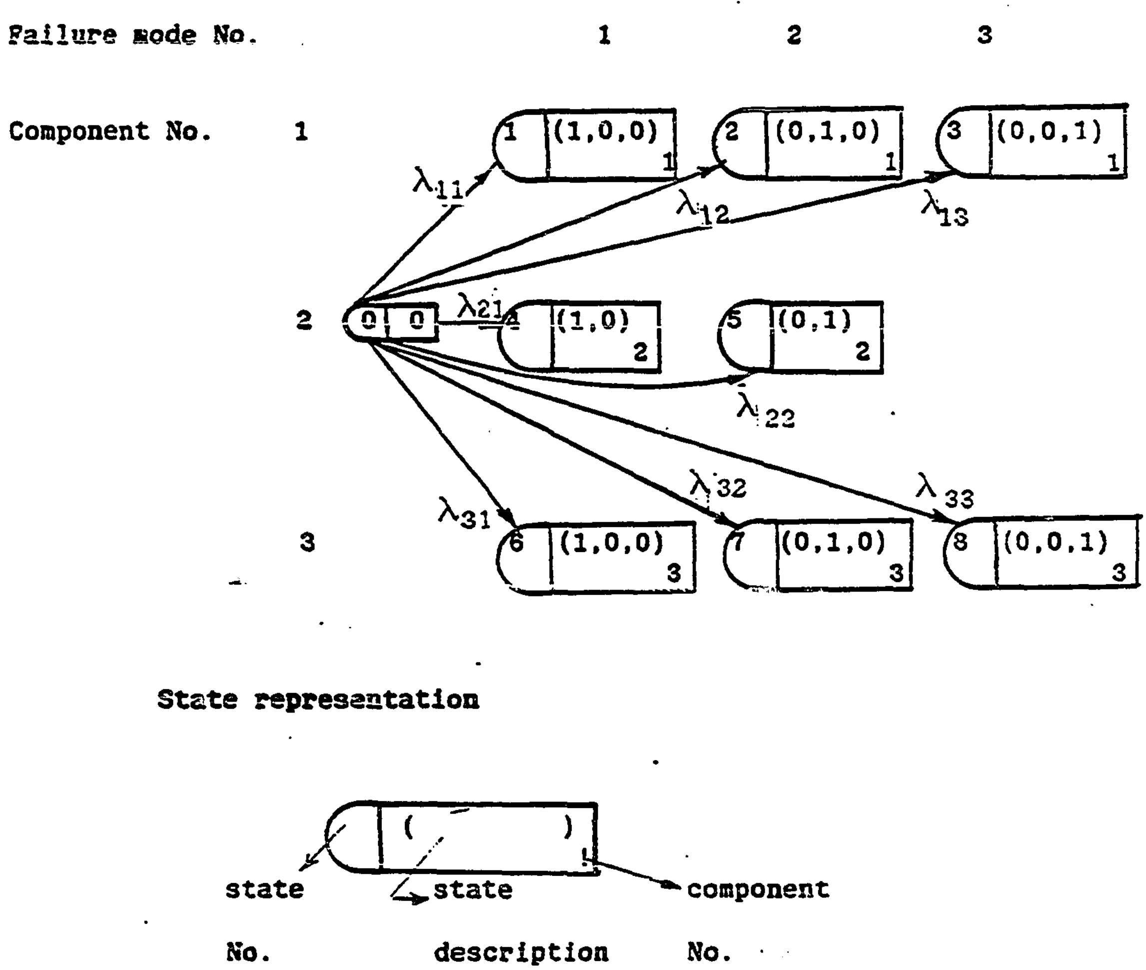

FIGURE 4. Transition diagram for the example in model A

Component down No.	0 $(0\ 0\ 0)$	1 $(1\ 0\ 0)_1$	$(0\ 1\ 0)_1$	$(0\ 0\ 1)_1$	2 $(1\ 0)_2$	$(0\ 1)_2$	3 $(1\ 0\ 0)_3$	$(0\ 1\ 0)_3$	$(0\ 0\ 1)_3$
0 $(0\ 0\ 0)$	$-\sum\lambda_{ij}$	μ_{11}	μ_{12}	μ_{13}	μ_{21}	μ_{22}	μ_{31}	μ_{32}	μ_{33}
1 $(1\ 0\ 0)_1$	λ_{11}	$-\mu_{11}$							
$(0\ 1\ 0)_1$	λ_{12}		$-\mu_{12}$						
$(0\ 0\ 1)_1$	λ_{13}			$-\mu_{13}$					
$(1\ 0)_2$	λ_{21}				$-\mu_{21}$				
$(0\ 1)_2$	λ_{22}					$-\mu_{22}$			
$(1\ 0\ 0)_3$	λ_{31}						$-\mu_{31}$		
$(0\ 1\ 0)_3$	λ_{32}							$-\mu_{32}$	
$(0\ 0\ 1)_3$	λ_{33}								$-\mu_{33}$

FIGURE 5. The transition matrix for the example in model A

Model B: System with one group of identical parallel components

This model represents a system that consists of X identical components in active parallel, each of which has N failure modes. The number of repair crews available and the repair policy will influence the transition matrix. For the description of this model, it is assumed that there are enough crews to have each failed component simultaneously under repair.

The system has q states,

$$q = 1 + \sum_{i=0}^{X-1} C_{N-1}^{N+i} \tag{13}$$

and q_o, number of operating states is equal to,

$$q_o = 1 + \sum_{i=0}^{X-2} C_{N-1}^{N+i} \tag{14}$$

In this model, a system state q_a is N-tuple $\{f_1 n f_2 n \ldots n f_N\}$ such that $\sum_{n=1}^{N} f_n \leqslant X$. To simplify the analysis of the model, the states of the system can be described as follows:

Group 0 State 0, corresponds to the case where all components in active parallel are running.

Group 1 States $\{(1,0,\ldots,0),\ldots,(0,0,\ldots,1)\}$ correspond to the case where one component is failed by the n^{th} failure mode.

Group 2 States $\{(2,0,0,\ldots,0),\ldots,(0,0,0,\ldots,2),(1,1,0,\ldots,0),\ldots(0,\ldots,$

0,1,1)} correspond to the case where two of the X components are down.

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Group X States {(X,0,...,0),...,(0,...,0,X),(X-1,1,0,...,0),...,(0,0,...,1,X-1),(1,1,...,1)} correspond to the case where all X components have failed.

The transition matrix of this model can be subdivided into (1+2xX) areas. The general procedure to find k_{ac} values for any area, is to consider the possible failures and repairs that can be made in one time for the states in the area. By comparing the two states, a and c, the constant k_{ac} is obtained as the corresponding λ or μ of the failure mode, not found in one of the two states. For example, consider the two states, a: "1,0,1" and c: "1,1,1", the constant k_{ac} is equal to μ_2 and k_{ca} is equal to λ_2, since the failure mode 2 is zero in state a.

The variables information shown in Table 4, have been applied to a system consisting of three parallel components, each of which has three failure modes. Figure 6 shows the transition diagram for such a system. The transition matrix, as shown in Figure 7, is divided into seven areas which have been labeled I,II,...,VII. The analysis of K_{ac} is conducted according to two possible values of f_n: a) $f_n = 1$, b) $1 < f_n \leq X$. When $f_n = 1$, λ_{rn} is used to represent the failure rate of the n^{th} failure mode in the regular operation. But when $1 < f_n \leq X$, λ_{hn} is used to represent the failure rate of the n^{th} failure mode in the heavy operation. The "regular" and "heavy" operation are described in detail in Chapter 3.

TABLE 4. Variable information for model B

Area	Description	a	c	K_{ac}
I	repair of 1 component	0	(1,0,0)-(0,0,1)	$\mu_1 - \mu_N$
II	failure of 1 component	(1,0,0)-(0,0,1)	0	$3\lambda_{r1} - 3\lambda_{rN}$
III	repair of 2 components	(1,0,0)-(0,0,1)	(2,0,0)-(0,1,1)	$2\mu_1 - 2\mu_N$
IV	failure of 2 components	(2,0,0)-(0,1,1)	(1,0,0)-(0,0,1)	$2\lambda_{h1} - 2\lambda_{hN}$
V	repair of 3 components	(2,0,0)-(0,1,1)	(3,0,0)-(1,1,1)	$3\mu_1 - 3\mu_N$
VI	failure of 3 components	(3,0,0)-(1,1,1)	(2,0,0)-(0,1,1)	$\lambda_{h1} - \lambda_{hN}$
VII	Diagonal elements	a = c		$- \sum_{\substack{a=0 \\ a \neq c}}^{q} K_{ac}$

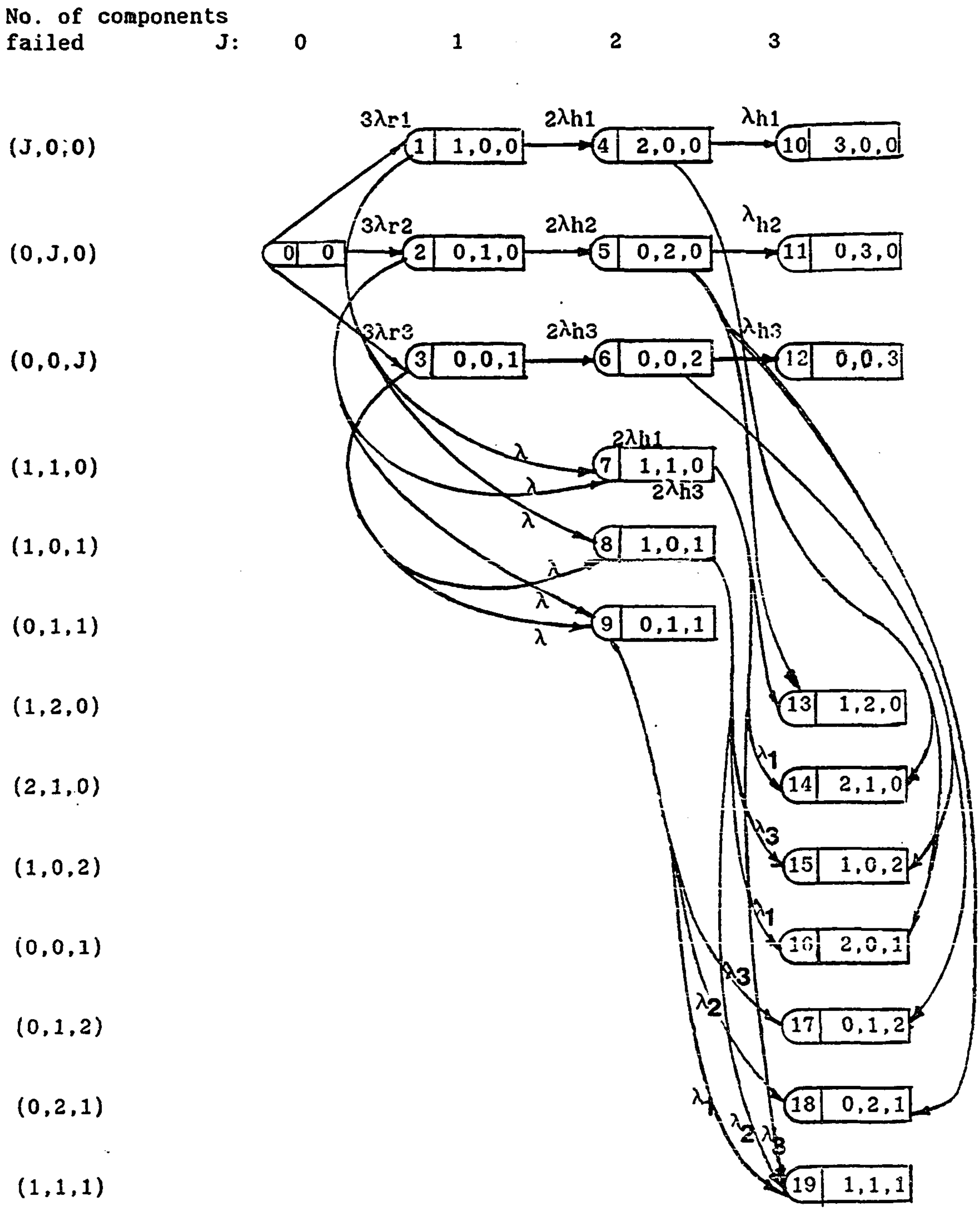


FIGURE 6. Transition diagram for the example in model B

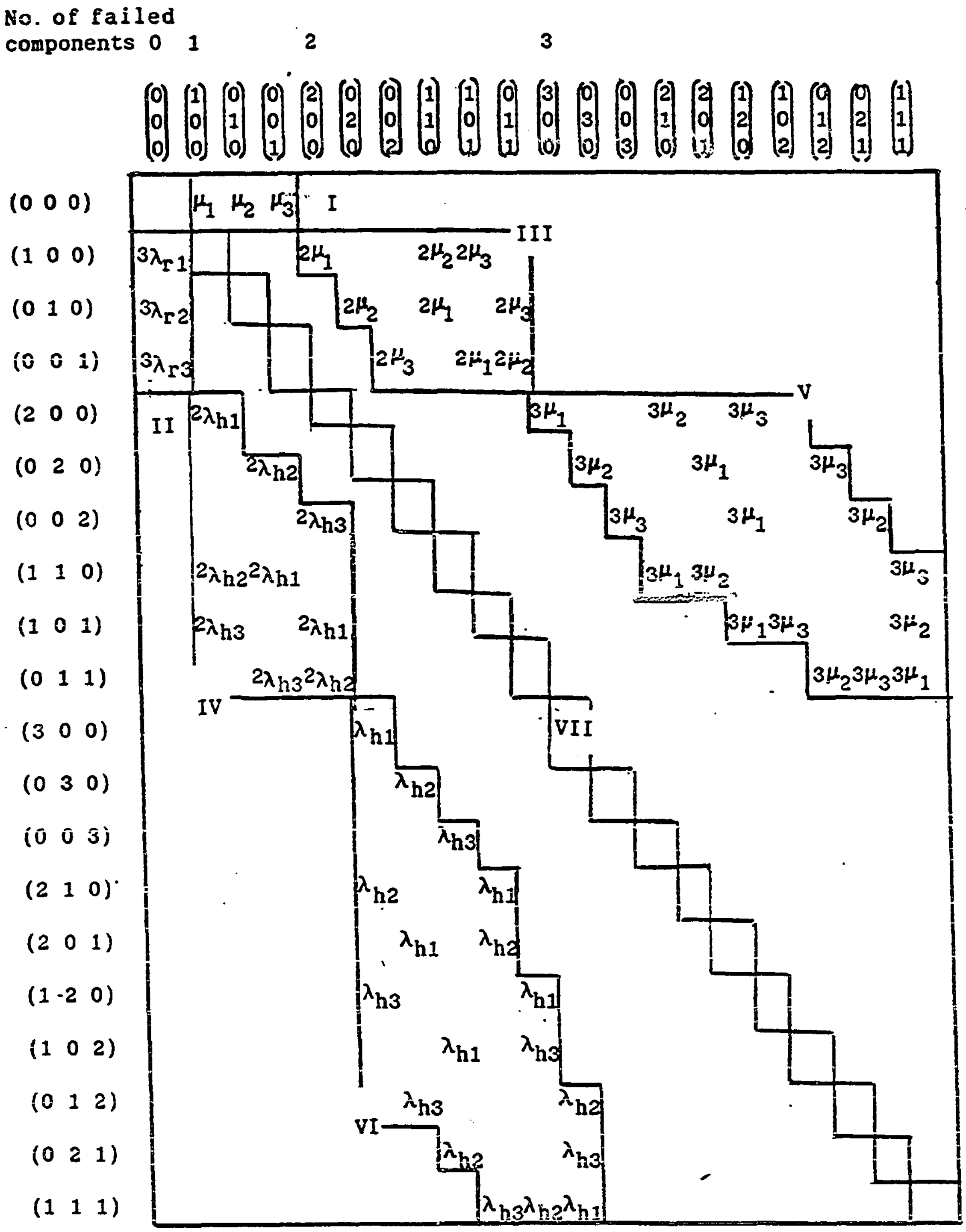


FIGURE 7. Partitioning of the transition matrix of model B

Model C: Combined system

This model represents a manufacturing system that consists of L groups of parallel components and series components. The physical system for this model represents the combination of models A and B. The following description of this model is limited to two groups of parallel components and S series components (i.e., L=2+S). For specified integer values of S, X, N's the system represented by this model, has q different states,

$$q = \left[\prod_{l=1}^{2} \sum_{j=0}^{X_l-1} C^{N_l+j}_{N_l-1} + 1\right] - \prod_{l=1}^{2} C^{N_l+X_l-1}_{N_l-1} + \left(\prod_{l=1}^{2} q_{ol}\right) \times \left(\sum_{l=3}^{L} N_l\right)$$

where q_{ol} is the number of operating states of group l, defined in relation (14).

The system state q_a is an L-tuple of the form

$$\{(Z_1 \cap Z_2) \cap (Z_3 \cup Z_4 \cup \ldots \cup Z_L)\} \tag{16}$$

where Z_1 and Z_S refer to the S series components, and Z_{S+1} to Z_L refer to the two parallel groups. Each subset Z_l is represented by the unions defined in the relation (12). The elements K_{ac} of the transition matrix can be determined by comparing the failure modes in the two states as described in model B. An illustrated application of this model is presented in Chapter 4.

To simplify the analysis of the model, the states of the system can be classified according to three scenarios:

a) States that correspond to component failures in either parallel group, such that $f_n \leqslant X-1$. These states and the elements of the transition matrix are similar to those described in model B. But the transition matrix for this part is subdivided into

$[1+2x(\sum_{l=1}^{2} X_l)]$ areas for the two parallel groups.

b) States that correspond to the combinations of component failures in the parallel groups, that do not cause the entire system to shut down. The number of states is equal to the product of q_o of each parallel group. Consider a system consisting of two parallel groups, one has three components with two failure modes and the other has two components with three failure modes, the number of states is equal to,

$$\text{Total } q_o = \prod_{l=1}^{L} q_o l = [\sum_{i=0}^{3-2} C_{N_2-1}^{N_2+i}] x [\sum_{i=0}^{2-2} C_{N_1-1}^{N_1+i}] = (2xN_1+1) \text{ x } N_2 = 15$$

where N_1 and N_2 are the number of failure modes in each group respectively. The system state q_a is defined as the first part in the relation (16), i.e. $q_a = \{Z_1 \cap Z_2\} =$

$\{(f_1 \cup ... \cup f_N)_1 \cap (f_1 \cup ... \cup f_N)_2\}$, where $\sum_{n=1}^{N} f_n$, in each group, is strictly less than X. Consider the above example and given that one component in group 1 fails with failure mode 2, and two components in group 2 fail with failure mode 1, the system state will be $\{(0,1,0)_1 \cap (2,0)_2\}$.

c) States that correspond to the failure of either all components in one parallel group or any series component. Thus, the transmission of production flow from an input point to an output point, is not possible. This case can be divided in two parts. The first part represents the failure of all components in any parallel group. Table 5 shows the number of possible states for the same example as in (b). Thus the number of states is equal to the sum for those states states marked by "*" in the table. The second part represents the states that can be reached from an operating states by the failure of any series component. The number of states of this part is equal to the number of operating states, q_a multiplied by the sum of the number of failure modes for the series components. The values of K_{ac} are based on the failure and repair rates of series components. Thus the elements, K_{ac}, follow a repeated pattern of $\mu_{11},\ldots,\mu_{SN}$.

Table 5. Number of states for two groups of parallel components (one group has 2 components and the other has 3)

$l=2$, $N=2$ --> $l=1$, $N=3$	0	1	2	3
0	1	2	3	4*
1	3	6	9	12*
2	6*	12*	18*	

Based on the above analysis of the three Markovian models, a computer code is developed to carry out the methodology described in this chapter to evaluate the performance measures described in the next chapter. A complete description of the computer code is provided in Appendix A. The computer program consists of two parts. The first part is the program AVAL, which is written in BASIC. It prepares the necessary transition matrix for the second part. It also computes all the performance measures, for the steady-state conditions, discussed in Chapter 3.

The second part is the program ODE, which is written in FORTRAN to perform the Markovian-process analysis. It also computes the system availability and system effectiveness as a function of time.

PERFORMANCE MEASURES

Performance measures discussed below include availability, production rate, component utilization, and system effectiveness.

Availability

It is a very essential performance measure because it deals with the requirements of both the operation and the repairs. The choice of availability measures requires consideration of whether the main penalty of system failures depends on the total duration of failures or the frequency of failures. If the total duration of failures is important, then the appropriate measure can be related to the availability of the system. If the frequency of failures is important, then the appropriate measure can be related to the MTBF (mean time between failures).

Numerical values of the appropriate availability can be obtained either by using simulation methods or by setting up and solving mathematical models. The system availability at time t is the sum of the probabilities that corresponds to the operating states at time t.

$$A(t) = \sum_{i \in Q_0} P_i(t)$$

The above formula usually requires the solution of the system state equations, which can be obtained by running the computer program.

Table 6 summarizes the general formula of the instantaneous availability for the three Markovian models. A numerical comparison of instantaneous and steady-state availability of different systems is shown in Table 7. The systems consist of one, two or three components that operate in series, in active parallel or in stand by. The computation of the two availabilities for the combined system shown at the end of the table, consists of one parallel group and a series component. This numerical comparison is based on the information of two types of machine with different failure and repair rates which are measured in the same units of time (these values are included in Chapter 4).

TABLE 6. Instantaneous availability of the three Markovian models

No. of machines	Model type	No. of failure mode	A(t)
S	A	$N_1, \ldots, N_S$	$P_0(t)$
X	B	N	$\sum_{i \in Q_0} P_i(t)$
$\bar{X}_1$'s	C	$\bar{N}_I$	$\sum_{i \in Q_0} \bar{P}_i(t)$

Availability is a good performance measure for a single component or multiple components (in series) of a maintainable system. However, for a group of parallel components or parallel/series network, availability can not serve properly as a performance measure because each failure configuration has a different probability.

TABLE 7. Numerical comparison of instantaneous and steady-state availability

No. of Machines	Machine Type	Type of System	No. of Failure Modes	A(t) t=8	t=16	t=24	t=120	t=∞
1	I	Single	2	.896	.841	.812	.773	.773
1	II	Single	2	.893	.865	.858	.855	.855
1	I	Single	3	.884	.820	.783	.706	.691
1	II	Single	3	.887	.857	.850	.853	.846
2	I's	Series	2	.804	.715	.673	.630	.630
2	II's	Series	2	.802	.760	.750	.746	.746
2	I,II	Series	2	.803	.737	.711	.683	.683
2	I's	Series	3	.783	.681	.630	.543	.528
2	II's	Series	3	.791	.746	.736	.732	.732
2	I,II	Series	3	.787	.714	.682	.625	.614
2	I	Active //	2	.988	.970	.955	.924	.923
2	II	Active //	2	.986	.975	.970	.967	.967
2	I	Standby	2	.994	.984	.975	.952	.951
2	II	Standby	2	.993	.986	.983	.981	.981
2	I	Active //	3	.989	.963	.894	.896	.876
2	II	Active //	3	.984	.970	.963	.930	.889
2	I	Standby	3	.992	.979	.968	.928	.915
2	II	Standby	3	.992	.983	.979	.959	.934
1	I	Series	3					
&				.870	.798	.758	.668	.636
2	II	Active //	3					

Utilization

The most important performance measure for an individual component is its utilization. There are several ways to define utilization. Normal industrial practice defines it as the fraction of time, over the long run, that a component is busy. However, for technical reasons, utilization can be defined as the long run average number of busy components in the parallel group. If the system has only one component, the two definitions are equivalent. If, on the other hand, the system has multiple components, utilization cannot be interpreted as a fraction, it may be larger than one. To obtain the average utilization per component, U, which can be interpreted as the fraction of time that each is busy, divide the desired system output DOUT by the total production rate of the parallel components, i.e., U = DOUT/(Xxw), where w is the production rate of each component.

Production Rate

Production rate is the average number of completed parts per unit time, and is denoted by w. The average production rate of each component is given by the reciprocal of the production time t,

$$w = 1/t$$

The net production rate which can be achieved from the system depends on the occurrence of various types of stoppages such as: breakdowns of machines and material handling, tool failures and maintenance, and the effect of these stoppages on the whole system.

The production rate of each component is denoted by w and the expected production rate at time t is denoted by PRATE(t) with the corresponding index for system structure. The following formulae express the production rate for the three models,

a) For s dependent components (series),

$$PRATE(t) = P_0(t) \times w \quad \text{or} \quad PRATE(t) = A(t) \times w$$

where $w = \min \{w_1, \ldots, w_s\}$

b) For one group of parallel components:

In the process of performance analysis of this type of system, the following conditions are assumed:

1. The work load of the system is shared equally by all the components in this group. Thus the rate of flow of material out of the system must equal to the rate of flow into the system.

2. The components, in the same group, have the same operating conditions and consequently the same failure and repair rate for the different failure modes.

3. When all X components in the group operate, it is referred to as "regular operation" and PRATE is less than or equal to the desired system output. When f out of X components fail, the production rate of the remaining components can be increased instantaneously, up to 100 % utilization and it is referred to as "heavy operation". Given the desired system output, DOUT, the maximum number of failed components, F, to maintain constant production rate, is determined as follows:

$$U = DOUT/(X \times w)$$

$$X \times w \times U = (X-F) \times w$$

so, $$F = X \times (1-U)$$

The production rate distribution of a group of parallel components is given by

$$\text{PRATE}(t) = \sum_{y=0}^{X-1} P_y(t) \times \tau_y(f)$$

where $\tau(f)$ is the corresponding production rate for each failure state and it can be formulated as follows:

$$\text{where } \tau(f) = \begin{cases} \text{DOUT} & 0 < f \leqslant F \\ (w/U)(X-f) & F < f \leqslant X \\ 0 & f = X \end{cases}$$

c) for combined system, each series component represents a group, i.e. w_1 to w_S equal to τ_1 to τ_S respectively, and

$$\text{PRATE}(t) = \sum_{y=0}^{q_0} P_y(t) \times \tau_y$$

where τ can be interpreted as

$$\tau = \min \{\tau_1, \ldots, \tau_S, \ldots, \tau_L(f)\}$$

System Effectiveness

System effectiveness, E, is defined as the probability that a system can successfully meet an overall operational demand within a given time when operated under specified conditions. System effectiveness is a term used in a broad context to reflect the system performance and may be expressed differently depending on the specific application. In this study the system effectiveness, E, is defined as:

$$E = \text{PRATE} / \text{DOUT}$$

CASE STUDY

The Physical System

The models developed in this research have been used to investigate state-of-the-art FMS for a manufacturer in state of IOWA. The FMS consists of 16 machine tools, five head indexers, and eleven machining centers, an integrated towline conveyor system controlled by the D.E.C. PDP 11-44 host computer, four load/unload stations, and the necessary equipment that is used in monitoring the quality of the output.

The horizontal 2-axis head indexers (H.I.) are used for precision boring and multi-spindle drilling and tapping operations. They use as many as 7 different spindles per operation. The vertical 3-axis CNC machining centers (M.C.), with each having a 69 tool capacity magazine, are used to do milling, drilling, boring, and tapping operations. They use 10 to 23 tools per operation. The computer-controlled towline conveyor uses identification codes on pallets to control the routing of parts to the right machine tool. The layout, as shown in Figure 8, provides two interconnected towline loops that serve the two rows of the CNC machines.

The load/unload station is heavy steel fabrication and is arranged to accept one 31 by 48 inches metal pallet at a time from the towline carts. Each load/unload station has pallet readers and one CRT/keyboard terminal.

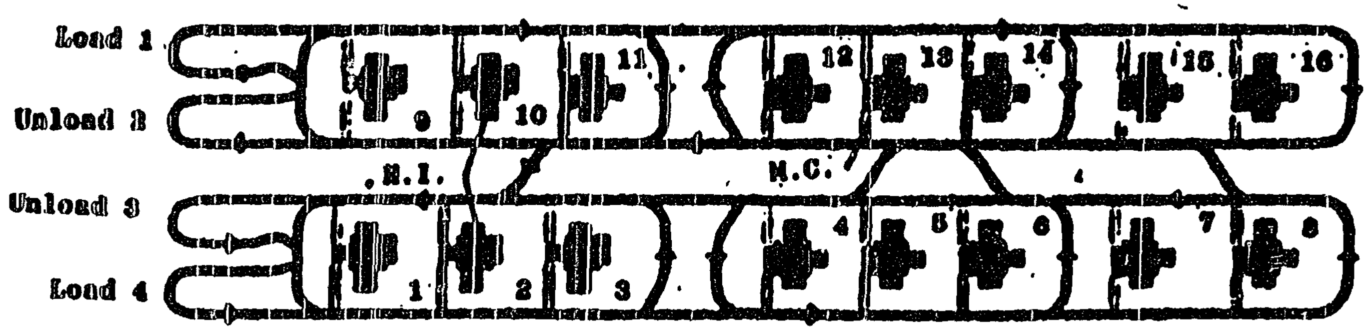


FIGURE 8. System layout

FMS Operations

Fork lift trucks bring incoming castings to the load/unload stations. In the meantime, the towline carts arrive carrying fixtures on machining pallets, workers load parts on the fixtures, report part numbers and pallet codes at a CRT/computer terminal, and release the carts to the towline. These metal pallets remain on the carts after finished castings have been removed, (31). The computer, then, routes the part to the machine and downloads the NC program to the machine.

After the palletized part arrives at the machine, a shuttle-mounted hydraulic cylinder actuates the transfer device that unloads and reloads a towline cart. But, first, a stop mechanism disengages the cart's tow pin from the in-floor conveyer chain, and holds the cart in proper alignment for the transfer.

Each part is usually machined on (1-2) machining centers and (1-2) head indexers. It also requires (2-6) fixtures (sequences) and (2-4) operations for each sequence. It is possible to machine all types of parts at once, with different operations being performed on all 16 machines.

The computer routes a part from any machine to the next one that is available to handle the part and selects CNC machines on a random basis, within the two categories of machines. After machining, carts pass through each machine for pick up on the opposite side and carry parts to the next machine or to the load/unload station.

Parts and their Characteristics

The finished products of this system are a family of eight large, heavy castings, used in drive-train assemblies. The FMS was purchased to produce a daily requirement of 218 pieces in three shifts. There are 30 different operations being performed at any one time in the system, on the two types of machining modules: five head indexers (machines 1,2,3,9, and 10) and eleven machining centers (machines 4 to 8 and 11 to 16).

The cycle times range from 6 to 30 minutes per operation. Table 8 shows, for each family of parts, the part routings, the load/unload station number, the number of orientation fixtures and total process time in minutes. A schematic diagram for parts routings is illustrated in Figure 9. It is to be pointed out here that alternative routings are specified as it is allowed in practice.

In addition, set-up time for any of the parts is done simultaneously as the machines are tooled to run all parts and orientations. The average loading time of a part is 4.65 minutes and the average unloading time is 2.61 minutes. The pallet exchange time is very small, 30-45 seconds because there can be two parts on the shuttle at each machine. Although the complete determination of the performance measures await the solution of the transition matrix of the models, a few preliminary calculations yield some important information about the system. Table 9 summarize of the deterministic calculations.

TABLE 8. Family of parts information

Family parts number	Sequence number	Machine sequence[a]	Load/ unload station	No. of orientation fixtures	Total process time (min.)	Daily demand
1	1	7/8-1	L1-U2	3	18.201	
	2	1/2-4/5/6	L1-U2	5	49.158	
	3	14/15/16	L1-U2	6	68.264	21
2	1	4/5/6-1/2	L1-U2	4	42.165	
	2	3-14/15/16	L1-U2	4	34.542	37
3	1	7/8-1	L4-U3	2	29.753	
	2	1/2-4/5/6	L1-U2	4	60.684	
	3	3-9-14/15/16	L4-U3	4	87.129	16
4	1	4/5/6-1/2	L4-U3	3	49.246	
	2	9-14/15/16	L4-U3	2	32.337	35
5	1	9/10-11/12/13	L4-U3	3	28.386	33
6	1	9-10-11/12/13	L4-U3	5	47.721	23
7	1	10-11/12/13	L4-U3	2	28.405	33
8	1	10-11/12/13	L4-U3	3	40.545	21

[a]"/" in this table implies "or".

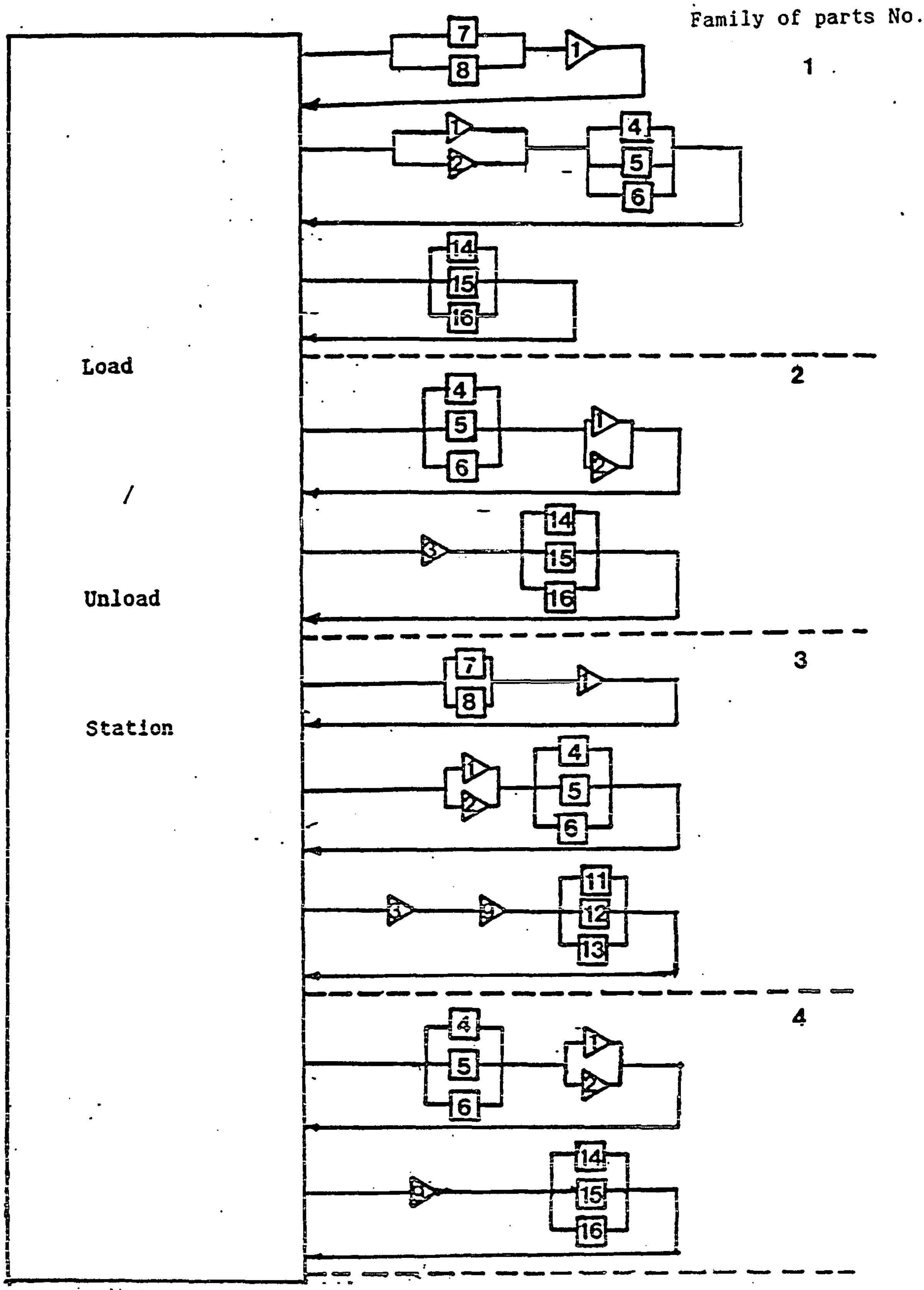


Figure 9. Schematic diagram for part routings

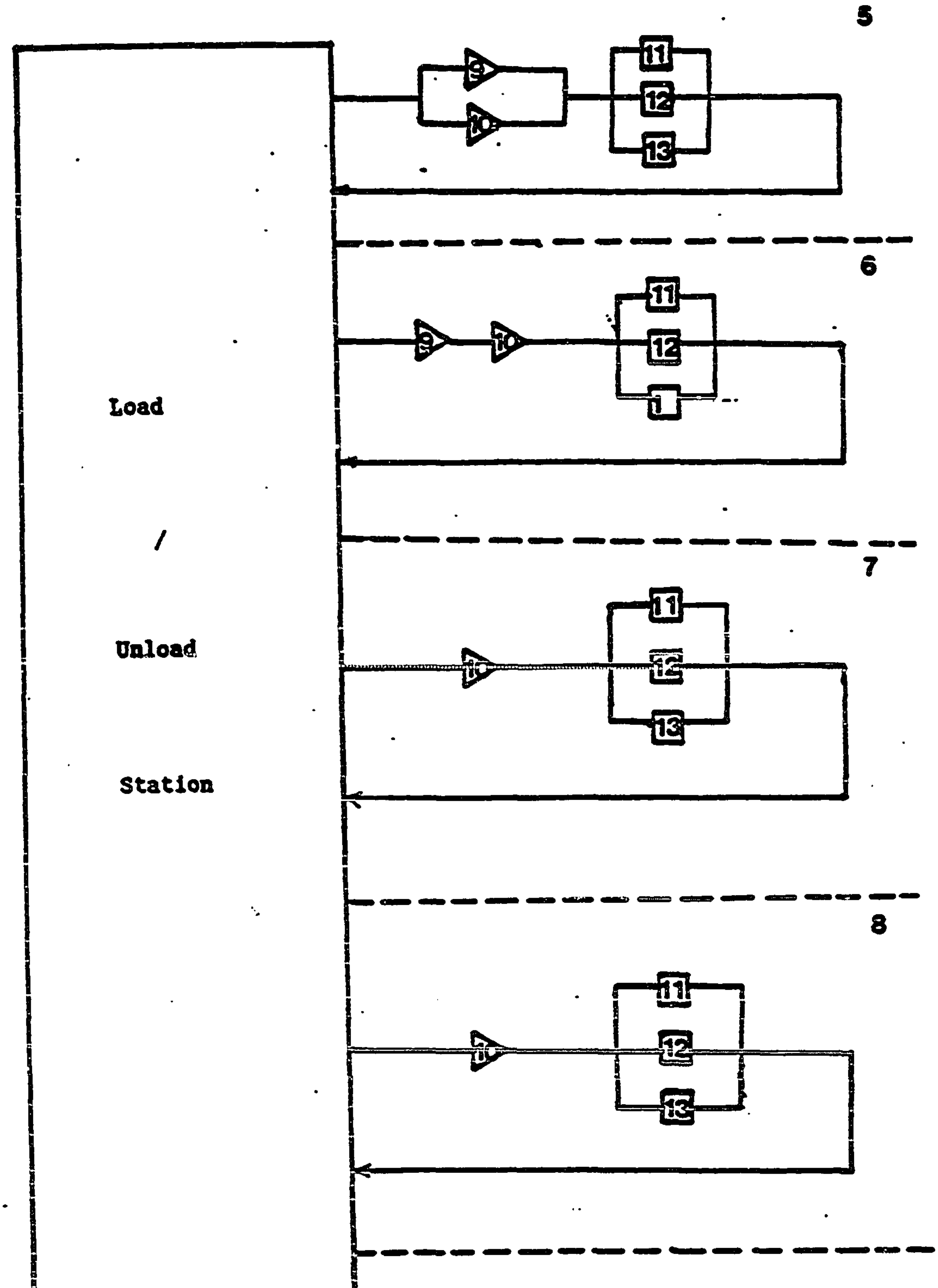


Figure 9. Continued

Example of Deterministic Calculations

A. Total production time:

Total process time per part = sum of process time of the different sequences for each part

Total load and unload time per part = (number of sequences/part) x (load+unload) time/sequence

Total pallet exchange time per part = (total number of operations/ x (pallet exchange time/operation) / parts on the shuttle

Total production time = total process time + (load + unload) time + pallet exchange time

B. System effectiveness, assuming 100% availability, is equal to,

$$\text{System Effectiveness} = \frac{\text{Total production time in hours}}{\text{Total hours}}$$

$$= \frac{\text{Average time/part x No. of parts}}{\text{No. of machines x 24 hrs./day}} = \frac{(731.3 \text{x} 218) \ / \ (60 \text{x} 8)}{16 \text{ x } 24}$$

$$= .865 \text{ or } 86.5\%$$

C. Failure Data Analysis

An analysis was done in an attempt to define the failure modes associated with two types of machine modules. Mechanical and hydraulic failures were combined since mechanics handle both types of failures. Electrical and electronic failure were also combined, since electricians repair both types of failures. The data needed for this analysis are given in Appendix D. Table 10 summarizes the results of this analysis. It indicates that 65.2 % of the repair jobs, for the vertical machining center, were electrical in nature and these repairs accounted for 39.2 % of the total downtime. It is obvious that the electrical failure was more critical than the other two types of failure. On the other hand, the average repair times for the three failure modes of the head indexer were reasonably close. In addition, it was pointed out that electrical failures account for a large share of downtime. Based on this discussion, further analyses were developed to define the nature of these problems.

TABLE 9. Summary of the deterministic calculations
(Note: all times are in minutes)

Family of parts No.	Process time/part	Load/unload time/part	Total pallet exchange time	Total prod. time/part
1	135.622	21.78	2.625	160.027
2	76.707	14.52	1.875	93.102
3	177.566	21.78	3.375	202.721
4	81.583	14.52	1.875	97.978
5	28.386	7.26	0.750	36.396
6	47.721	7.26	0.750	55.731
7	28.405	7.26	1.125	36.790
8	40.545	7.26	0.750	48.555
Total	616.535	101.64	13.125	731.300

Application

To illustrate the methodology developed in Chapter 2, the time dependent-availability and other performance measures are calculated for the family of parts No. 5. The basic configuration, based on the description in Table 8, leads to the concept of treating this system as a collection of two groups of parallel components. Each group consists of identical components. The transition diagram of the system is illustrated in Figure 10. The analysis of the system is performed by the methodology developed for model C.

A list of all components and their regular and heavy failure rates, λ_r and λ_h, as well as the repair rate μ for each component, is shown in table 11. The desired system output is 33 parts/day (1.375 parts/hr). For a numerical example of failure rate for heavy operation, consider a machining center with values of λ_r and μ of .013 and .073, respectively. The mean time between failures is 200 hours. Therefore, the failure rate for heavy operation is equal to:

$$\lambda_h = \frac{2 * 0.013 + 0.073}{2 * 200 * 0.013 - 1} = 0.025$$

Computer Model Usage

The computation procedures for this model have been coded in BASIC. The program was designed to determine the performance measures discussed in Chapter 3. The first part of the code, generates the system states and the transition matrix. The transition matrix is, then, transferred to the ODE program to compute the transition probabilities and production rate as a function of time.

TABLE 10. Results of failure analysis

	Failure mode	% of the[a] total jobs	% of the total downtime	Average[b] repair time	Failure rate	Repair rate
Vertical	Elect	65.2	39.2	13.71	.013	.073
Machining	Mech	9.1	26.3	24.04	.005	.042
Center	Tool	25.7	34.5	30.00	.008	.033
Head	Elect	71.3	64.3	6.43	.018	.154
Indexer	Mech	25.4	28.5	8.66	.006	.117
	Tool	5.3	7.2	9.68	.004	.103

[a] all times are in minutes.
[b] all rates are in units/hr.

Table 11. List of failure and repair rates

Resources	Production Rate/mach. (parts/hr.)	Failure Mode	λ_r*	λ_h*	μ *	Number of identical Components
Machining	1.05	1	.013	.025	.073	2
Center		2	.005	.008	.042	
Head	.70	1	.018	.023	.154	3
Indexer		2	.006	.009	.117	

Steady State Solution

The output of program AVAL consists of three parts. The first part contains information concerning the states of the system. The states are divided into 11 clusters as shown in Table 12. The first 6 clusters contain the operating states with the number of components down. The last 5 clusters contain the failed states with the number of components down.

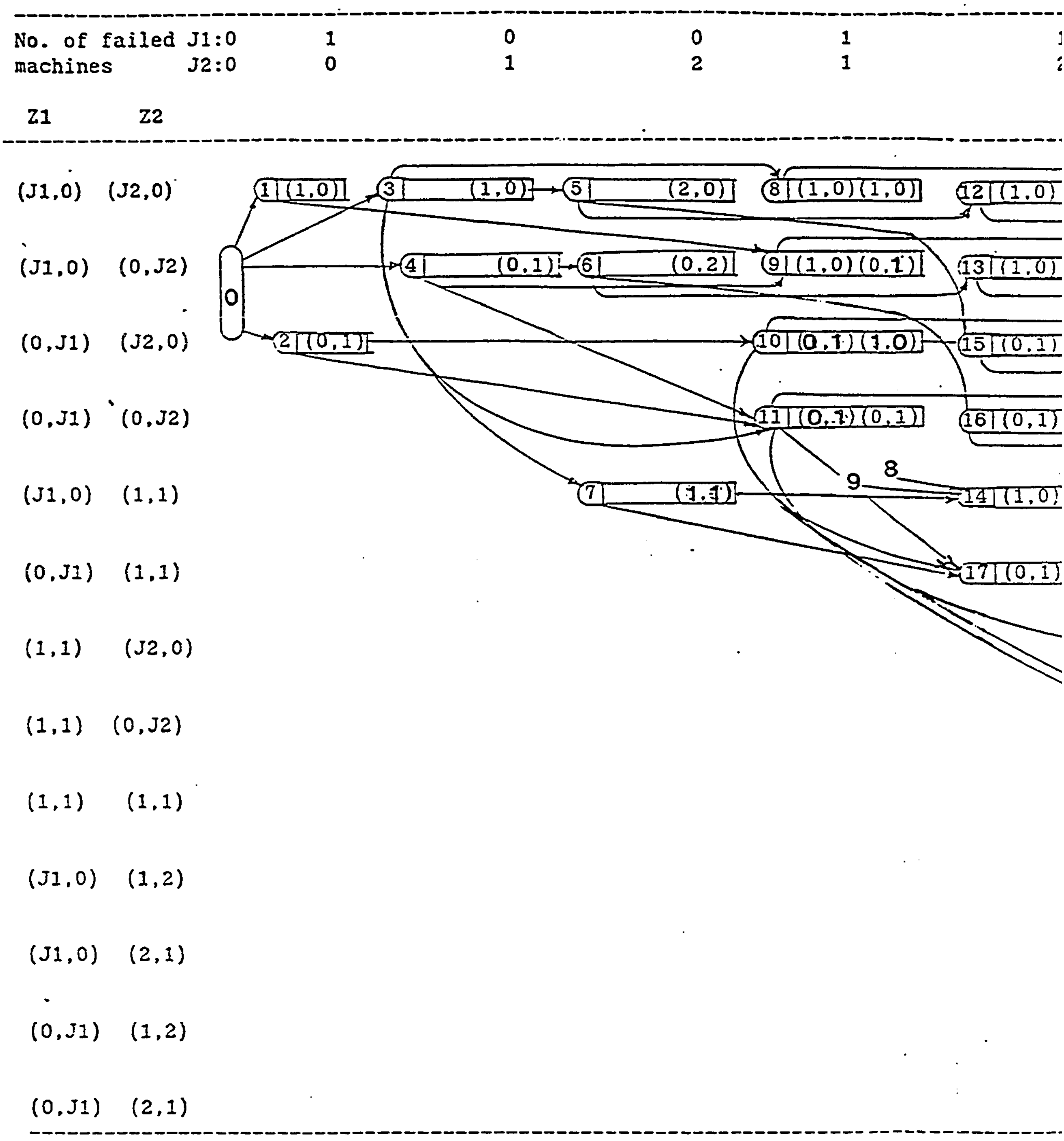
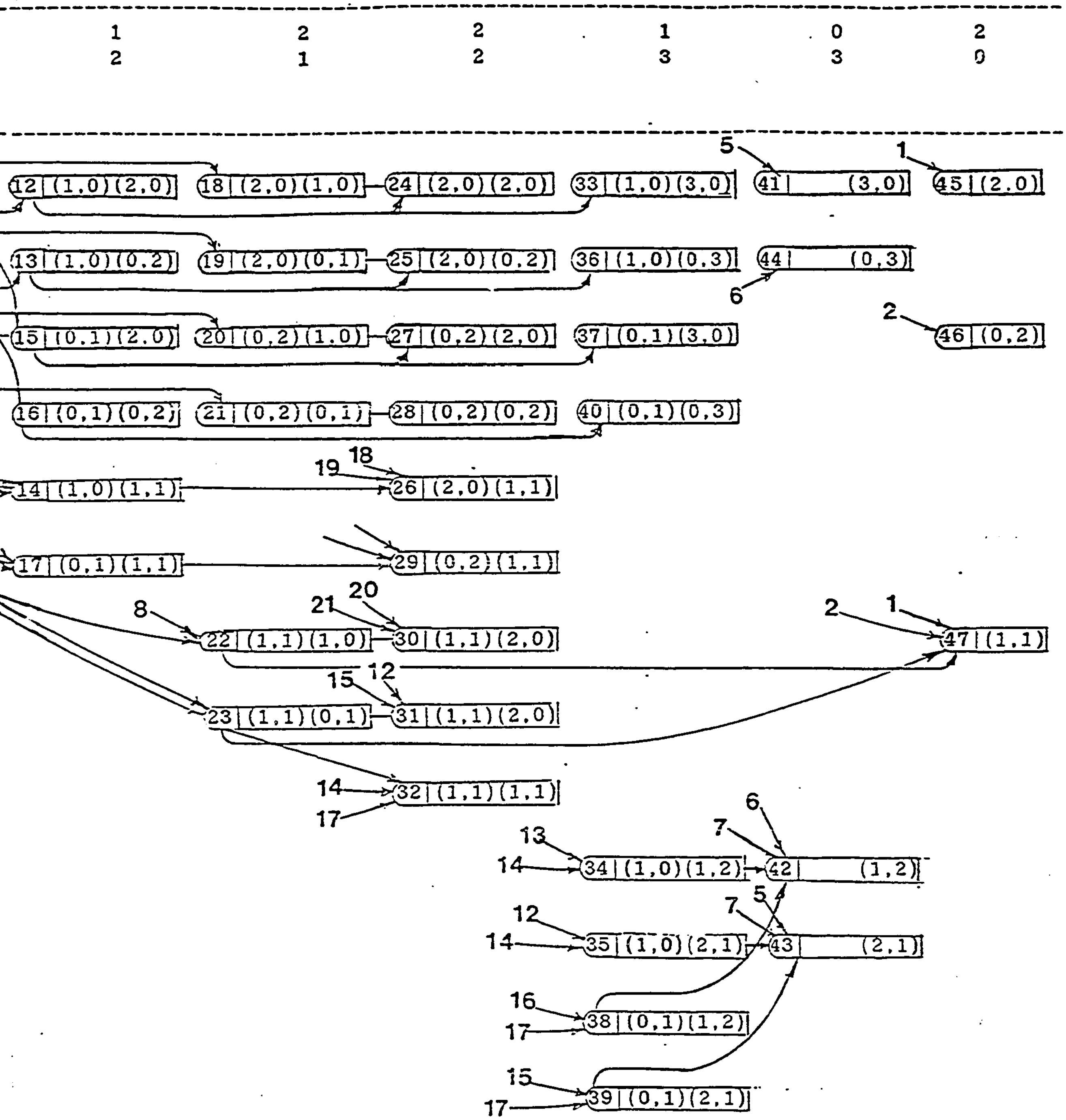


FIGURE 10. Transition diagram of the case study


1 2
2 1
2 2
1 3
0 3
2 0
12 | (1,0)(2,0)
18 | (2,0)(1,0)
24 | (2,0)(2,0)
33 | (1,0)(3,0)
41 | (3,0)
45 | (2,0)
13 | (1,0)(0,2)
19 | (2,0)(0,1)
25 | (2,0)(0,2)
36 | (1,0)(0,3)
44 | (0,3)
15 | (0,1)(2,0)
20 | (0,2)(1,0)
27 | (0,2)(2,0)
37 | (0,1)(3,0)
46 | (0,2)
16 | (0,1)(0,2)
21 | (0,2)(0,1)
28 | (0,2)(0,2)
40 | (0,1)(0,3)
14 | (1,0)(1,1)
26 | (2,0)(1,1)
17 | (0,1)(1,1)
29 | (0,2)(1,1)
22 | (1,1)(1,0)
30 | (1,1)(2,0)
47 | (1,1)
23 | (1,1)(0,1)
31 | (1,1)(2,0)
32 | (1,1)(1,1)
34 | (1,0)(1,2)
42 | (1,2)
35 | (1,0)(2,1)
43 | (2,1)
38 | (0,1)(1,2)
39 | (0,1)(2,1)

The failure modes shown in the output correspond to the states which are illustrated in the transition diagram. For example, state No. 10, $\{(0,1)_1,(1,0)_2\}$, shows that a component in group 1 has a failure mode 2 and a component in group 2 has a failure mode 1.

The second part of the output consists of two matrices. The transition matrix M and the matrix K for steady state. This part of the output is optional and it is printed for checking purposes.

The third part of the output contains information concerning system performance. The steady-state probabilities are printed first followed by the performance measures as shown in Table 13.

This output indicates that the proportion of time the system is available, is 92.6%. It also shows that each component is able to attain utilization of 65.5% and the expected production rate is 1.26 parts/hr. Thus the system effectiveness is equal to 0.915.

TABLE 12. The first part of AVAL output (system states)

Cluster No.	Number of States	State No.	Failure modes in group 1	Failure modes in group 2
0	1	0		
1	2	1	(1,0)	
		2	(0,1)	
2	2	3		(1,0)
		4		(0,1)
3	3	5		(2,0)
		6		(0,2)
		7		(1,1)
4	4	8	(1,0)	(1,0)
		9	(1,0)	(0,1)
		10	(0,1)	(1,0)
		11	(0,1)	(0,1)
5	6	12	(1,0)	(2,0)
		13	(1,0)	(0,2)
		14	(1,0)	(1,1)
		15	(0,1)	(2,0)
		16	(0,1)	(0,2)
		17	(0,1)	(1,1)
6	6	18	(2,0)	(1,0)
		19	(2,0)	(0,1)
		20	(0,2)	(1,0)
		21	(0,2)	(0,1)
		22	(1,1)	(1,0)
		23	(1,1)	(0,1)
7	9	24	(2,0)	(2,0)
		25	(2,0)	(0,2)
		26	(2,0)	(1,1)
		27	(0,2)	(2,0)
		28	(0,2)	(0,2)
		29	(0,2)	(1,1)
		30	(1,1)	(2,0)
		31	(1,1)	(0,2)
		32	(1,1)	(1,1)
8	8	33	(1,0)	(3,0)
		34	(1,0)	(1,2)
		35	(1,0)	(2,1)

TABLE 12. Continued

Cluster No.	Number of States	State No.	Failure modes in group 1	2
		36	(1,0)	(0,3)
		37	(0,1)	(3,0)
		38	(0,1)	(1,2)
		39	(0,1)	(2,1)
		40	(0,1)	(0,3)
9	4	41		(3,0)
		42		(1,2)
		43		(2,1)
		44		(0,3)
10	3	45	(2,0)	
		46	(0,2)	
		47	(1,1)	

TABLE 13. The third part of AVAL output (performance measures)

State No.	Probability	State No.	Probability
0	+ 0.3674	24	+ 0.0003
1	+ 0.1357	25	+ 0.0001
2	+ 0.0871	26	+ 0.0001
3	+ 0.1263	27	+ 0.0001
4	+ 0.0570	28	+ 0.0000
5	+ 0.0188	29	+ 0.0000
6	+ 0.0044	30	+ 0.0003
7	+ 0.0090	31	+ 0.0001
8	+ 0.0432	32	+ 0.0001
9	+ 0.0194	33	+ 0.0006
10	+ 0.0277	34	+ 0.0002
11	+ 0.0125	35	+ 0.0004
12	+ 0.0060	36	+ 0.0001
13	+ 0.0014	37	+ 0.0005
14	+ 0.0029	38	+ 0.0001
15	+ 0.0039	39	+ 0.0003
16	+ 0.0009	40	+ 0.0001
17	+ 0.0019	41	+ 0.0011
18	+ 0.0040	42	+ 0.0002
19	+ 0.0021	43	+ 0.0005
20	+ 0.0011	44	+ 0.0001
21	+ 0.0006	45	+ 0.0291
22	+ 0.0030	46	+ 0.0110
23	+ 0.0015	47	+ 0.0169

Steady state availability = .9256

Expected production rate = 1.2576

System effectiveness = .9146

The effect of DOUT on performance measures

Having determined the performance measures, the next step was to use the model to conduct a sensitivity analysis on the results of the computer program. To test the effect of the desired system output on the other performance measures, several runs of computer program were made with varying values of DOUT. Pertinent results of these runs are summarized in Table 14 and presented graphically in Figure 11.

TABLE 14. Results of sensitivity analysis

DOUT	PRATE	UTL	A	E
.50	.466	.238	.926	.926
1.00	.926	.477	.926	.926
1.37	1.258	.655	.926	.915
1.50	1.353	.714	.926	.902
1.60	1.375	.762	.926	.859
1.70	1.402	.809	.926	.825
1.80	1.400	.857	.926	.777
1.90	1.399	.905	.926	.736
2.00	1.398	.952	.926	.699
2.10	1.397	1.000	.926	.665

As the figure indicates, the system effectiveness is not affected when DOUT increases up to 1 part/hr. Also, it is obvious that as DOUT increases, the utilization increases and the system effectiveness decreases. If the system is capable of processing 2.1 parts/hour, at a 100% utilization for each component (point c), the expected production rate of 1.397 parts/hr will be achieved. On the other hand, the system effectiveness, at point a, is equal to .926, and hence the actual production rate is .926 parts/hour.

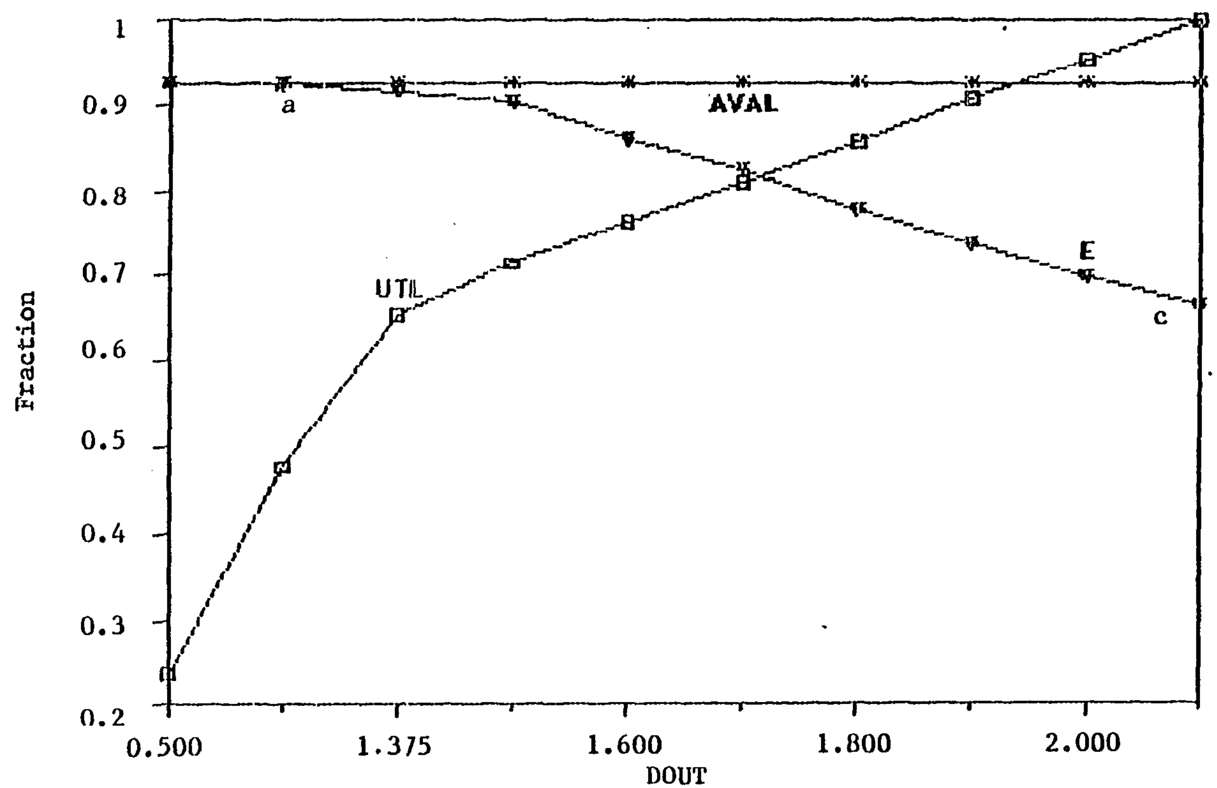


FIGURE 11. Effect of DOUT on performance measures

However, the net production rate, PRATE, for the system is equal to the desired system output, DOUT, multiplied by the system effectiveness. Thus, PRATE could reach a maximum value of this product and then declines. This characteristic is evident from Figure 12. It can also be seen that the highest steady-state production rate, 1.14 parts/hour, is achieved at DOUT of 1.7 parts/hour and utilization of .809.

Critical component

The critical component can be determined for each system after computing the production rate for different failure configurations. Table 15 shows the output production rate of the application example for the different groups of states which represent the system failures. For example, cluster No. 5, represents the system in which one component failed in group 1 and two components failed in group 2. At cluster No.5, if one of the two machines in group 2 will be up, the system will be restored to cluster No. 4 in which the production is 1.375 parts/hr. On the other hand, if the machine in group 1 will be up, the system will be restored to cluster No. 3, in which the production rate is only 1.07 parts/hr. Therefore, the critical component in this case is the machine in group 2 (a machining center).

TABLE 15. Output rate for different system failures

Cluster No.	Number of states	Production rate (parts/hr.)	Machine failed in group 1	2
0	1	1.375	0	0
1	2	1.375	1	0
2	2	1.375	0	1
3	3	1.070	0	2
4	4	1.375	1	1
5	6	1.070	1	2
6	6	0.0	2	1
7	9	0.0	2	2
8	8	0.0	1	3
9	4	0.0	0	3
10	3	0.0	2	0

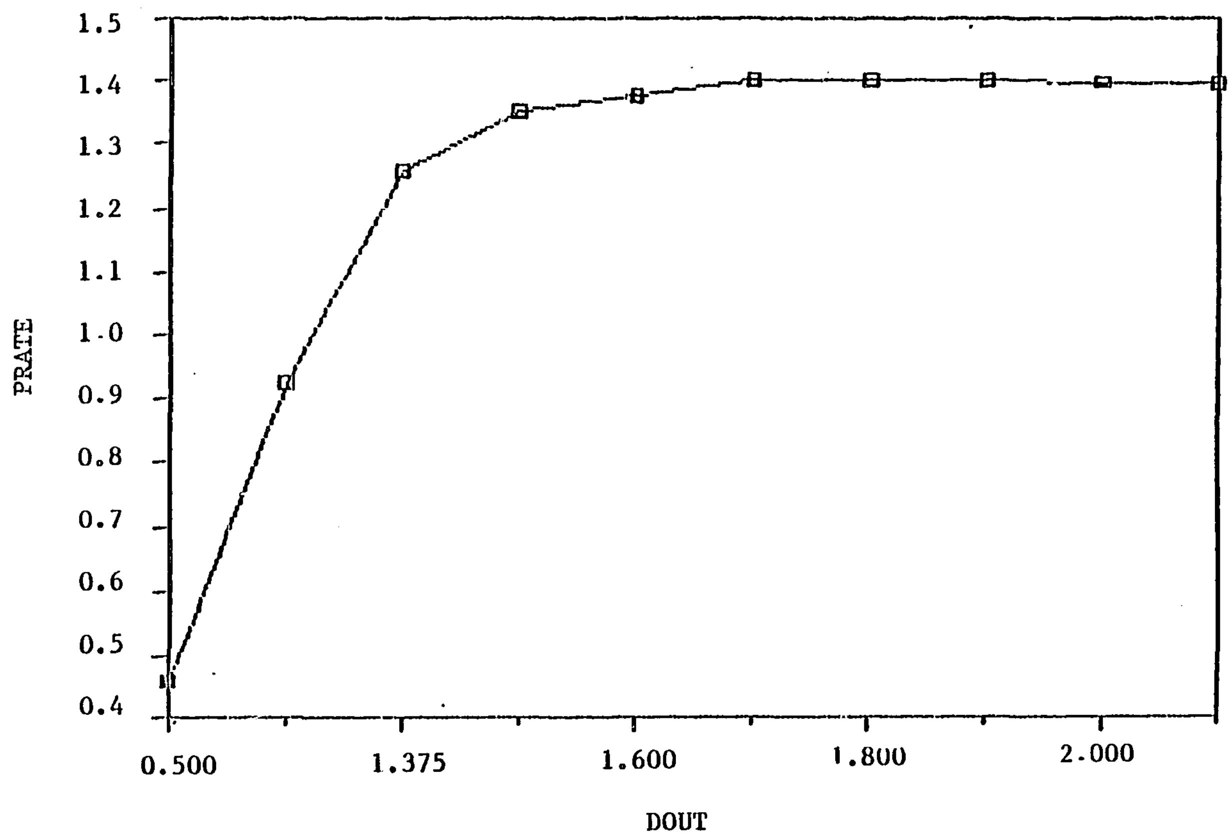


FIGURE 12. Relationship between DOUT and PRATE

Transient Solution

The output of program ODE consists of the transition probabilities, availability, production rate and system effectiveness as a function of time. Starting with the initial condition at time 0, the numerical values of the transition probabilities were determined for each successive point in time by step integration of the state equation. The same procedure was used three times, each time using different values of DOUT. The system is assumed to run at time 0, i.e.,

$$P_0(0) = 1 \quad \text{and} \quad P_i(0) = 0 \qquad \text{for} \quad i > 1$$

Table 16 shows the transition probabilities and performance measures for the system till it reaches the steady state. The results provide a comparison between the behavior of the state probabilities. As intuitively expected, P_0 is "decreasing". The results validate this reasoning with a graph depicting P_0 as a function of time, Figure 13. As a basis of comparison, Figure 14 shows the behavior of certain of the transition probabilities for 1024 hours. The two lines P_1 and P_3 represents the behavior of the first failure mode in group 1 and 2, respectively. The line P_7 represents the behavior of state No. 7, in which two components in group 2 failed with failure mode 1. The line P_{15} represents the behavior of the combination of component failures in state No. 15.

The transition probabilities are normally affected by the failure and repair rates. By examining the behavior of P_1 and P_3, as shown in Figure 14, the value of P_1 increases from 0 at t=0 to the value .136 at

TABLE 16. Transient solution

Pk(t)	Time t 0	2	4	8	16	32	64	128	256	512	1024
k=0	1.000	.825	.708	.570	.454	.390	.370	.367	.367	.367	.367
1	0.000	.040	.064	.091	.115	.132	.136	.135	.135	.135	.135
2	0.000	.016	.026	.040	.056	.073	.084	.087	.087	.087	.087
3	0.000	.077	.116	.144	.147	.134	.127	.126	.126	.126	.126
4	0.000	.027	.042	.056	.062	.060	.057	.057	.057	.057	.057
5	0.000	.003	.008	.016	.020	.020	.020	.019	.019	.019	.019
6	0.000	.000	.001	.003	.004	.004	.004	.004	.004	.004	.004
7	0.000	.002	.004	.008	.010	.010	.010	.010	.010	.010	.010
8	0.000	.003	.010	.023	.036	.043	.043	.043	.043	.043	.043
9	0.000	.001	.004	.009	.015	.019	.019	.019	.019	.019	.019
10	0.000	.001	.004	.010	.017	.024	.027	.027	.027	.027	.027
11	0.000	.000	.001	.004	.007	.010	.012	.012	.012	.012	.012
12	0.000	.000	.001	.002	.005	.006	.006	.006	.006	.006	.006
13	0.000	.000	.001	.000	.001	.001	.001	.001	.001	.001	.001
14	0.000	.000	.000	.001	.002	.003	.003	.003	.003	.003	.003
15	0.000	.000	.000	.001	.002	.003	.004	.004	.004	.004	.004
16	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
17	0.000	.000	.000	.000	.001	.002	.002	.002	.002	.002	.002
18	0.000	.000	.000	.001	.003	.004	.004	.004	.004	.004	.004
19	0.000	.000	.000	.000	.001	.002	.002	.002	.002	.002	.002
20	0.000	.000	.000	.000	.000	.000	.001	.001	.001	.001	.001
21	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
22	0.000	.000	.000	.000	.002	.000	.003	.003	.003	.003	.003
23	0.000	.000	.000	.000	.000	.003	.001	.001	.001	.001	.001
24	0.000	.000	.000	.000	.000	.001	.000	.000	.000	.000	.000
25	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
26	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
27	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
28	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
29	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
30	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
31	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
32	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
33	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
34	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
35	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
36	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
37	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
38	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
39	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
40	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
41	0.000	.000	.000	.000	.000	.001	.001	.001	.001	.001	.001

TABLE 16. Continued

Pk(t)	Time t 0	2	4	8	16	32	64	128	256	512	1024
42	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
43	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
44	0.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
45	0.000	.001	.003	.008	.017	.003	.030	.030	.030	.030	.030
46	0.000	.000	.000	.001	.003	.007	.010	.010	.011	.011	.011
47	0.000	.001	.002	.005	.010	.014	.016	.017	.017	.017	.017
A	1.000	.998	.993	.980	.958	.936	.927	.926	.925	.925	.925
PRATE	1.375	1.370	1.360	1.338	1.303	1.272	1.259	1.257	1.257	1.257	1.257

t=64 and then decreases to the value .135, while the value of P_3 increases to the value .147 at t=16 and then decreases to the value .126. From this figure, an evident effect of the repair rate is the subsequent reduction in the transition probabilities.

However, the ergodic theorem gives the conditions under which an average over time of a stochastic process will converge as the number of observed periods becomes large. In general, to estimate a mean value of a transition probability, a single observation of the entire process is needed, but over a sufficiently long time duration. Then, the steady-state probability can be used as an estimate of the constant mean. As can be expected, the behavior as $t \to \infty$ of the transition probabilities of Markov processes is similar to that of the steady-state.

Of more interest are other quantities derived from the transition probabilities, such as, probability of each cluster of operating states, system availability and system effectiveness.

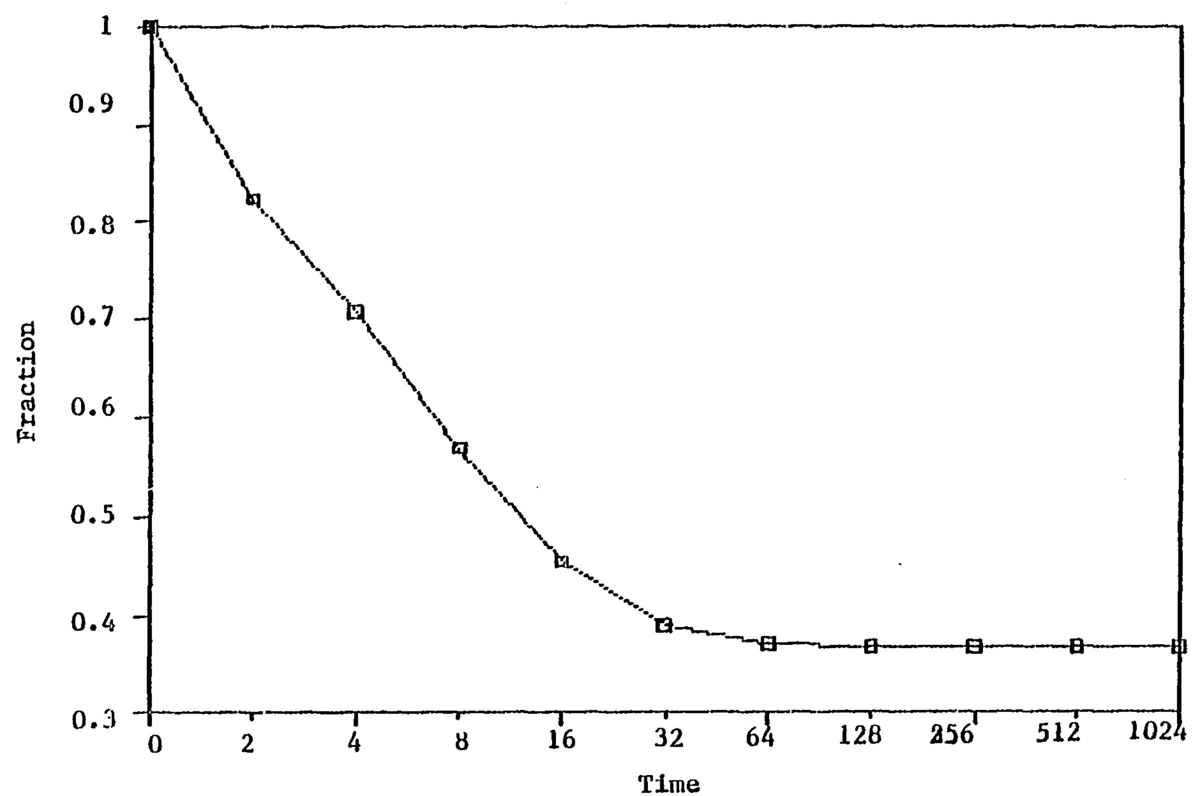


FIGURE 13. Transient behavior of P_0

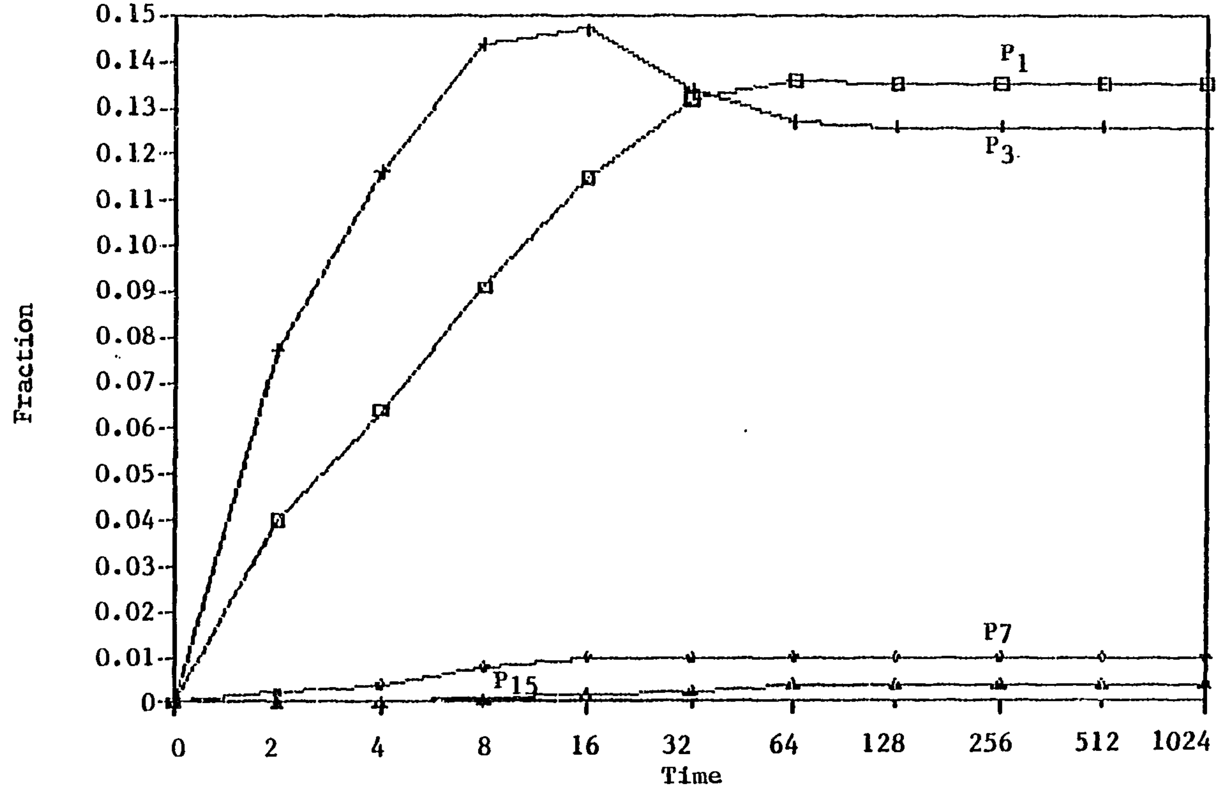


FIGURE 14. Transient behavior of P_1, P_3, P_7, P_{15}

Table 17 shows the transition probabilities of the six clusters of operating states and the performance measures for three different values of DOUT. These results are illustrated in three graphs. The first graph, Figure 15, describes the transient behavior of these probabilities. As the figure indicates that P_3 and P_4 are equal between time 0 and 2 hours. Consider the critical component discussed in the steady state analysis and by examining the transient behavior of system states, we can conclude the following:

1. When the system is in state 12 or 15, an electrical repair for the Machining Center, could be needed till time 24. After this time, the need for this type of repair is less likely, since P_{10} is higher than P_5.
2. When the system is in state 13 or 16, a mechanical repair for the Machining Center is less likely, since both P_9 and P_{11} are higher than P_6.
3. When the system is in state 14 or 17, an electrical repair for the Head Indexer could be needed till time 2 and a mechanical repair for this machine could be needed till time 8.

As a result, the repair rate of mechanical failure for the Head Indexer should be increased up to time 8. The repair rate of electrical failure for the Machining Center should be increased up to time 24. To maintain optimum production rate by increasing the repair rate, two alternatives can be considered:

1. Improve repair methods.
2. Decreasing the response time which is a part of the repair time.

TABLE 17. Results of operating states

Time (t)	0	2	4	8	16	32	64	128	256	512	1024
P_0	1.000	.825	.708	.570	.454	.390	.370	.367	.367	.367	.367
P_1	0.000	.056	.090	.131	.171	.205	.220	.222	.222	.222	.222
P_2	0.000	.104	.158	.200	.209	.194	.184	.183	.183	.183	.183
P_3	0.000	.005	.013	.034	.034	.033	.033	.033	.033	.033	.033
P_4	0.000	.005	.019	.046	.075	.078	.078	.078	.078	.078	.078
P_5	0.000	.000	.002	.004	.011	.015	.016	.016	.016	.016	.016
A	1.000	.998	.993	.980	.958	.936	.927	.926	.925	.925	.925
DOUT = 1.375											
E1	1.00	.99	.98	.97	.94	.90	.89	.89	.89	.89	.89
PRATE1	1.38	1.37	1.36	1.34	1.30	1.24	1.22	1.22	1.22	1.22	1.22
DOUT = 1.7											
E2	1.00	.98	.96	.96	.88	.82	.81	.80	.80	.80	.80
PRATE2	1.70	1.66	1.63	1.57	1.49	1.40	1.37	1.36	1.36	1.36	1.36
DOUT = 1.9											
E3	1.00	.95	.91	.86	.80	.74	.72	.72	.72	.72	.72
PRATE3	1.90	1.80	1.73	1.63	1.51	1.40	1.37	1.36	1.36	1.36	1.36

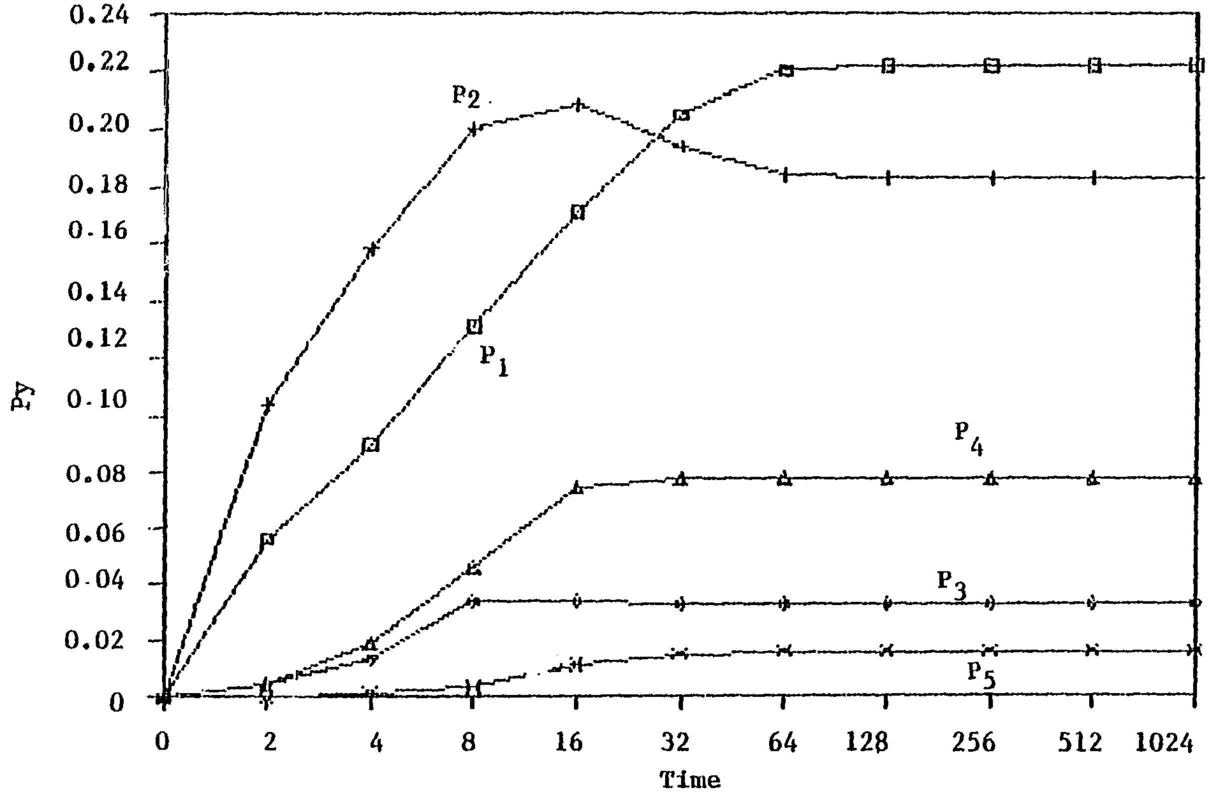


FIGURE 15. Transient behavior of operating states probabilities

The second graph, Figure 16 represents the transient behavior of system availability and system effectiveness. As the figure indicates, the variations of the system effectiveness as a function of time is significantly higher than that of system availability. Both measures reach the steady-state condition at time 128 hours with typical results to that of program AVAL. It is also apparent that E(t) is more sensitive to DOUT than that of availability measure. Thus, availability can not serve properly as a performance measure for this system.

The third graph, Figure 17, was derived showing PRATE as a function of time for three values of DOUT. It can be concluded that after 32 hours, PRATE is the highest for DOUT of 1.7 parts/hr. Therefore, the system can be loaded with 1.5 parts/hr. up to time 32 hours. Then, DOUT should be increased to 1.7 parts/hr. to maintain the daily production of 1.375 parts/hr.

Accordingly, the same analysis were applied to the remaining systems. Table 18 shows the different data sets for the 8 families of parts. The performance measures of these systems are summarized in Table 19. The results from the transient solutions are illustrated in a series of graphs that are plotted from the data generated by the computer program. These graphs are included in Appendices E, F AND G. Figures E.1-E.9 show the transient behavior of the group of operating states of the different systems. Figures F.1-F.13 represent the variations of A(t) and E(t) of each of the 14 systems, respectively. In Figures G.1-G.13, the systems treated in Figures F.1-F.13 are each subjected to three different values of DOUT, to show its effect on the

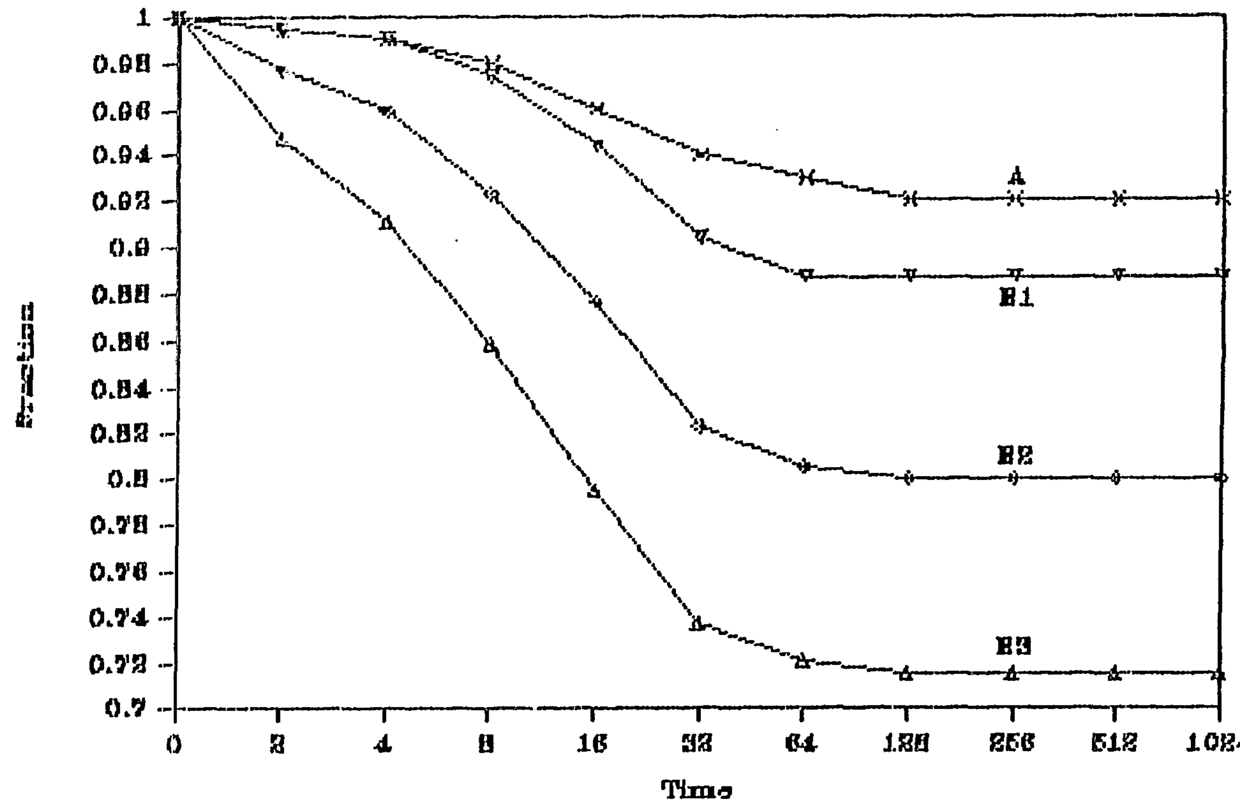


FIGURE 16. Transient behavior of A(t) and E(t)

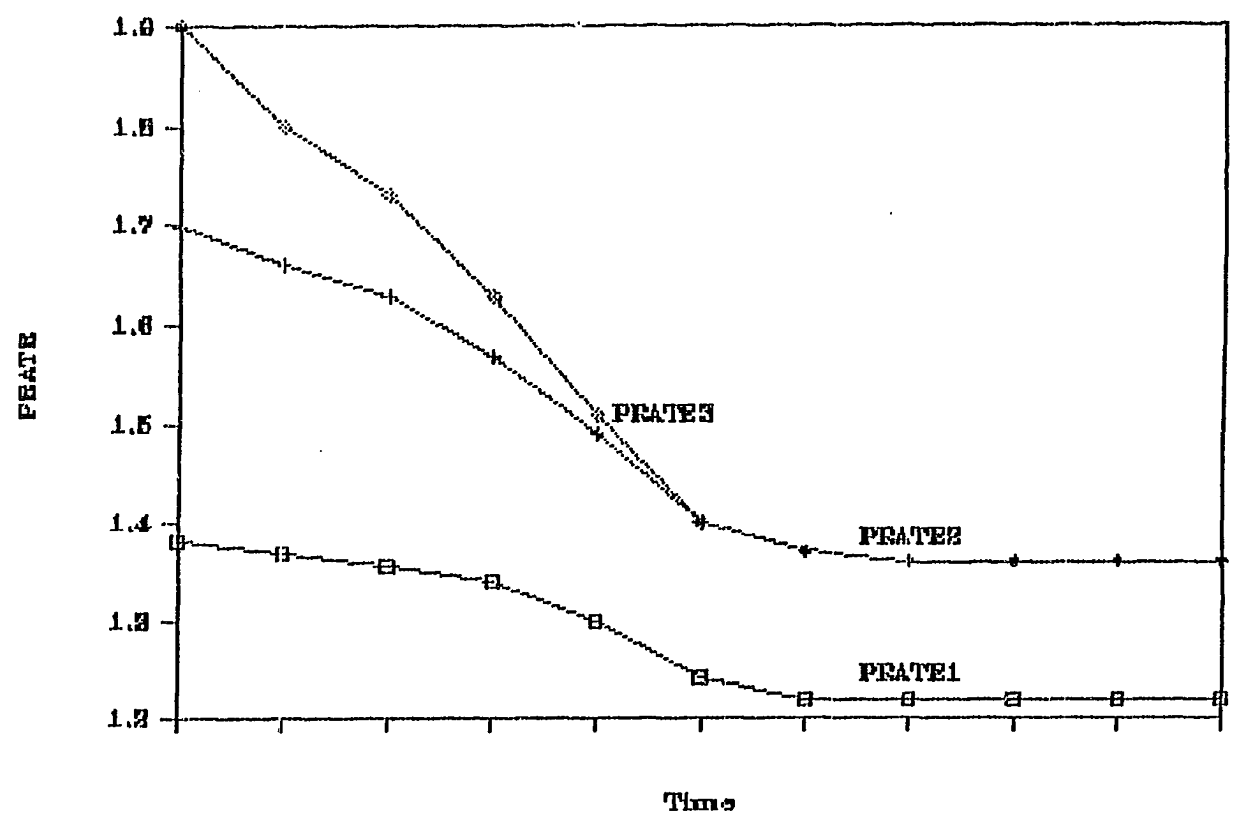


FIGURE 17. Transient behavior of PRATE

TABLE 18. Data sets for the 8 families of parts

(E:electrical, M:mechanical and T:tool failure)

System No.	Family of parts No.	Sequence number	No. of components	failure modes No.	Type	λ_r	λ_h	μ
1	1	1	2 M.C	3	E	.013	.025	.073
					M	.005	.026	.042
					T	.008	.022	.033
			1 H.I	2	E	.018		.154
					M	.006		.117
2		2	3 M.C	2	M	.005	.026	.042
					T	.008	.022	.033
			2 H.I	2	E	.018	.023	.154
					T	.006	.009	.117
3		3	3 M.C	3	E	.013	.025	.073
					M	.005	.026	.042
					T	.008	.022	.033
4	2	1	3 M.C	2	M	.005	.026	.042
					T	.008	.022	.033
			2 H.I	2	E	.018	.023	.154
					M	.006	.009	.117
5		2	3 M.C	2	M	.005	.026	.042
					T	.008	.022	.033
			1 H.I	3	E	.018		.154
					M	.006		.117
					T	.004		.103
6	3	1	2 M.C	3	E	.013	.025	.073
					M	.005	.026	.042
					T	.008	.022	.033
			1 H.I	2	E	.018		.154
					M	.006		.117
7		2	3 M.C	2	M	.005	.026	.042
					T	.008	.022	.033
			2 H.I	2	E	.018	.023	.154
					M	.006	.009	.117

TABLE 18. Continued

System No.	Family of parts No.	Sequence number	No. of components	failure modes No.	Type	λ_r	λ_h	μ
8		3	3 M.C	2	E	.013	.025	.073
					M	.005	.026	.042
			1 H.I	2	M	.006		.117
					T	.004		.103
			1 H.I	3	E	.018		.154
					M	.006		.117
					T	.004		.103
9	4	1	3 M.C	2	M	.005	.026	.042
					T	.008	.022	.033
			2 H.I	2	E	.018	.023	.154
					M	.006	.009	.117
10		2	3 M.C	3	E	.013	.025	.073
					M	.005	.026	.042
					T	.008	.022	.033
			1 H.I	2	E	.018		.154
					M	.006		.117
11	5	1	3 M.C	2	E	.013	.025	.073
					M	.005	.026	.042
			2 H.I	2	E	.018	.023	.154
					M	.006	.009	.117
12	6	1	3 M.C	2	E	.013	.025	.073
					M	.005	.026	.042
			1 H.I	2	E	.018		.154
					M	.006		.117
			1 H.I	2	E	.018		.154
					M	.006		.117
13	7	1	3 M.C	2	E	.013	.025	.073
					M	.005	.026	.042
			1 H.I	2	E	.018		.154
					M	.006		.117
14	8	1	3 M.C	2	E	.013	.025	.073
					M	.005	.026	.042
			1 H.I	2	E	.018		.154
					M	.006		.117

TABLE 19. Results of performance measures

Family of Parts No.	Sequence No.	No. of compnts.	w	DOUT	UTL	E (PRATE)	A
1	1	2 M.C 1 H.I	1.60 3.30	.875	.27	.576 (.504)	.576
	2	3 M.C 2 H.I	.41 .60	.875	.72	.780 (.883)	.887
	3	3 M.C	.30	.875	.97	.563 (.492)	.897
2	1	3 M.C 2 H.I	.60 .90	1.540	.85	.662 (1.02)	.887
	2	3 M.C H.I	.60 1.70	1.54	.90	.431 (.663)	.611
3	1	2 M.C 1 H.I	1.00 2.00	.670	.33	.576 (.386)	.576
	2	3 M.C 2 H.I	.32 .50	.670	.67	.887 (.554)	.887
	3	3 M.C 1 H.I 1 H.I	.25 .70 .70	.670	.96	.469 (.314)	.658
4	1	3 M.C 2 H.I	.60 .80	1.460	.91	.686 (1.00)	.887
	2	3 M.C 1 H.I	.62 1.80	1.460	.81	.444 (.648)	.604
5	1	3 M.C 2 H.I	.70 1.05	1.375	.65	.915 (1.26)	.926
6	1	3 M.C 1 H.I 1 H.I	.45 1.25 1.25	.960	.77	.535 (.513)	.622
7	1	3 M.C 1 H.I	.70 2.10	1.375	.65	.631 (.868)	.694

TABLE 19. Continued

Family of Parts No.	Sequence No.	No. of compnts.	w	DOUT	UTL	E (PRATE)	A
8	1	3 M.C 1 H.I	.50 1.48	.875	.59	.689 (.603)	.694

other performance measures.

The results of this analysis, shown in Table 20, leads to the following:

1. DOUT of systems 1,2,6,11,12,13 and 14 should be increased to the corresponding value in the table.

2. DOUT of systems 3,4,5,7,8,9 and 10 should not change.

TABLE 20. Optimum DOUT

System No.	Family of Parts	Sequence No.	Optimum DOUT	PRATE	E	UTL	A
1	1	1	1.520	.875	.576	.46	.887
2		2	1.000	.686	.686	.81	.897
3		3	.875	.492	.562	.97	.897
4	2	1	1.540	1.019	.662	.85	.887
5		2	1.540	.665	.432	.86	.611
6	3	1	1.200	.670	.558	.60	.576
7		2	.670	.595	.888	.67	.887
8		3	.670	.314	.469	.96	.658
9	4	1	1.460	1.001	.686	.81	.887
10		2	1.460	.648	.444	.81	.604
11	5	1	1.700	1.402	.825	.81	.926
12	6	1	1.100	.558	.507	.88	.622
13	7	1	1.800	.936	.520	.86	.694
14	8	1	1.500	.743	.849	1.00	.694

Conclusion of the Application Example

According to the results discussed in this chapter, the desired system output for any family of parts, is not achieved. Therefore different values of DOUT should be applied for each family of parts. The values of PRATE, according to the optimum DOUT, are summarized in Table 21. Also listed are the maximum values of DOUT and current PRATE.

Thus, applying the optimum DOUT, increases the production rate by;

$$\% \text{ increase} = \frac{5.731 - 5.361}{5.731} \times 100 = 6.5 \%$$

This value is equivalent to an increase, in the daily production rate, of 9 parts/day.

TABLE 21. Summary of the total FMS results.

Family of Parts No.	Maximum DOUT	Current PRATE	Time t hrs.	Optimum DOUT before	Optimum DOUT after	Expected PRATE
1	.875	.492	16	.90	.70	.492
2	1.540	.663	32	1.70	1.54	.663
3	.670	.314	16	.70	.67	.314
4	1.460	.648	32	1.80	1.46	.648
5	1.375	1.260	32	1.50	1.70	1.375
6	.960	.513	1024	1.10	1.10	.558
7	1.375	.868	1024	1.80	1.80	.936
8	.875	.603	1024	1.50	1.50	.743
Total	9.130	5.361				5.731

RESULTS OF ANALYSIS

The application problem given in Chapter 4, is an indication of the types of performance measures that can be explored with the aid of the Markovian models. It takes few minutes to prepare the data and run the program to test the different problems. The ability to obtain quick responses tends to encourage the analysis, which would in turn lead to a deeper understanding of the systems modeled.

It is apparent from this analysis, that the probability of failure with a higher repair rate, will reach a maximum level shortly after start up and then decreases as time increases. In addition, the effect of high component downtime with infrequent breakdowns, has a greater impact in the transition probabilities.

The variations of the system effectiveness as a function of time is significantly higher than that of system availability. It is also apparent that the system effectiveness is more sensitive to DOUT than of availability measure.

The results show that conducting the analysis, developed in this research, provides significantly higher production rate than the current one. The purpose of maximizing a production rate is to reduce the cost of manufacturing all families of parts.

Savings are realized through the reduction of system downtime. Indirectly, savings can also be gained by the reduction of station queues, resulting from any component failure. The gain of the system is the result of applying the optimum DOUT. Accordingly, PRATE for each family of parts could reach a maximum level.

The program code can be run in an IBM or compatible microcomputer. The following are the recommended procedures to be applied in the analysis of FMS. First, a failure mode analysis should be performed as discussed in Chapter 2. Second, the program code should be implemented in the computer. A sensitivity analysis is conducted and the optimum capacity planning will be displayed or printed for each sequence of family of parts. Third, the critical component will be determined for each system configuration.

CONCLUSIONS

Based on the analysis developed in this research, we can draw the following conclusions:

1. The analysis, adopted to the whole FMS and not to an individual component, explicitly demonstrates the effect of failures in modeling the performance of FMS.
2. The Markovian process was applied to the availability analysis of FMS, taking account of failure modes in regular and heavy operations.
3. Availability can not serve properly as a performance measure for an FMS, since each failure configuration could have different probabilities.
4. The system effectiveness decreases with increasing DOUT. The production rate of a system reaches a maximum value of the product (DOUTxE), then it declines. The corresponding value of DOUT can be used as the optimum capacity planning for the system.
5. The critical component for each system can be determined after computing the production rate for each failure configuration.
6. The transient behavior of state probabilities and performance measures would provide management with optimum decisions in the analysis of FMS. Thus the managers of FMS should therefore have planning decisions that ensure system demand within the capacity of the system. Determining the transition probabilities, the managers could pay attention to those states with higher

probabilities. Also, they could expect when and which of the failure modes is crucial.

7. The computer program, developed in this study, evaluate the time dependent availability and average availability of an FMS described by a Markov process. It also evaluate other performance measures, such as, expected production rate, system effectiveness and average component utilization. The program can be implemented in a microcomputer, which determines the optimum capacity planning.

Further studies can be investigated, in particular the following:

1. Extension of the model to include bigger systems.
2. Alternative repair policies.
3. Alternative scheduling sequences.
4. Developing control rules for an AGVS using the Markovian model B.

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APPENDIX A:

COMPUTER CODE FOR MARKOVIAN AVAILABILITY ANALYSIS

Introduction

This chapter is a brief description of the computer codes AVAL and ODE that evaluates the time dependent availability and all the performance measures described in Chapter 4, of a manufacturing system modeled by Markov process. A flow chart of the code is given in Figure 18. The methodology upon which the codes are based is presented in Chapters 2 and 3. The code consists of two parts:

1. AVAL which is written in BASIC, prepares the necessary transition matrix for the second part;
2. ODE which is written in FORTRAN, performs the Markovian availability analysis as a function of time.

Running the Program

The user can run the program either in an interactive mode or in a batch mode.

Interactive Mode

After the program has been loaded and the run command has been executed, an introduction to the program is displayed on the CRT. The user chooses the type of system from the menu. The program will then start to ask for input information such as the number of components of the system, the number of failure modes and the production rate for each component, the failure rate and the repair rate for each mode, and the

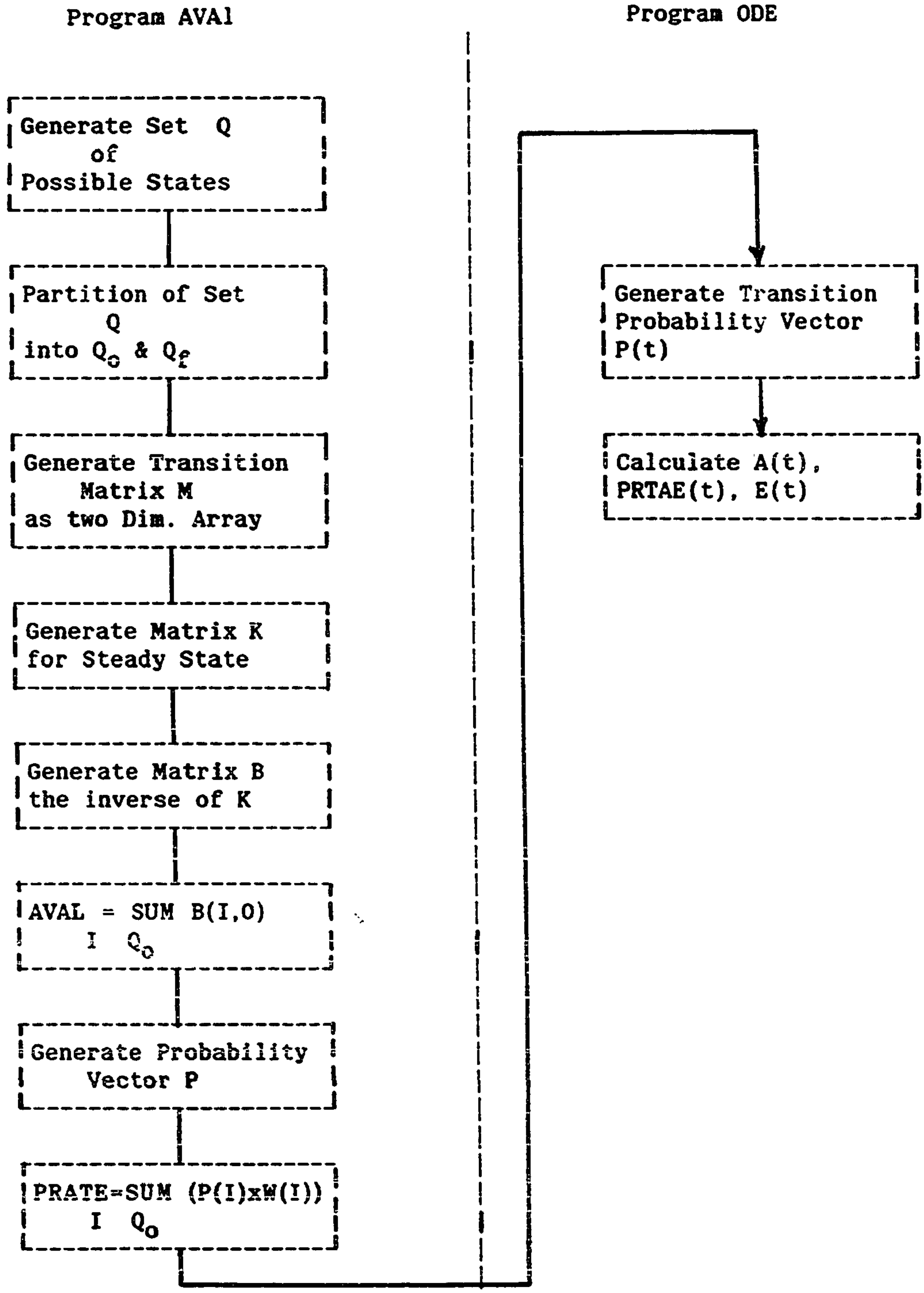

FIGURE 18. Flow chart of computer program

desired system output. Next, a summary list will display the input information and give the user a chance to make changes if there are input errors.

If nothing is to be changed at this point, the program will then perform the necessary calculations for both steady state and transient solution. The output of each program is described later.

Batch Mode

In this mode, the first 10 lines in the program are reserved for multiple DATA statements. A separate DATA statement is used for each component. Each statement contains the following variables separated by commas. The order in which these variables should appear is:

System type 1:

Number of components in series,
number of failure modes of component 1,
production rate of component 1,
...,
...,
...,
number of failure modes of last component,
production rate of last component,
failure rate of mode 1 for component 1,
repair rate of mode 1 for component 1,
...,
...,
...,
failure rate of last mode for the last component,
repair rate of last mode for the last component.

System type 2:

Number of parallel components,
number of failure modes for each component,
production rate of each component,
failure rate of mode 1 for regular operation,

failure rate of mode 1 for heavy operation,
repair rate of mode 1,
...,
...,
...,
failure rate of last mode for regular operation,
failure rate of last mode for heavy operation,
repair rate of last mode.

System type 3:

Number of groups of parallel components (maximum 2),
number of components in series,
Number of components in group 1,
Number of failure modes in group 1,
production rate of each component in group 1,
number of component in group 2,
number of failure modes in group 2,
production rate of each component in group 2,
failure rate of mode 1 for regular operation,
failure rate of mode 1 for heavy operation,
repair rate of mode 1,
...,
...,
...,
failure rate of last mode for regular operation,
failure rate of last mode for heavy operation,
repair rate of last mode.
number of failure modes of series components,
number of failure modes of series 2,
...,
...,
...,
number of last series component,
failure rate of mode 1 for series component 1,
repair rate of mode 1 for series component 1,
...,
...,
...,
failure rate of last mode for the last series component,
repair rate of last mode for the last series component.

IBM Compatible Microprocessors

The program, although written on an IBM PC, was adapted to be compatible with a wide range of microprocessors such as Zenith, Kaypro and Corona. In an effort to achieve greater accuracy, double precision variables have been used.

The procedure for the compatible microcomputers is slightly different. Thus, the two programs, AVAL and ODE, should be run separately, because of the limitation of GW BASIC of running an executable program inside BASIC.

Program AVAL

This part of the code written in BASIC, generates the set of all possible states of the system, partitions it into subset q_0 and q_f and generates the transition matrix. In addition, this program calculates the following performance measures: steady state availability, average production rate, component utilization, and system effectiveness.

Subroutines

The program uses the following subroutines:

1. Subroutine Transition

This subroutine consists of three parts based on the user's system structure. These are single component or component in series, components in parallel, and combined system. It also generates the states and the transition matrix.

2. Subroutine Factorial

This subroutine calculates the number of states of each system configuration. For each number of failure modes N, with repeated removal of the same number permitted, the number of combinations formed by the removal of each f, number of components down, is calculated using the following formula:

$$\sum_{i=0}^{f-1} C_{N-1}^{N+i} = \frac{1}{(N-1)!} \left(\frac{N!}{1!} + \frac{(N+1)!}{2!} + \frac{(N+2)!}{3!} \ldots \frac{(N+f-1)!}{f!} \right)$$

$$= N + \frac{N(N+1)}{2!} + \frac{N(N+1)(N+2)}{3!} \ldots \frac{N(N+1)\ldots(N+f-1)}{f!}$$

3. Subroutine Inverse

This subroutine generates the inverse of the steady state matrix K. An identity matrix of the same size as K is added to the matrix. Then, row operations are performed. The first column of the inverse matrix is the steady state probability vector.

4. Subroutine Performance

This subroutine calculates the steady state availability, AVAL, the average production rate, PRATE, the average component utilization, U, and the system effectiveness, E.

Description of the Output

The program output consists of three parts. The first part contains information concerning the states of the system. For each possible system state, the number of operating states or the number of failed states and the total number of states are printed out. The states themselves are printed out and divided into groups. Each group contains either the operating states with the number of components "down" or the failed states with the number of components "down".

The second part of the output consists of two matrices: the transition matrix (M), and the steady-state matrix (K). This part of the output is printed for checking purposes and can be deleted. The transition matrix is automatically saved in an ASCII file under the name "Matrix".

The third part of the output contains information concerning system performance. The steady state probabilities are printed first, then the performance measures.

Source List of AVAL

Source list of AVAL and all other subroutines are given in Appendix B.

Application Problem

The output of the application problem is given in the CASE STUDY.

Dimensions Variables for AVAL

One-Dimensional array:

N(*) number of failure modes for each component.

LMDA(*) failure rate

MU(*) repair rate

W(*) production rate

SG$(*), IT$(*) string identifies the state

COMB$(*) string combines the left and right characters of other string.

UTL(*) component utilization in each parallel group

X(*) number of components in each parallel group

Two-dimensional array

M(*,*)	transition matrix
K(*,*)	steady-state matrix
B(*,*)	inverse of matrix K
RLMDA(*,*)	failure rate for regular operation
HLMDA(*,*)	failure rate for heavy operation
STATE(*,*)	number of states for each system configuration.

Note: * can be any integer.

Program ODE

This part of the code performs the solutions of system state equations and generates the transition probability vector $\underline{P}$. In addition, the same performance measures as a function of time are calculated. The main program calls subroutine LSODA once for each point at which answers are desired.

Input Information

The input information for the ODE program is read from the ASCII file which is a part of AVAL output. The following variables are the input information for this part of the code.

NEQ	Number of states
u	system type
H	number of groups of states
GRUP(*)	number of states in each group of states (system configuration)

PR(*)   production rate for each system configuration

Y(*)   initial conditions

F(*,*)   equivalent to the transition matrix

where * can be any integer as explained earlier.

Initial Conditions

In the ODE program, the initial conditions are denoted by the 1-dimensional vector array Y(i) where i denotés the system state and the time t=0 is already included at the beginning of the program. In the present program, the system is assumed to run at time t=0, i.e.,

$$Y(1) = 1 \quad \text{and } Y(i) = 0 \qquad \text{for } i > 1$$

If different initial conditions are desired (to incorporate failures at t=0) the user can change the appropriate statements in the program (see listing of DATA statements).

Subroutine FEX

This subroutine, which is written in FORTRAN, defines the ODE system. The system is put in the first-order form

DY/DT = FEX(T,Y)

where FEX is a vector-valued function of the scalar T and the vector Y. Subroutine FEX has the form;

```
SUBROUTINE FEX(NEQ,T,Y,YDOT)
DIMENSION Y(*),YDOT(*)
```

where NEQ, T and Y are inputs, and the array YDOT=FEX(T,Y) is output. Y and YDOT are arrays of length NEQ.

Output of ODE

The output of ODE consists of the transition probabilities, availability, production rate and system effectiveness as a function of time.

Source List of ODE

A source list of ODE is given in Appendix B.

Model Problem

The output of ODE for the application problem is given in the CASE STUDY.

Dimensioning Variables of ODE

One-Dimensional Array

Y(*)	Array of computed values of Y(T)
YDOT(*)	Array of the first derivatives of Y(T)
ATOL(*)	Absolute tolerance parameter (scalar or array of dimension NEQ)
RWORK(*)	Real work array of length at least 22+NEQ*MAX(16,NEQ+9)
IWORK(*)	Integer work array of length at least 20+NEQ
AVAL(*)	Availability as a function of time
PRATE(*)	Production rate as a function of time

Two-Dimensional Array

F(*,*)	Transition matrix

APPENDIX B:

SOURCE LIST OF COMPUTER PROGRAM

<u>Source List of Program AVAL</u>

```
1 CLEAR
3 DATA 2,2,15,25,.0127,.0245,.073,.005,.008,.0416
5 DATA 2,2,15,25,.0183,.023,.1544,.012,.03,.117
6 DATA
8 REM ***************************************************
10 REM                INITIAL MESSAGE
15 REM ***************************************************
20 PRINT "THIS PROGRAM DETERMINES THE TRANSITION MATRIX,"
25 PRINT "STEADY STATE AVAILABILITY AND PRODUCTION RATE "
30 PRINT "FOR DIFFERENT MANUFACTURING SYSTEMS AND "
35 PRINT "VARIOUS FAILURE MODES."
40 PRINT
45 PRINT
50 PRINT
55 PRINT "            BY GEORGE ABDOU"
60 PRINT "         IOWA STATE UNIVERSITY"
65 PRINT "               AMES, IOWA"
70 REM *******************************************************
75 REM *               EDITING SECTION                      *
80 REM *******************************************************
85 PRINT CHR$ (7)
90 PRINT "THE DIFFERENT SYSTEM'S STRUCTURES ARE:"
95 PRINT " 1) A SINGLE COMPONENT OR SERIES COMPONENTS"
100 PRINT " 2) ONE GROUP OF PARALLEL COMPONENTS"
110 PRINT " 3) SERIES-PARALLEL NETWORK"
120 PRINT
130 PRINT
140 INPUT "THE SYSTEM TO BE ANALYZED IS OF STRUCTURE NO.  ";U
150 IF U>3 OR U<1 THEN 85
160 ON U GOSUB 600,800,2000
170 REM ****************************************************
180 REM                  PRINTING SECTION
190 REM ****************************************************
191 ERASE M
192 OPEN "I",#1,"MATRIX"
193 INPUT #1,Q,U,H:Q=Q-1
194 FOR I=0 TO H:INPUT #1,GRUP(I),PR(I):NEXT I
195 DIM M(Q,Q)
196 FOR I=1 TO Q
198 FOR J=0 TO Q:INPUT #1,M(I,J):NEXT J
200 NEXT I
202 CLOSE #1
235 FOR J=0 TO Q
```

```
240 M(0,J)=1
260 NEXT J
263 IF Q < 30 THEN 277
265 CLS:PRINT "            THE MATRIX K":PRINT TAB(10) "   FROM STATE
   ........./ Kac":PRINT " TO \":PRINT
266 FOR I=0 TO Q
267 K=0:IT$(0)=" 0"
268 PRINT "STATE";I;"|";
269 FOR J=0 TO Q
270 IF M(I,J)=0 THEN 274
273 PRINT TAB(12) IT$(J);"/";:PRINT USING "+#.### ";M(I,J)
274 NEXT J
275 PRINT:NEXT I
276 GOTO 281
277 GOSUB 3050
281 GOSUB 360
282 AVL=B(0,0)
283 IF U=1 THEN PRATE=PR(0)*AVL:GOTO 320
285 CNT=1:SOM=0:PRATE=AVL*PR(0)
287 FOR R=1 TO H
288 PROB=0:FOR J=CNT TO GRUP(R)+SOM:PROB=PROB+B(J,0):NEXT J
290 IF PR(R)>0 THEN AVL=AVL+PROB:PRATE=PRATE+PR(R)*PROB
291 CNT=J:SOM=CNT-1:NEXT R
320 PRINT:PRINT TAB(5) "STEADY STATE AVAILABILITY= ";AVL
322 PRINT:PRINT TAB(5) "EXPECTED STEADY-STATE PRODUCTION RATE IN
    UNITS/HR = "; PRATE
328 PRINT:PRINT TAB(5) "SYSTEM EFFECTIVENESS = "; PRATE/DOUT
330 SHELL "ODE.EXE"
350 END
360 REM *****************************************************
370 REM                    MATRIX INVERSION
380 REM *****************************************************
385 DIM B(Q,Q)
390 FOR J=0 TO Q
405 B(J,J)=1
410 NEXT J
412 FOR J=0 TO Q
415 FOR I=J TO Q
420 IF M(I,J)<>0 THEN 430
425 NEXT I
430 FOR O=0 TO Q
435 Y=M(J,O)
440 M(J,O)=M(I,O)
445 M(I,O)=Y
450 Y=B(J,O)
455 B(J,O)=B(I,O)
460 B(I,O)=Y
465 NEXT O
470 T=1/M(J,J)
```

```
475 FOR O=0 TO Q
480 M(J,O)=T*M(J,O)
485 B(J,O)=T*B(J,O)
490 NEXT O
495 FOR L=0 TO Q
500 IF L=J THEN 550
510 T=-M(L,J)
520 FOR O=0 TO Q
530 M(L,O)=M(L,O)+T*M(J,O)
540 B(L,O)=B(L,O)+T*B(J,O)
545 NEXT O
550 NEXT L
555 NEXT J
556 CLS
557 PRINT:PRINT "         THE STEADY-STATE PROBABILITY VECTOR PI"
570 PRINT
572 FOR I=0 TO Q
576 PRINT "P(";I;")=";:PRINT USING "  +##.####";B(I,O):NEXT I
580 RETURN
600 REM ******************************************************
610 REM              CASE A:A SINGLE COMPONENT OR
615 REM                     SERIES COMPONENTS
616 REM ******************************************************
618 DIM N(20),LMDA(20),MU(20),W(20),M(20,20),STATE(20,20),IT$(20)
619 PRINT "HOW MANY COMPONENTS IN SERIES";:INPUT S
620 PRINT "DESIRED SYSTEM OUTPUT IN UNITS/HR";:INPUT DOUT
621 Q=0:MIN=DOUT
622 FOR I=1 TO S
623 PRINT "NUMBER OF FAILURE MODES OF COMPONENT";I;:INPUT N(I):PRINT
    "PRODUCTION RATE OF COMPONENT";I;"IN UNITS/HR";:INPUT W(I):IF
    W(I)<MIN THEN MIN=W(I)
624 FOR J=1 TO N(I):Q=Q+1:PRINT "FAILURE RATE (IN UNITS/HR) OF
    COMPONENT";I;"WITH FAILURE MODE";J;:INPUT LMDA(Q)
625 PRINT "REPAIR RATE (IN UNITS/HR) FOR COMPONENT";I;"WITH FAILURE
    MODE";J;:INPUT MU(Q):STATE(Q,I)=J
626 IT$(Q)=STR$(I)+STR$(J)
627 NEXT J
628 NEXT I
630 PRINT:INPUT "             DO YOU WANT TO CHANGE DATA [Y or N]";U$
635 IF LEFT$(U$,1)="N" OR LEFT$(U$,1)="n" THEN 688
636 IF LEFT$(U$,1)="Y" OR LEFT$(U$,1)="y" THEN 619
688 REM ******************************************************
690 REM          GENERATE SET OF POSSIBLE STATES
692 REM ******************************************************
693 CLS: PRINT "          PROGRAM OUTPUT": FOR I=1 TO S: PRINT "AVERAGE
       UTILIZATION OF COMPONENT ";I;" = ";DOUT/W(I):NEXT I
694 CLS:PRINT TAB(5) "CLUSTER No. * 0 * ALL COMPONENTS UP ":PRINT TAB(5)
       "NUMBER OF STATES IN THIS CLUSTER = 1":GRUP(0)=1:PR(0)=MIN
696 FOR I=1 TO S: PRINT TAB(8*I) USING "#";0;:NEXT I
```

```
697 PRINT:PRINT:PRINT TAB(5) "CLUSTER No. * 1 * 1 COMPONENT DOWN"
698 PRINT TAB(5) "NUMBER OF STATES IN THIS CLUSTER =
    ";Q:GRUP(1)=4:PR(1)=0
699 FOR J=1 TO Q:PRINT J;",";:FOR I=1 TO S:PRINT TAB(8*I) USING
    "#";STATE(J,I);:NEXT I:PRINT
710 NEXT J
712 PRINT:PRINT :PRINT
715 TTAL=0
720 FOR J=1 TO Q
725 M(0,J)=MU(J):M(J,0)=LMDA(J)
730 TTAL=TTAL+M(J,0)
735 M(0,0)=-TTAL:M(J,J)=-M(0,J):NEXT J
742 L=S
743 U=1:H=1
745 OPEN "O",#1,"MATRIX"
748 PRINT #1,Q+1,U,H:FOR I=0 TO H:PRINT #1,GRUP(I),PR(I):NEXT I
749 FOR I=0 TO Q
750 FOR J=0 TO Q:A#=M(I,J):PRINT #1,A#:NEXT J
751 NEXT I
755 CLOSE #1
757 PRINT "        THE TRANSITION MATRIX M":PRINT:GOSUB 3000
760 RETURN
800 REM ***************************************************************
803 REM             ONE GROUP OF PARALLEL COMPONENTS
804 REM ***************************************************************
805 CLEAR:DIM RLMDA(2,5),HLMDA(2,5),MU(2,5),M(30,30),COMB$(30)
806 DIM STATE(2,5),W(2,5),SG$(100),IT$(30)
807 PRINT "HOW MANY COMPONENTS IN ACTIVE PARALLEL";:INPUT X
808 PRINT "HOW MANY FAILURE MODES ASSOCIATED WITH EACH COMPONENT";:INPUT
    N
810 PRINT "PRODUCTION RATE (IN UNITS/HR) OF EACH COMPONENT";:INPUT WP
812 PRINT "DESIRED SYSTEM OUTPUT (IN UNITS/HR)";:INPUT DOUT
814 L=1
822 L=1:R=1
825 FOR I=1 TO N
827 PRINT "FAILURE RATE (IN UNITS/HR) OF MODE";I;"FOR REGULAR
    OPERATION";:INPUT RLMDA(L,I)
828 PRINT "FAILURE RATE (IN UNITS/HR) OF MODE";I;"FOR HEAVY
    OPERATION";:INPUT HLMDA(L,I)
830 PRINT "REPAIR RATE (IN UNITS/HR) OF MODE";I;"FOR EITHER
    OPERATION";:INPUT MU(L,I)
840 NEXT I
841 PRINT:INPUT "              DO YOU WANT TO CHANGE YOUR DATA [Y or
    N]";U$
842 IF LEFT$(U$,1)="N" OR LEFT$(U$,1)="n" THEN 859
843 IF LEFT$(U$,1)="Y" OR LEFT$(U$,1)="y" THEN 807
859 E=0
860 GOSUB 1500
862 S=1
```

```
863 FOR J=0 TO X
864 PRINT:PRINT TAB(5) "CLUSTER NO. * ";J;" * ";J;" COMPONENTS DOWN"
865 H=J:PR(J)=W(R,J):IF J=0 THEN PRINT TAB(5) "NUMBER OF STATES IN THIS
CLUSTER = 1":GOTO 871
866 PRINT TAB(5) "NUMBER OF STATES IN THIS CLUSTER  = ";STATE(R,J)-
STATE(R,J-1):GRUP(J)=STATE(R,J)-STATE(R,J-1)
867 FOR I=S TO STATE(R,J)
868 IT$(I)=SG$(I):PRINT I",";TAB(9) SG$(I)
869 NEXT I
870 S=1+STATE(R,J)
871 NEXT J
872 GOSUB 873:GOTO 1125
873 REM ******************************
874 REM    ONE COMPONENT DOWN
876 REM ******************************
878 FOR J=1 TO N
880 M(0,J+E)=MU(R,J)
885 M(J+E,0)=X*RLMDA(R,J)
890 NEXT J
891 REM **********************************
892 REM    MORE THAN ONE COMPONENTS DOWN
893 REM **********************************
894 FOR K=1 TO X-1
895 FOR I=STATE(R,K)+1 TO STATE(R,K+1)
900 FOR J=STATE(R,K-1)+1 TO STATE(R,K)
905 IF LEFT$(SG$(I),2*K)=SG$(J) THEN
    Y=VAL(RIGHT$(SG$(I),2)):M(J+E,I+E)=(K+1)*MU(R,Y):M(I+E,J+E)=(X-
    K)*HLMDA(R,Y)
910 IF RIGHT$(SG$(I),2*K)=SG$(J) THENY=VAL(LEFT$(SG$(I),2)):M(J+E,I+E)=
    (K+1)*MU(R,Y):M(I+E,J+E)=(X-K)*HLMDA(R,Y)
915 COMB$(I)=LEFT$(SG$(I),2)+RIGHT$(SG$(I),2)
920 IF COMB$(I)=SG$(J) THEN Y=VAL(MID$(SG$(I),3,2)):M(J+E,I+E)=(K+1)*
    MU(R,Y):M(I+E,J+E)=(X-K)*HLMDA(R,Y)
925 NEXT J
930 NEXT I
935 NEXT K
940 RETURN
1125 FOR I=0 TO STATE(R,X)
1130 TTAL = 0
1135 FOR J=0 TO STATE(R,X)
1140 TTAL=TTAL+M(J,I)
1142 NEXT J
1145 M(I,I)=-TTAL
1148 NEXT I
1150 U=2
1151 OPEN "O",#1,"MATRIX"
1152 PRINT #1,Q+1,U,H:PRINT:PRINT:PRINT "CLUSTER No.   No. OF STATES
PRATE":FOR I=0 TO H:PRINT #1,GRUP(I),PR(I):PRINT I,GRUP(I),PR(I):NEXT I
1153 FOR I=0 TO Q
```

```
1154 FOR J=0 TO Q:A#=M(I,J):PRINT #1,A#:NEXT J
1155 NEXT I
1156 CLOSE #1
1157 PRINT:PRINT:PRINT "       THE TRANSITION MATRIX M":PRINT:GOSUB 3000
1160 GOTO 170
1500 REM ******************************************************
1505 REM                    FACTORIAL/COMBINATION
1510 REM ******************************************************
1515 Q=0
1520 FOR I=0 TO X
1525 A=N+I-1:G=N+I-1:C=N-1
1530 TK=G-C
1535 IF TK=0 THEN GRP=1:GOTO 1562
1540 A=A-1
1545 IF A=TK THEN 1555
1550 G=G*A:GOTO 1540
1555 GRP=G/C
1560 Q=Q+GRP
1561 STATE(R,I)=Q
1562 MOUT=X*WP
1563 UTL=DOUT/MOUT
1575 FR(R)=X*(1-UTL)
1580 IF I=<FR(R) THEN W(R,I)=DOUT:GOTO 1587
1585 W(R,I)=(WP/UTL)*(X-I):IF W(R,I)>DOUT THEN W(R,I)=DOUT
1587 NEXT I
1590 PRINT:PRINT "       PROGRAM OUTPUT":PRINT:PRINT "AVERAGE UTILIZATION
      OF PARALLEL GROUP No.";R;" = ";UTL
1591 REM *************************************************************
1592 REM *           GENERATE SET OF POSSIBLE STATES                 *
1593 REM *************************************************************
1594 FOR I=0 TO N
1595 SG$(I)=STR$(I)
1598 NEXT I
1601 FOR J=1 TO N
1604 SG$(J+I-1)=SG$(J)+SG$(J)
1607 NEXT J
1610 S=0
1613 FOR Z=1 TO N-1
1616 SG$(2*N+Z+S)=SG$(Z)+SG$(Z+1)
1619 IF Z+1>N-1 THEN 1628
1622 SG$(2*N+Z+1)=SG$(Z)+SG$(Z+2)
1625 S=S+1
1628 NEXT Z
1631 GRP=STATE(R,2)-STATE(R,1)
1634 FOR I=1 TO GRP
1637 SG$(STATE(R,2)+I)=SG$(1)+SG$(STATE(R,1)+I)
1640 NEXT I
1643 S=0
1646 FOR K=1 TO GRP
```

```
1649 IF LEFT$(SG$(STATE(R,1)+K),1) = "1" THEN 1658
1652 SG$(STATE(R,2)+I+S)=SG$(2)+SG$(STATE(R,1)+K)
1655 S=S+1
1658 NEXT K
1661 IF X=3 THEN SG$(STATE(R,X))=SG$(N)+SG$(N)+SG$(N)
1691 RETURN
2000 REM ****************************************************
2010 REM                COMBINED SYSTEM
2011 REM ****************************************************
2012 DIM X(3),N(3),WP(3),UTL(3),COMB$(100)
2013 DIM RLMDA(3,10),HLMDA(3,10),MU(3,10)
2017 INPUT "HOW MANY GROUP OF PARALLEL COMPONENTS ";L
2018 INPUT "HOW MANY COMPONENTS IN SERIES ";SER:IF L=1 AND SER=0 THEN
     800
2019 IF L=1 AND SER>0 THEN 2550
2023 FOR R=1 TO L
2024 PRINT "HOW MANY COMPONENTS IN GROUP";R;:INPUT X(R ):PRINT "HOW MANY
FAILURE MODE ASSOCIATED WITH EACH COMPONENT IN GROUP";R;:INPUT N(R)
2025 PRINT "PRODUCTION RATE (IN UNITS/HR) OF EACH COMPONENT IN
GROUP";R;:INPUT WP(R):PRINT "DESIRED SYSTEM OUTPUT (IN UNITS/HR)";:INPUT
DOUT
2028 FOR J=1 TO N(R)
2029 PRINT "FAILURE RATE (IN UNITS/HR) OF MODE";J;"FOR REGULAR
     OPERATION";:INPUT RLMDA(R,J)
2030 PRINT "FAILURE RATE (IN UNITS/HR) OF MODE";J;"FOR HEAVY
     OPERATION";:INPUT HLMDA(R,J)
2031 PRINT "REPAIR RATE (IN UNITS/HR) OF MODE";J;"FOR EITHER
     OPERATION";:INPUT MU(R,J)
2032 NEXT J
2033 NEXT R
2034 PRINT:INPUT "              DO YOU WANT TO CHANGE YOUR DATA [Y or
     N]";U$
2035 IF LEFT$(U$,1)="N" OR LEFT$(U$,1)="n" THEN 2039
2036 IF LEFT$(U$,1)="Y" OR LEFT$(U$,1)="y" THEN 2017
2039 REM ****************************************************
2040 REM *    DETERMINE SET OF POSSIBLE STATES              *
2045 REM ****************************************************
2050 Y1=0:Y2=1:Y3=1
2052 DIM STATE(L,4),W(2,4),SG$(50),GS$(L,50)
2053 DIM M(80,80),IT$(80)
2055 FOR R=1 TO L
2060 X=X(R):N=N(R):WP=WP(R)
2062 GOSUB 1500
2065 Y1=Y1+STATE(R,X):Y2=Y2*STATE(R,X):Y3=Y3*((STATE(R,X))-(STATE(R,X-
     1)))
2070 NEXT R
2075 Y2=Y2+Y1-Y3:A=Y2
2076 PRINT:PRINT TAB(5) "CLUSTER NO. *  0  *  0 COMPONENT DOWN":PRINT
TAB(5) "NUMBER OF STATES IN THIS CLUSTER = 1":GRUP(H)=1
```

```
2078 E=0:H=0:PR(H)=DOUT
2080 FOR R=1 TO L
2082 P=1
2085 X=X(R):N=N(R):WP=WP(R)
2086 GOSUB 1591
2089 FOR I=1 TO STATE(R,X):GS$(R,I)=SG$(I):IT$(I+E)=GS$(R,I):NEXT I
2090 GOSUB 873
2094 FOR J=1 TO X-1:H=H+1:GRUP(H)=STATE(R,J)-STATE(R,J-1):PR(H)=W(R,J):
     PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * ";J;"COMPONENT OF GROUP
     ";R;" ARE DOWN":PRINT TAB(5) "NUMBER OF STATES IN THIS CLUSTER =
     ";GRUP(H
2095 FOR I=P+E TO STATE(R,J)+E:PRINT I",": TAB(9) IT$(I):NEXT I
2097 P=1+STATE(R,J):NEXT J
2098 FOR I=STATE(R,X)+E TO STATE(R,X-1)+E+1 STEP-1
2100 FOR J=STATE(R,X-2)+F TO STATE(R,X-1)+E
2105 M(J,A)=M(J,I):M(A,J)=M(I,J)
2107 M(J,I)=0:M(I,J)=0
2110 NEXT J
2115 IT$(A)=IT$(I)
2117 A=A-1
2120 NEXT I
2125 E=E+STATE(R,X-1):F=E+1
2126 STATE(R,0)=0:V(0,0)=1
2127 FOR I=1 TO X(R)
2128 IF R=1 THEN V(0,I)=STATE(1,I)-STATE(1,I-1)
2129 IF R=2 THEN V(I,0)=STATE(2,I)-STATE(2,I-1)
2130 NEXT I
2135 NEXT R
2136 FOR I=1 TO X(1)
2137 FOR J=1 TO X(2):V(I,J)=V(0,I)*V(J,0):NEXT J
2138 NEXT I
2139 H=H+1
2140 Y=1:S=1:Z=1:T=1:D1=F
2142 PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * ";S;"COMPONENT OF GROUP 1
AND ";T;" COMPONENT OF GROUP 2 ARE DOWN"
2143 PRINT TAB(5) "NUMBER OF STATES IN THIS CLUSTER =
";V(S,T):GRUP(H)=V(S,T)
2144 GOSUB 3200:PR(H)=MIN
2145 FOR I=Y TO STATE(1,S)
2150 FOR J=Z TO STATE(2,T)
2155 IT$(F)=GS$(1,I)+GS$(2,J)
2156 PRINT F",": TAB(9) IT$(F)
2157 F=F+1
2158 NEXT J
2159 NEXT I
2160 FOR P1=F-V(S,T) TO F-1
2161 FOR K1=1 TO STATE(1,S)
2162 IF LEFT$(IT$(P1),2)<>IT$(K1) THEN 2164
2163 O=VAL(RIGHT$(IT$(P1),2)):M(K1,P1)=MU(2,O):M(P1,K1)=X(2)*RLMDA(2,O)
```

```
2164 NEXT K1
2165 FOR L=K1 TO STATE(2,T)+K1-1
2166 IF RIGHT$(IT$(P1),2)<>IT$(L) THEN 2168
2167 O=VAL(LEFT$(IT$(P1),2)):M(L,P1)=MU(1,O):M(P1,L)=X(1)*RLMDA(1,O)
2168 NEXT L
2175 NEXT P1
2176 H=H+1:D2=F
2177 Z=J:T=T+1
2178 PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * ";S;" COMPONENT OF GROUP
     1 AND ";T;" COMPONENT OF GROUP 2 ARE DOWN":PRINT TAB(5) "NUMBER OF
     STATES IN THIS CLUSTER = ";V(S,T):GRUP(H)=V(S,T):GOSUB
3200:PR(H)=MIN
2180 FOR I=Y TO STATE(1,S)
2185 FOR J=Z TO STATE(2,T)
2190 IT$(F)=GS$(1,I)+GS$(2,J)
2191 PRINT F","; TAB(9) IT$(F)
2194 F=F+1
2195 NEXT J
2196 D3=F
2197 NEXT I
2198 FOR P1=F-V(S,T) TO F-1
2199 IF X(2)=3 THEN 2201
2200 GOTO 2204
2201 FOR K=D1-V(2,0) TO D1-1:IF RIGHT$(IT$(P1),4)<>IT$(K) THEN 2203
2202 O=VAL(LEFT$(IT$(P1),2)):M(K,P1)=MU(1,O):M(P1,K)=X(1)*RLMDA(1,O)
2203 NEXT K
2204 FOR L=D1 TO D1+V(1,1)-1:IF LEFT$(IT$(P1),2)<>LEFT$(IT$(L),2) THEN
2207
2205 IF MID$(IT$(P1),3,2)=RIGHT$(IT$(L),2) THEN
O=VAL(RIGHT$(IT$(P1),2)):M(L,P1)=2*MU(2,O):M(P1,L)=(X(2)-1)*HLMDA(2,O)
2206 IF RIGHT$(IT$(P1),2)=RIGHT$(IT$(L),2) THEN
O=VAL(MID$(IT$(P1),3,2)):M(L,P1)=2*MU(2,O):M(P1,L)=(X(2)-1)*HLMDA(2,O)
2207 NEXT L
2208 NEXT P1
2209 Y=I:Z=1:H=H+1
2210 PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * ";T;" COMPONENT OF GROUP
     1 AND ";S;" COMPONENT OF GROUP 2 ARE DOWN":PRINT TAB(5) "NUMBER OF
STATES IN THIS CLUSTER ";V(T,S):GRUP(H)=V(T,S):S=T:GOSUB
3200:PR(H)=MIN:S=1
2211 FOR I=Y TO STATE(1,T)
2212 FOR J=Z TO STATE(2,S)
2213 IT$(F)=GS$(1,I)+GS$(2,J)
2214 PRINT F","; TAB(9) IT$(F)
2215 F=F+1
2216 NEXT J
2217 NEXT I
2218 FOR P1=F-V(T,S) TO F-1
2219 IF X(1)>2 THEN 2221
2220 GOTO 2224
```

```
2221 FOR K=STATE(1,1)+1 TO STATE(1,2):IF
     LEFT$(IT$(P1),4)<>LEFT$(IT$(K),4) THEN 2223
2222 O=VAL(RIGHT$(IT$(P1),2)):M(K,P1)=MU(2,0):M(P1,K)=X(2)*RLMDA(2,0)
2223 NEXT K
2224 FOR L=D1 TO D1+V(1,1)-1:IF RIGHT$(IT$(P1),2)<>RIGHT$(IT$(L),2) THEN
2225 IF MID$(IT$(P1),3,2)=LEFT$(IT$(L),2) THEN O=VAL(LEFT$(IT$(P1),2)):
     M(L,P1)=2*MU(1,0):M(P1,L)=(X(1)-1)*HLMDA(1,0)
2226 IF LFT$(IT$(P1),2)=LEFT$(IT$(L),2) THEN
     O=VAL(MID$(IT$(P1),3,2)):M(L,P1)=2*MU(1,0):M(P1,L)=(X(1)-1)*HLMDA
      (1,0)
2227 NEXT L
2228 Z=Y2-(V(0,X(1)))+1
2229 FOR G=Y2 TO Z STEP-1:IF LEFT$(IT$(P1),4)=LEFT$(IT$(G),4) THEN
O=VAL(RIGHT$(IT$(P1),2)):M(G,P1)=MU(2,0)
2230 NEXT G
2231 NEXT P1
2233 S=S+1:Z=J:IF S+1>X(1) AND T+1>X(2) THEN 2330
2234 H=H+1
2235 PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * ";S;" COMPONENT OF GROUP
1 AND ";T;" COMPONENT OF GROUP 2 ARE DON":PRINT TAB(5) "NUMBER OF
STATES IN THIS CLUSTER = ";V(S,T):GRUP(H)=V(S,T):GOSUB 3200:PR(H)=MN
2236 FOR I=Y TO STATE(1,S)
2237 FOR J=Z TO STATE(2,T)
2238 IT$(F)=GS$(1,I)+GS$(2,J)
2239 PRINT F","; TAB(9) IT$(F)
2240 F=F+1
2241 NEXT J
2242 NEXT I
2243 FOR P1=F-V(2,2) TO F-1
2244 FOR L=D2 TO D2+V(1,2-1:IF RIGHT$(IT$(P1),4)<>RIGHT$(IT$(L),4) THEN
2247
2245 IF MID$(IT$(P1),3,2)=LEFT$(IT$(L),2) THENO=VAL(LEFT$(IT$(P1),2)):
M(L,P1)=2*MU(1,0):IF X(2)>2 THEN M(P1,L)=(X(1)-1)*HLMDA(1,0)
2246 IF LEFT$(IT$(P1),2)=LEFT$(IT$(L),2) THEN O=VAL(MID$(IT$(P1),3,2)):
M(L,P1)=*MU(1,0):IF X(2)>2 THEN M(P1,L)=(X(1)-1)*HLMDA(1,0)
2247 NEXT L
2248 FOR K=D3 TO D3+V(2,1)-1:IF LEFT$(IT$(P1),4)<>LEFT$(IT$(K),4) THEN
     2255
2249 IF MID$(IT$(P1),5,2)=RIGHT$(IT$(K),2) THEN O=VAL(RIGHT$(IT$(P1),2))
     :M(K,P1)=2*MU(2,0):IF X(1)>2 THEN MP1,K)=(X(2)-1)*HLMDA(1,0)
2254 IF RIGHT$(IT$(P1),2)=RIGHT$(IT$(K),2) THEN O=VAL(MID$(IT$(P1),5,2))
    :M(K,P1)=2*MU(2,0):IF X(1)>2 THEN M(P1,K)=(X(2)-1)*HLMDA(1,0)
2255 NEXT K
2256 NEXT P1
2257 IF T+1>X(2) THEN 2280
2258 S=1:Y=1:T=T+1:Z=J
2259 H=H+1
2260 PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * ";S;"COMPONENT OF GROUP 1
AND ";T;" COMPOENT OF GROUP 2 ARE DOWN":PRINT TAB5) "NUMBER OF STATES
IN THIS CLUSTER = ";V(S,T):GRUP(H)=V(S,T):GOSUB 3200:PR(H)=MIN
```

```
2261 FOR I=1 TO STATE(1,S)
2262 FOR J=Z TO STATE(2,T)
2263 IT$(F)=GS$(1,I)+GS$(2,J)
2264 PRINT F","; TAB(9) IT$(F)
2265 F=F+1
2266 NEXT J
2267 NEXT I
2268 FOR P1=F-V(S,T) TO F-1
2269 FOR L=D2 TO D2+V(S,2)-1:IF LEFT$(IT$(P1),2*S)<>LEFT$(IT$(L),2*S)
     THEN 2273
2270 IF MID$(IT$(P1),3,4)=RIGHT$(IT$(L),4) THEN O=VAL(RIGHT$(IT$(P1),2))
     :M(L,P1)=MU(2,O):M(P1,L)=HLMDA(2,O)
2271 IF RIGHT$(IT$(P1),4)=RIGHT$(IT$(L),4) THEN O=VAL(MID$(IT$(P1),3,2))
     :M(L,P1)=MU(2,O):M(P1,L)=HLMDA(2,O)
2272 COMB$(L)=MID$(IT$(P1),3,2)+RIGHT$(IT$(P1),3):IF COMB$(L)=MID$(IT$
     (P1),3,4) THEN O=VAL(MID$(IT$(P1),4,2)):M(L,P1)=MU(2,O):M(P1,L)=
     HLMDA(2,O)
2273 NEXT L
2274 FOR L=F TO G:IF RIGHT$(IT$(P1),6) = RIGHT$(IT$(L),6) THEN O=VAL(
     LEFT$(IT$(P1),2)):M(L,P1)=MU(1,O)
2275 NEXT L
2276 NEXT P1
2277 S=S+1
2278 IF S+1>X(1) THEN S=2:GOTO 2280
2279 Y=I:D2=D4:GOTO 2257
2280 IF S+1>X(1) THEN 2330
2285 Y=I:S=S+1:T=1:Z=1
2290 H=H+1
2291 PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * ";S;" COMPONENT OF GROUP
     1 AND ";T;" COMPONENT OF GROUP 2 ARE DOWN":PRINT TAB(5) "NUMBER OF
     STATES IN THIS CLUSTER = ";V(S,T):GRUP(H)=V(S,T):GOSUB
3200:PR(H)=MIN
2292 FOR I=Y TO STATE(1,S)
2295 FOR J=Z TO STATE(2,T)
2300 IT$(F)=GS$(1,I)+GS$(2,J)
2305 PRINT F","; TAB(9) IT$(F)
2307 F=F+1
2310 NEXT J
2315 NEXT I
2317 T=T+1
2320 IF T+1>X(2) THEN 2330
2322 Z=J:GOTO 2290
2330 FOR R=2 TO 1 STEP-1
2331 H=H+1
2332 PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * ";X(R);"COMPONENTS OF
GROUP ";R;"ARE DOWN":GOSUB 3200:PR(H)=MIN
2333 IF R=2 THEN V=V(X(R),0)
2334 IF R=1 THEN V=V(0,X(1))
2335 PRINT TAB(5) "NUMBER OF STATES IN THIS CLUSTER = ";V:GRUP(H)=V
```

```
2337 FOR I=1 TO V:PRINT F",";  TAB(9) IT$(F):F=F+1:NEXT I
2340 NEXT R
2341 Q=Y2
2360 FOR I=0 TO Q
2362 TTAL = 0
2363 M(I,I)=0
2365 FOR J=0 TO Q
2370 TTAL=TTAL+M(J,I)
2380 NEXT J
2385 M(I,I)=-TTAL
2390 NEXT I
2391 U=3:MIN=0
2392 OPEN "O",#1,"MATRIX"
2393 PRINT #1,Q+1,U,H:PRINT:PRINT:PRINT "CLUSTER NO.  No. OF STATES
     PRATE":FOR I=0 TO H:PRINT #1,GRUP(I),PR(I):PRINT I,GRUP(I),PR(I):
     NEXT I
2394 PRINT "        THE MATRIX M":PRINT:PRINT:PRINT TAB(10) "   FROM
     STATE ......../ Kac":PRINT " TO \":PRINT
2396 FOR I=0 TO Q
2400 K=0:IT$(0)=" 0"
2402 PRINT "STATE";IT$(I);"|";
2404 FOR J=0 TO Q
2405 IT$(0)=" 0"
2406 A#=M(I,J):PRINT #1,A#
2408 IF M(I,J)=0 THEN 2414
2412 PRINT TAB(12) IT$(J);"/";:PRINT USING "+.### ";M(I,J)
2414 NEXT J
2416 PRINT:NEXT I
2417 CLOSE #1
2500 RETURN
2550 CLEAR
2554 DIM RLMDA(1,5),HLMDA(1,5),MU(1,5),M(50,50),COMB$(30),IT$(50)
2562 DIM STATE(2,5),W(1,5),SG$(100),N(5),WP(5),LMDA(5),SMU(5),GATE(5)
2601 INPUT "HOW MANY COMPONENTS IN ACTIVE PARALLEL";X
2602 INPUT "HOW MANY FAILURE MODES ASSOCIATED WITH EACH COMPONENT";N
2603 INPUT "PRODUCTION RATE OF EACH COMPONENT IN UNITS/HR";WP
2604 L=1:INPUT "DESIRED SYSTEM OUTPUT IN UNITS/HR";DOUT
2605 FOR I=1 TO N
2606 PRINT "FAILURE RATE OF MODE No.  ";I;"FOR REGULAR OPERATION,IN
     UNITS/HR";:INPUT RLMDA(L,I)
2607 PRINT "FAILURE RATE OF MODE No.  ";I;"FOR HEAVY OPERATION,IN
     UNITS/HR";:INPUT HLMDA(L,I)
2608 PRINT "REPAIR RATE,IN UNITS/HR,FOR MODE No.  ";I;"= ";:INPUT
     MU(L,I)
2609 NEXT I
2610 INPUT "HOW MANY COMPONENTS IN SERIES";SER:KM=0:MIN=DOUT
2611 FOR I=1 TO SER
2612 PRINT "NUMBER OF FAILURE MODES OF COMPONENT";I;:INPUT N(I):PRINT
     "PRODUCTION RATE OF COMPONENT";I;:INPUT WP(I):IF WP(I)<MIN THEN
     MIN=WP(I)
```

```
2613 FOR J=1 TO N(I):KM=KM+1:PRINT "FAILURE RATE OF COMPONENT";I;"WITH
     FAILURE MODE";J;:INPUT LMDA(KM):PRINT "REPAIR RATE OF COMPONENT";I;
     "WITH FAILURE MODE ";J;:INPUT SMU(KM):GATE(KM)=J:NEXT J
2614 NEXT I
2615 PRINT:INPUT "              DO YOU WANT TO CHANGE YOUR DATA [Y or
     N]";U$
2616 IF LEFT$(U$,1)="N" OR LEFT$(U$,1)="n" THEN 2618
2617 IF LEFT$(U$,1)="Y" OR LEFT$(U$,1)="y" THEN 2601
2618 E=0:R=1
2619 GOSUB 1500
2620 S=1
2621 FOR J=0 TO X
2622 PRINT:PRINT TAB(5) "CLUSTER NO. * ";J;" * ";J;" COMPONENTS DOWN"
2624 H=J:PR(J)=W(R,J):IF J=0 THEN PRINT TAB(5) "NUMBER OF STATES IN THIS
CLUSTER = 1":GOTO 2636
2626 PRINT TAB(5) "NUMBER OF STATES IN THIS CLUSTER = ";STATE(R,J)-
STATE(R,J-1):GRUP(J)=STATE(R,J)-STATE(R,J-1)
2628 FOR I=S TO STATE(R,J)
2630 IT$(I)=SG$(I):PRINT I",";TAB(9) SG$(I)
2632 NEXT I
2634 S=1+STATE(R,J)
2636 NEXT J
2637 D9=I
2638 FOR J=1 TO N
2640 M(0,J+E)=MU(R,J)
2642 M(J+E,0)=X*RLMDA(R,J)
2644 NEXT J
2646 FOR K=1 TO X-1
2648 FOR I=STATE(R,K)+1 TO STATE(R,K+1)
2650 FOR J=STATE(R,K-1)+1 TO STATE(R,K)
2652 IF LEFT$(SG$(I),2*K)=SG$(J) THEN
     Y=VAL(RIGHT$(SG$(I),2)):M(J+E,I+E)=MU(R,Y):M(I+E,J+E)=(X-K)*HLMDA
     (R,Y)
2654 IF RIGHT$(SG$(I),2*K)=SG$(J) THEN Y=VAL(LEFT$(SG$(I),2)):M(J+E,I+E)
     =MU(R,Y):M(I+E,J+E)=(X-K)*HLMDA(R,Y)
2656 COMB$(I)=LEFT$(SG$(I),2)+RIGHT$(SG$(I),2)
2658 IF COMB$(I)=SG$(J) THEN
     Y=VAL(MID$(SG$(I),3,2)):M(J+E,I+E)=MU(R,Y):M(I+E,J+E)=(X-K)*HLMDA
       (R,Y)
2660 NEXT J
2662 NEXT I
2664 NEXT K
2666 H=H+1:PRINT:PRINT:PRINT TAB(5) "CLUSTER NO. * ";H;" * 1 SERIES
COMPONENT DOWN"
2668 PRINT TAB(5) "NUMBER OF STATES IN THIS CLUSTER = ";KM
2670 FOR J=1 TO KM
2672 M(0,J+Q)=SMU(J):M(J+Q,0)=LMDA(J)
2674 PRINT D9",";TAB(9) GATE(J):IT$(STATE(R,X)+J)=STR$(GATE(J)):D9=D9+1
2676 NEXT J
```

```
2678 C=1:Q=Q+KM
2680 FOR L=1 TO X-1
2681 H=H+1:PRINT:PRINT:PRINT "CLUSTER NO. * ";H;" * 1 SERIES COMPONENT
     AND ";L;"PARALLEL COMPONENT DOWN"
2684 PRINT TAB(5) "NUMBER OF STATES IN THIS CLUSTER = ";KM*(STATE(1,L)-
     STATE(1,L-1))
2685 FOR K=C TO STATE(1,L)
2686 FOR I=1 TO SER
2688 FOR J=1 TO N(I):Q=Q+1:M(K,Q)=SMU(J):M(Q,K)=LMDA(J):PRINT
     D9",";TAB(9) GATE(J);SG$(K):D9=D9+1:NEXT J
2690 NEXT I
2691 C=STATE(1,L)+1
2692 NEXT K
2694 NEXT L
2695 FOR I=0 TO Q
2696 TTAL = 0
2697 M(I,I)=0
2698 FOR J=0 TO Q
2699 TTAL=TTAL+M(J,I)
2700 NEXT J
2701 M(I,I)=-TTAL
2702 NEXT I
2703 U=3:MIN=0
2704 OPEN "O",#1,"MATRIX"
2705 PRINT #1,Q+1,U,H:FOR I=0 TO H:PRINT #1,GRUP(I),PR(I):NEXT I
2706 FOR I=0 TO Q
2707 FOR J=0 TO Q:A#=M(I,J):PRINT #1,A#:NEXT J
2708 NEXT I
2709 CLOSE #1
2800 GOSUB 2900:GOTO 170
2900 REM ************************************************************
2910 REM *               PRINTING THE TRANSITION MATRIX   M          *
2920 REM ************************************************************
3000 Q1=0:Q2=9:IT$(0)=" 0"
3002 IF Q2>Q THEN Q2=Q
3003 PRINT:PRINT:PRINT
3004 PRINT TAB(10):FOR K=Q1 TO Q2:PRINT USING "\     \";"STATE";:NEXT K
3006 PRINT TAB(7):IF Q2>9 THEN FOR J=Q1 TO Q2: PRINT "   ";J;:NEXT
J:GOTO 3008
3007 FOR J=Q1 TO Q2:PRINT "    ";J;:NEXT J
3008 PRINT TAB(7) "|----"
3010 PRINT TAB(7) "v";:PRINT " ";:FOR K=1 TO 9*(Q2-Q1):PRINT "-";:NEXT K
3014 FOR I=0 TO Q
3015 IT$(0)=" 0"
3016 PRINT:PRINT "STATE";I;"|";
3018 FOR J=Q1 TO Q2:IF M(I,J)><0 THEN PRINT USING "+.#### ";M(I,J);:GOTO
3020
3019 PRINT "        ";
3020 NEXT J
```

```
3022 NEXT I
3024 Q1=J:IF Q-Q2=<10 AND Q-Q2>0 THEN Q2=Q:GOTO 3003
3026 Q2=Q2+10:IF Q2<Q THEN 3003
3030 RETURN
3050 REM ***********************************************************
3055 REM *                  PRINTING MATRIX K                        *
3060 REM ***********************************************************
3063 CLS
3065 PRINT:PRINT "      THE MATRIX K"
3070 PRINT:PRINT:PRINT "The matrix K is obtained by deleting the last
     row and"
3075 PRINT "adding a vector of 1, the sum of probabilities at each time"
3080 PRINT "interval, in the first row of the matrix."
3100 Q1=0:Q2=9
3102 IF Q2>Q THEN Q2=Q
3103 PRINT:PRINT:PRINT
3104 PRINT:PRINT TAB(10);:FOR K=Q1 TO Q2:PRINT USING "\    \";"STATE";:
     NEXT K
3106 PRINT TAB(7);:IF Q2>9 THEN FOR J=Q1 TO Q2: PRINT "   ";J;:NEXT J:
     GOTO 3108
3107 FOR J=Q1 TO Q2: PRINT "    ";J;:NEXT J
3108 PRINT TAB(7) "|----"
3110 PRINT TAB(7) "v";:PRINT " ";:FOR K=1 TO 9*(Q2-Q1):PRINT "-";:NEXT K
3112 PRINT
3114 FOR I=0 TO Q
3115 IF I=0 THEN PRINT "SUM Pi= |";:GOTO 3118
3116 PRINT:PRINT "STATE";I;"|";
3118 FOR J=Q1 TO Q2:IF M(I,J)><0 THEN PRINT USING "+#.### ";M(I,J);:GOTO
3120
3119 PRINT "       ";
3120 NEXT J
3122 NEXT I
3124 Q1=J:IF Q-Q2=<10 AND Q-Q2>0 THEN Q2=Q:GOTO 3103
3126 Q2=Q2+10:IF Q2<Q THEN 3103
3130 RETURN
3200 MIN=W(1,S)
3210 IF W(2,T)<MIN THEN MIN=W(2,T)
3230 RETURN
```

Source List of Program ODE

```
      EXTERNAL FEX
      DOUBLE PRECISION ATOL,RWORK,RTOL,T,TOUT,Y
      DIMENSION Y(2550),ATOL(50),RWORK(2972),IWORK(70)
      DIMENSION GRUP(15),PR(15)
      INTEGER SOM,CNT,H,GRUP,U
      OPEN(1,FILE='MATRIX')
      READ(1,*) NEQ,U,H
      IF (U.EQ.1) GO TO 7
      DO 5 I=1,H+1
5      READ(1,*) GRUP(I),PR(I)
7     NNEQ = NEQ +(NEQ*NEQ)
      READ(1,*)(Y(K),K=NEQ+1,NNEQ)
      CLOSE (1)
      Y(1)=1.0D0
      DO 10 I=2,NEQ
10       Y(I)=0.0D0
      T=0.0D0
      TOUT=0.0D0
      ITOL=2
      RTOL=1.0D-4
      DO 15 I=1,NEQ
15     ATOL(I)=1.0D-6
      ITASK=1
      ISTATE=1
      IOPT=0
      LRW=2972
      LIW=70
      JT=2
      DO 40 IOUT=1,11
        CALL LSODA(FEX,NEQ,Y,T,TOUT,ITOL,RTOL,ATOL,ITASK,ISTATE,
     1     IOPT,RWORK,LRW,IWORK,LIW,JDUM,JT)
        AVL=Y(1)
        IF (U.GT.1) GO TO 24
        PRATE=H*AVL
        GO TO 37
24      CNT=2
        SOM=1
        PRATE=Y(1)*PR(1)
        DO 25 J=2,H
          PROB=0
          DO 26 K=CNT,GRUP(J)+SOM
26          PROB=PROB+Y(K)
          IF (PR(J).EQ.0) GO TO 37
          AVL=AVL+PROB
          PRATE=PRATE+PR(J)*PROB
          CNT=K
          SOM=CNT-1
```

```
25        CONTINUE
37       WRITE(*,31)T
31       FORMAT(1X,//,'    AT  T  =',E12.5)
         WRITE(*,32)(I,Y(I),I=1,NEQ)
32       FORMAT(1X,'   Y(',I2,' )=',E12.5/)
         WRITE(*,33)AVL
33       FORMAT(1X,10H   AVL   =,E12.5)
         WRITE(*,34)PRATE
34       FORMAT(1X,10H  PRATE  =,E12.5)
         IF (ISTATE .LT.0) GO TO 80
         IF (IOUT.GT.1) GO TO 38
         TOUT=TOUT+2.0D0
         GO TO 40
38       TOUT=TOUT*2.0D0
40       CONTINUE
      STOP
80     WRITE(*,90)ISTATE
90    FORMAT(1X,'ERROR HALT.. ISTATE =',I3)
      STOP
      END
C
      SUBROUTINE FEX(NEQ,T,Y,YDOT)
      DOUBLE PRECISION T,Y,YDOT
      DIMENSION Y(3550),YDOT(50)
      DO 100 I=1,NEQ
        YDOT(I)=0.0D0
        DO 150 J=1,NEQ
          M = I*NEQ + J
150       YDOT(I)=YDOT(I)+Y(M) * Y(J)
100   CONTINUE
      RETURN
      END
```

APPENDIX C:

TYPICAL PROBLEMS IN FMS

This section discusses the possible sources of failure of an FMS, which consists of three basic modules: machine, material handling, and computer control, Figure 19. In addition, typical problems in the inspection module are included.

Machine Module

Machine tool errors either in size, shape, location, or surface finish of a feature of the part can be the result of one or a combination of five broad classes of failures in the manufacturing process: Mechanical, hydraulic, Electrical, Electronic, and Tooling. Mechanical and hydraulic failures can be combined since mechanics handle both types of failures. Electrical and electronic failures can also be combined for the same reason.

Mechanical failure

A classification, by which all possible failure modes could be included, consists of the location of failure and the process of failure. Each specific failure mode is then identified as a combination of one or more process together with a failure location. The two failure locations, each with subcategories, are:

1. Body type:
    * Head stock
    * Axis (X and Y)

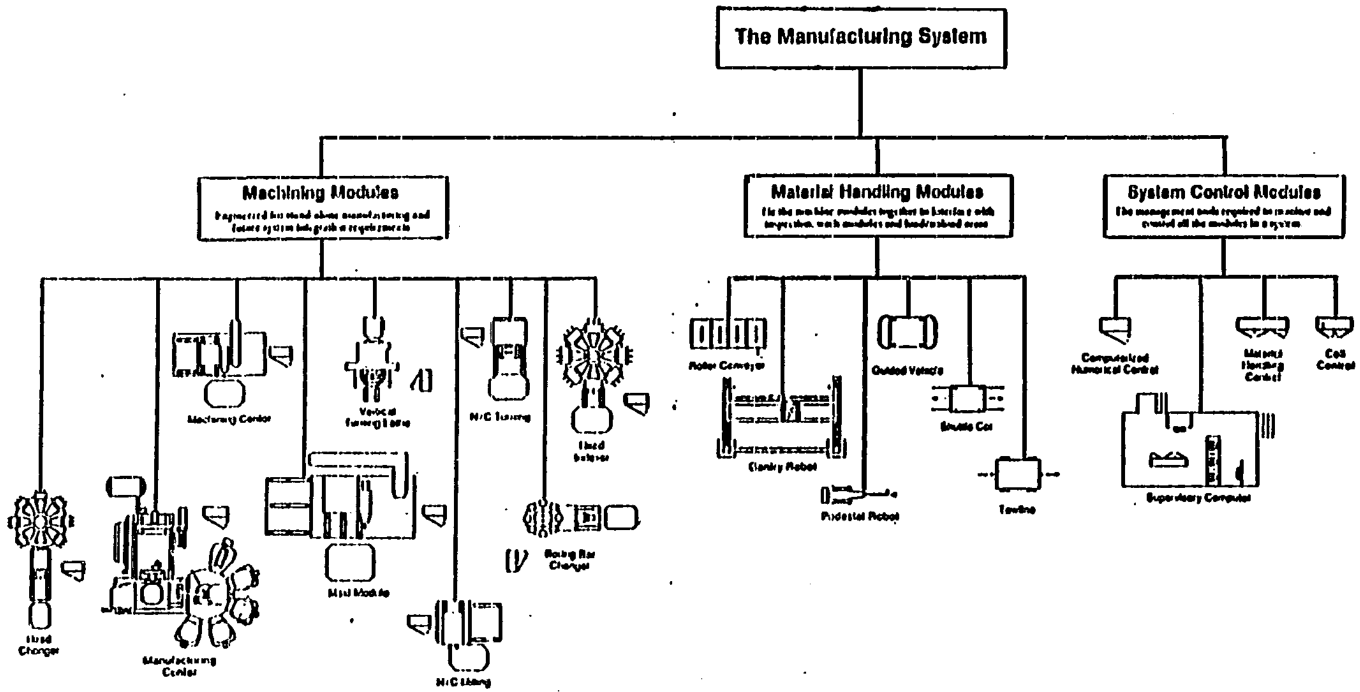

FIGURE 19. Basic modules of an FMS

* Actuators (air motors, air cylinder)
* Bearings
* Drives (gear box, clutches, couples)
* Valves
* Filters (air, coolant, lube)
* Pumps (accumulators, intensifiers)
* Belts or chains
* Clamping

2. Surface type
    * Fixture (clamp, locators, bushing plates, guide rails)
    * Bed (column, swing)
    * Actuators (feed screws)

The four processes of failure are:

1. Elastic and/or plastic deformation
2. Rupture or fracture
3. Vibrations
4. Material variation
    * Metallurgical
    * Chemical
    * Nuclear

The following list includes the most commonly observed failure modes of mechanical failure.

1. Force and/or temperature induced elastic deformation
2. Yielding
3. Ductile or brittle fracture

4. Fatigue (thermal, surface)
5. Corrosion (stress, cavitation, biological)
6. Wear (adhesive, abrasive)
7. Thermal shock
8. Radiation damage

Electrical and electronic

The failure locations are:

1. Control panel
2. Input devices (push buttons, tape recorder)
3. Output devices (servo's, programmable logic controller (PLC), printers)
4. Computer hardware (boards, modules, cathode ray tube, (CRT))
5. Computer software (part programs, patches offsets)
6. Relays (fuses, overloads)
7. Drives (transistor pack, SCR package)
8. Motor (AC, DC)

The following are examples of possible failure modes of electrical/ electronic failure.

1. Breakdowns due to overdiffusion
2. Bad connections due to corrosion
3. Function loss and leak currents
4. Increased resistivity due to oxidation of the bonding surface
5. Thermal transients
6. Capacity-induced breakdowns
7. Change in the frequency bandwidth

Tooling

The two failure locations are:

1. Tool chain magazine
2. Automatic tool changer

Examples of possible failure modes are:

1. Thermal deformation of cutter (elastic, plastic)
2. Tool wear (built up edge)
3. Cracking
4. Deformation due to clamping (material variation)
5. Tool insert dimensional variations.

Material Handling Module

The two basic material handling systems (MHS) used in the U.S.A. for fully flexible machining systems are the AGVS and towline. Table 22 shows a comparison between the two types of material handling.

MHS module failure can be the result of one or a combination of broad classes of failures: mechanical, electrical/ electronic. Examples of possible sources of failure in each class are listed below.

Mechanical failure

1. Guide path (chain drives, switch gear, cams, jacks, pins and diverters)
2. Shuttles (rollers or moving cables)
3. Carrier (truck or cart, battery)
4. Probes (trigger)

5. Delivery and discharge (rollers or moving cables, hydraulic cylinder)

Electrical/electronic failure

1. guide path (cable, magnets, reflective tape or painted strip)
2. Probes (departure-sensing switches, entrance detector, code recorder)
3. Traffic control (computer hardware and software)
4. Signals transmitted (radio or infrared)
5. Incremental position recognition: after a temporary failure of the control system or the AGV is removed from the network, the truck can no longer find its way using incremental position recognition. The use of absolute digital position recognition is more expensive in terms of the number of magnets which have to be installed and in terms of the control design. However, it offers more reliability of transport operations and has to be provided in complex systems.

System Control Modules

Figure 20 illustrates a three-level computer control hierarchy.

1. A minicomputer provides the overall system or master FMS control. The control functions of the master module involves four categories: operational control, production control, traffic control, and data management.

2. The direct numerical control (DNC) module provides a numerical

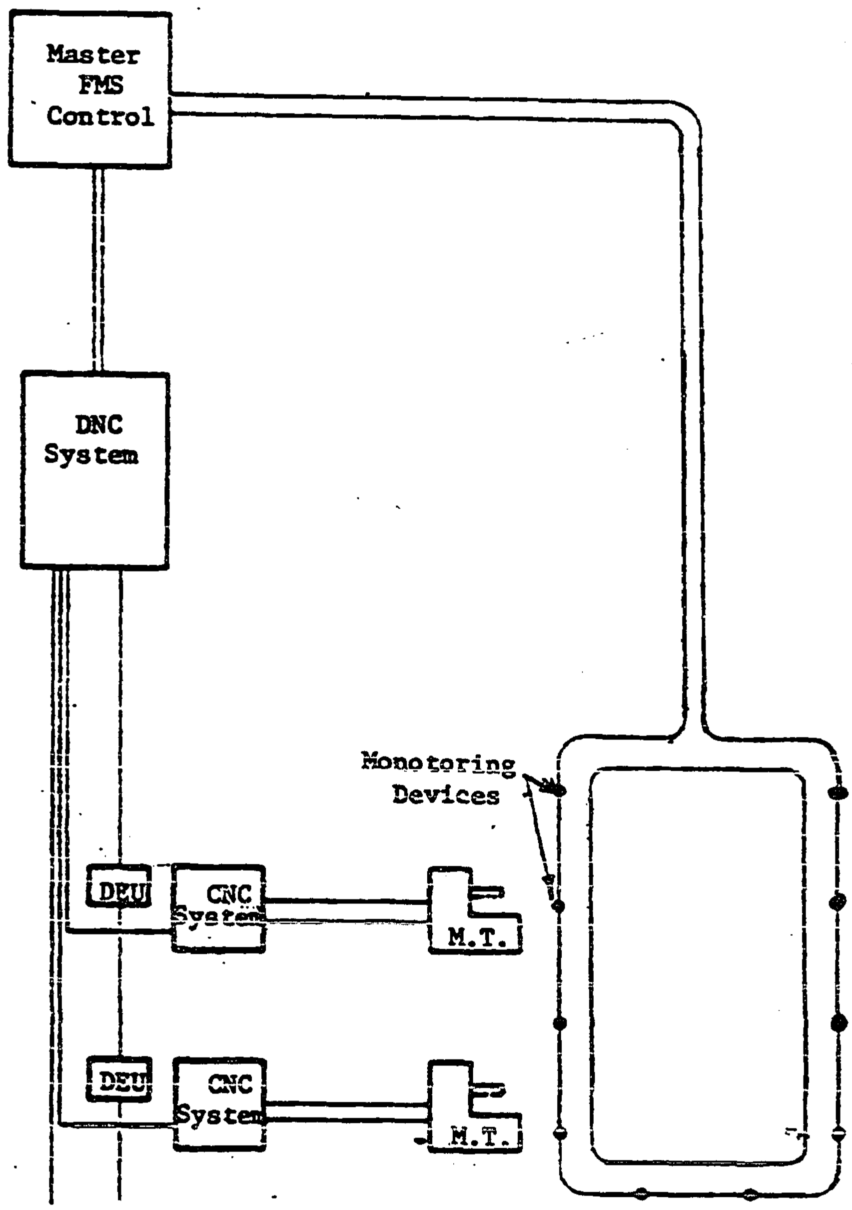

FIGURE 20. Hierarchy of computer control in FMS

control program librarian and distributor function. It is an independent subsystem within the total FMS control system.

3. Computer numerical control (CNC) module is the local machine tool control that provides the direct servo control of the machine axis drives. It is devoted to communicate with the DNC system.

Examples of possible sources of failure are listed below.

1. Terminal, printer, audible or visual alarm system.
2. Data entry unit.
3. Post-processor.
4. APT converter and compiler.
5. Status display board
6. N/C "match coded" to the machine station.
7. Cathode Ray Tube (CRT).
8. Data Terminal Equipment (DTE), if the machine control is hardwired.
9. Intelligent terminal for CNC module.
10. Diagnostic communication system (DCS).
11. Tape puncher, tape reader and microprocessors.
12. Computer Hardware: fixed head disk, disk drives, multiplexers, boards or cards.
13. Software: In most FMSs, the first 6 months to 1 year of deployment are essentially a "shakedown cruise", during which errors are discovered and fixed by the users or through a software group which supports field operation from the development site (18,19). The following are typical examples of software failure (29, Chapter 5):

   a. Bad sector in a floppy disk or in removable cartridge disk

b. Wrong version of subroutine

c. Incompatible program with operating system or hardware

d. Design error

1. The series expansion used for a special mathematical function does not converge for certain values.
2. The THEN ELSE branches can be mistakenly interchanged in an IF statement.

e. Human error

The following are examples of human operator errors:

1. Mounting wrong disk on drive.
2. Entering wrong data or making typographical error.
3. Clearing all memory by mistake.
4. Writing incorrect explanations in the manual.
5. Forgetting the right sequence of commands on occasion because there are too many steps.
6. Not being able to react fast enough to enter control commands in an emergency situation.

f. System overload

1. Timesharing system designed to handle 24 terminals performs poorly when over than 20 terminals are connected.
2. The input module of text-editing cannot keep up with a very fast typist.

Inspection Module

The introduction of FMS technology and "unmanned" machining has compounded the accuracy problem, mainly, because finished parts are inspected elsewhere off the machine tool. The problem exists for producing a number of bad parts before corrective action can be taken, even if coordinate measuring machines (CMM) are included in the manufacturing system (38).

Avoidance of this problem requires a shift in philosophy from post-process part inspection to installation of inspection module and preventive maintenance, instead of measuring the part to see if the machine is functioning properly, measure, adjust and maintain the machine to assure that the part is manufactured properly.

Typical examples of problems in the inspection module are:

1. Part measurements using current methods are difficult and tedious. Simpler, less expensive and less time-consuming are needed. One recommendation to improve reliability is that contact gauges can be replaced with noncontact devices such as those using optical effects, eddy currents or capacitance-change methods. The noncontact gauges are not only less likely to wear and often more reliable, but they also allow higher rates of inspection.

2. Alignment and testing: more complicated part design will require the machine to move in more axes that at present.

3. Accuracy of geometry and surface finish: high accuracy machines will be required to produce higher performance products, less scraps and less inspection effort.

Suggestions for FMS Users

If a manufacturer is considering the installation or remodeling of an FMS, the following suggestions could be valuable tools. Therefore, the system designer can:

1. Specify the company needs and compare alternate systems for features offered and prices charged for these features.
2. Research the plan with existing installations.
3. Review the conditions and maintenance of the machines to be run under DNC.
4. Not to split the total vendor responsibility of the system, including the control interface connections.
5. Require that the system operate in the vendor's plant for at least 30 days before shipping.
6. Pay special attention to the machine tool interfaces and their effects as a valuable tool in detecting many potential problems, particularly on older NC machines.
7. Not to shortcut any computer power isolation or cabling since these may affect system reliability.
8. Set an agreed-to-performance standards as to system reliability, to determine when the system will be operative.
9. Connect one machine tool first and exercise the system before the installation of additional machines.
10. Allow training programmers, clerks, and NC maintenance crew during start-up period.
11. Expect and plan on some machine tool downtime while debugging the

system.

12. Make sure that the system agreement includes a full maintenance contract for at least two years.

13. Keep detailed records about machine tool and other components failure to be able to track system progress and to take action accordingly.

TABLE 22. Comparison between AGVS and towline system

Definition	AGVS	Towline System	Proposed LIM
Description of carrier	Known as a truck. Three or four small hard-wheel trucks for assembly or random complex FMS.	Known as a cart. Four-wheel cart rolls on flat sheet ribbons embedded in the floor.	Represents one part of the motor (secondary) thus vehicle weight is less.
Power source	Most AGVS rely on lead-acid batteries (24V) for power to supply the drive and steering motor. They are recharged every 8-16 hours and exhausted after 1500 discharges.	The carts are powered by drop-forged, rivetless chain with telescoping action to facilitate the take-up mechanisms.	Uses a 3-phase AC source.
Speed	200 to 260 ft/min	120 to 150 ft/min	-300 ft/min
Guide Path	<u>Magnetic Guidance</u> A groove, 2-10mm wide and 15-20mm deep made into the floor surface, wire is layed in the groove and grounted in. The wire is supplied from a	The towchains slide in a 3"x2.25" track. Guide pins at the front and back of a cart engage the slot in the floor so that carts follow the pathway. The guide	A cable is embedded in a 10mm x 25mm groove which is made into the floor surface. The wire is supplied by a three-phase AC

TABLE 22. Continued

Definition	AGVS	Towline System	Proposed LIM
	low-frequency generator that with transmitter allows optimum magnetic field. The AGVS scanning head, with 2 antennae, reads the instruction, given directly from wire to the truck via 10 digit keyboard. Permanent magnets are embedded in the floor at either side of the wire, to control reed contact underneath the trucks.	pin is raised or lowered by a cam-type mechanism mounted in the floor and actuated by computer control. Control is accomplished on a "zone basis", which consists of a section of a chain, a stop blade and entrance/ departure detector. If the zones serve an on/off shuttle, an in-position	source. The frequency of a the electric current is controlled by a computer. A guide pin can be installed at the front or back of the vehicle to follow the pathway.
	<u>Optical</u> <u>Guidance</u> 1. Reflective tape or painted stripe on the floor. The trucks focus light beams on the guide path and by measuring the amplitude of the reflective light are able to track the path accurately. 2. Chemical path is painted on the floor. Trucks direct an ultra-violet light on the path, which responds at different wave lengths. 3. Radio control permits two way communications. It saves the installation cost of the data transmission loop. 4. Infra-red	detector or/and a push bar are also in the zone. The zone length varies from 3 to 20 ft. Two types of stop zones are used: 1. accumulator stops to buffer part flow 2. precision stops to securely restrain the cart to prevent any movemnt. More recently magnetic coding, photoelectrics, bar codes have alternatives to the mechanical probes.	

TABLE 22. Continued

Definition	AGVS	Towline System	Proposed LIM
	transmitters and receivers can be located on board the truck and in the floor.		
Delivery	1. Load bearing platform to lift or lower the part from or onto the delivery stand. 2. Power rollers are mounted on the truck. The pallet is rolled on/of the cart from similar rollers at the workstations. 3. Moving cables on the truck.	A hydraulic cylinder mounted on the shuttle slides the part from one side to the other.	A hydraulic and cylinder moun ted Discharge on the shuttle slides the part from one side to the other.
Accurate Stopping	Centering jacks on the truck are located on precision cones mounted on floor plates.	A hydraulically actuated ram holds cart in position to assure accurate stops.	Accurate stopping devices are eliminated.
Safety	1. The system software prevents a truck from entering into a segment of track that contain another truck by reducing the current behind the truck. 2. Yellow caution signals flash when trucks move. 3. A safety bumper extending 15" from front and rear of the truck, prevent injury or damage to objects in its path.	Only one cart is permitted to be in a zone at one time The minicomputer, being notified that a cart has passed a zone departure sensor, will check if the second zone's stop blade must be raised to halt the cart because the third zone is occupied.	Either a safety bumper or a stop blade are eliminated.

TABLE 22. Continued

Definition	AGVS	Towline System	Proposed LIM
Pros	1. Eliminates the risk of damage during transit. 2. Flexible with respect to breakdown and expansion. 3. Smaller battery size and lower charging costs. 4. Longer component life.	1. Low cost transporter. 2. Operates in normal environment of metal chips, coolant and oil. 3. High reliability. 4. Provides parts buffering between machines.	1. Low operating cost. 2. Less maintenance 3. Gears are eliminated. 4. Accurate stopping devices are eliminated. 5. More flexible.
Cons	1. Requires good floor condition; floor should be concrete (not tar), smooth and dry. 2. The signal from the wire can be destroyed by steel sheets, mesh, or grating on or near the surface.	1. High cost per foot for extended runs. 2. Can be used only above a distance of approximately 300 ft. 3. Failure shuts down an entire zone.	1. Fixed or constant air gap must be maintained. 2. 90 degree turns must be gradual.

APPENDIX D:

ANALYSIS OF FAILURE DATA

This Appendix will present the information which have been received from the company and used for the analysis in the research.

1. A schematic layout of the FMS.

2. There actually 8 different part numbers with 30 different operations being performed at any one time in the FMS.

R79804 Power Shift Mechanical Front Wheel Drive Clutch Hsg.
R79805 Power Shift Clutch Hsg.
R79807 Power Shift Mechanical Front Wheel Drive Clutch Hsg.
R79808 Power Shift Clutch Hsg.

R70600 Power Shift Transmission Case
R70601 Power Shift Transmission Case with Mech Front Wheel Drive
R70396 Power Shift Transmission Case
R70397 Power Shift Transmission Case with Mech Front Wheel Drive

All part numbers are running at the same time. The following are the part routings:

R79804 - Load part in 1st fixture at load station 1. Part is processed through machine 7 or 8; then through machine 1; part is unloaded at unload station 2. There are 3 fixtures for this orientation.
Load part in 2nd fixture at load station 1. Part is processed through machine 1 or 2; then machine 4, 5 or 6; part is unloaded at unload station 2. There are 5 fixtures for this orientation.
Load part in 3rd fixture at load station 1. Part is processed through machine 14, 15 or 16; part is complete and unloaded at unload station 2. There are 6 fixtures for this orientation.

R79805 - Load part in 1st fixture at load station 1. Part is processed through machine 4, 5 or 6; then through machine 1 or 2; part is unloaded at unload station 2. There are 4 fixtures for this orientation.
Load part in 2nd fixture at load station 1. Part is processed through machine 3; then machine 14, 15 or 16; part is complete and unloaded at unload station 2. There are 4 fixtures for this orientation.

R79807 - Load part in 1st fixture at load station 4. Part is processed through machine 7 or 8; then through machine 1; part is unloaded at unload station 3. There are 2 fixtures for this orientation.
Load part in 2nd fixture at load station 1. Part is processed through machine 1 or 2; then machine 4, 5 or 6; part is unloaded at unload station 2. There are 4 fixtures for this orientation.
Load part in 3rd fixture at load station 4. Part is processed through

machine 3; then through 9; then through 14, 15 or 16; part is complete and unloaded at unload station 3. There are 4 fixtures for this orientation.

R79808 - Load part in 1st fixture at load station 4. Part is processed through machine 4, 5 or 6; then through machine 1 or 2; part is unloaded at unload station 3. There are 3 fixtures for this orientation.
Load part in 2nd fixture at load station 4. Part is processed through machine 9; then through 14, 15 or 16; part is complete and unloaded at unload station 3. There are 2 fixtures for this orientation.

R70600 - Load part in fixture at load station 4. Part is processed through machine 9 or 10; then through 11,12 or 13; part is complete and unloaded at unload station 3. There are 3 fixtures for this orientation.

R70601 - Load part in fixture at load station 4. Part is processed through machine 9; then 10; then through 11,12 or 13; part is complete and unloaded at unload station 3. There are 5 fixtures for this orientation.

R70396 - Load part in fixture at load station 4. Part is processed through machine 10; then through 11,12 or 13; part is complete and unloaded at unload station 3. There are 2 fixtures for this orientation.

R70397 - Load part in fixture at load station 4. Part is processed through machine 10; then through 11,12 or 13; part is complete and unloaded at unload station 3. There are 3 fixtures for this orientation.

3. The FMS was purchased to produce a daily requirement of 109 clutch housings and 109 transmission cases. Because of the demand from dealers, the company is producing a varying percentage of the various part numbers.

4. The total process time in minutes:

(a)

Part	1st	2nd	3rd
R79804	18.201	49.158	68.264
R79805	42.165	34.542	
R79807	29.753	60.684	87.129
R79808	49.246	32.337	
R70600	28.386		
R70601	47.721		
R70396	28.405		
R70397	40.545		

(b) There is no setup time for any of the parts as the machines are tooled to run all parts and orientations.

(c) The average time to load either clutch housing and transmission case is 4.65 minutes. The average time to unload either clutch housing and transmission case from its fixture is 2.61 minutes.

(d) Because there can be 2 parts on the shuttle at each machine, the pallet exchange time is 30-45 seconds.

(e) There are 5 horiz. 2 axis head indexers (machine 1-2-3-9-10) that do boring and multi-spindle drilling and taping. There are 11 vert. 3 axis machining centers with each having a 69 tools capacity magazine that can do milling, driiling, boring and tapping.

An analysis of failure data was done in an attempt to define the types of failures associated with the two types of machine module. Tables D.1 and D.2 are associated with the machining center and tables D.3 and D.4 are associated with the head indexer. The time frame for these tables is 17 months and is summary of all emergency repair or unscheduled maintenance.

Analyzing the data for the machining center, Table D.1 shows that 65.2% of the repair job requests were electric in nature and these repairs accounted for 39% of the total downtime on that machine. And while only 9.1% of the requests were for tool failure, these failures accounted for 34%. Table D.2 shows the average for response time, repair time and total downtime. It is interesting to note that the electrical failure was more serious than the other two failure modes and that the large average repair time is for tool failure.

For the head indexer, Table D.3 shows that 71.3% of the emergency requests were for electricians, with failures accounting for 64.3% of total downtime. Table D.4 shows the averages for downtime and it should be pointed that the average for each failure mode is reasonably close.

The highest frequency of failures were occuring in the electrical control panel relays of the head indexers, while the part holding fixtures were responsible for a majority of the failures in the machining centers. Bed and tailstock failures, including both electrical and mechanical, have a relatively high frequency for both types of machine.

Table D.1. Summary of failure data of the machining center

Failure mode	No. of failures	% of total failures	Total downtime	% of total downtime
Electrical	114	65.2	1562.9	39
Mechanical	45	25.7	1081.8	27
Tool	16	9.1	1360.1	34
Total	175	100.0	4004.8	100

Table D.2. Summary of repair data of the machining center

Failure mode	No. of failures	Average Response time	Average repair time	Average downtime
Electrical	114	2.43	11.28	13.71
Mechanical	45	5.82	18.22	24.04
Tool	16	4.92	25.38	30.30

TABLE D.3. Summary of failure data of the head indexer

Failure mode	No. of failures	% of total failures	Total downtime	% of total downtime
Electrical	149	71.3	958.1	64.3
Mechanical	49	23.4	424.3	28.5
Tool	11	5.3	106.5	7.2
Total	209	100.0	1488.9	100

Table D.4. Summary of repair data of the head indexer

Failure mode	No. of failures	Average Response time	Average repair time	Average downtime
Electrical	149	1.46	4.97	6.43
Mechanical	49	2.12	6.53	8.66
Tool	11	2.50	7.17	9.68

APPENDIX E:

TRANSIENT BEHAVIOR OF OPERATING STATES

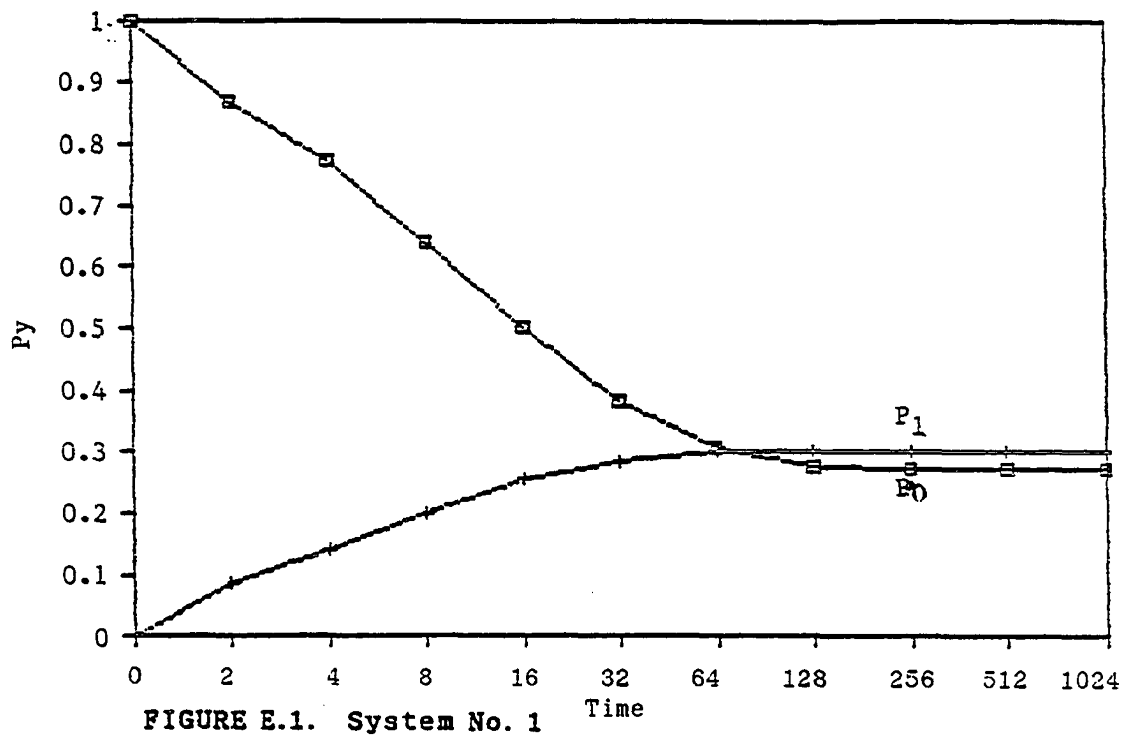

FIGURE E.1. System No. 1

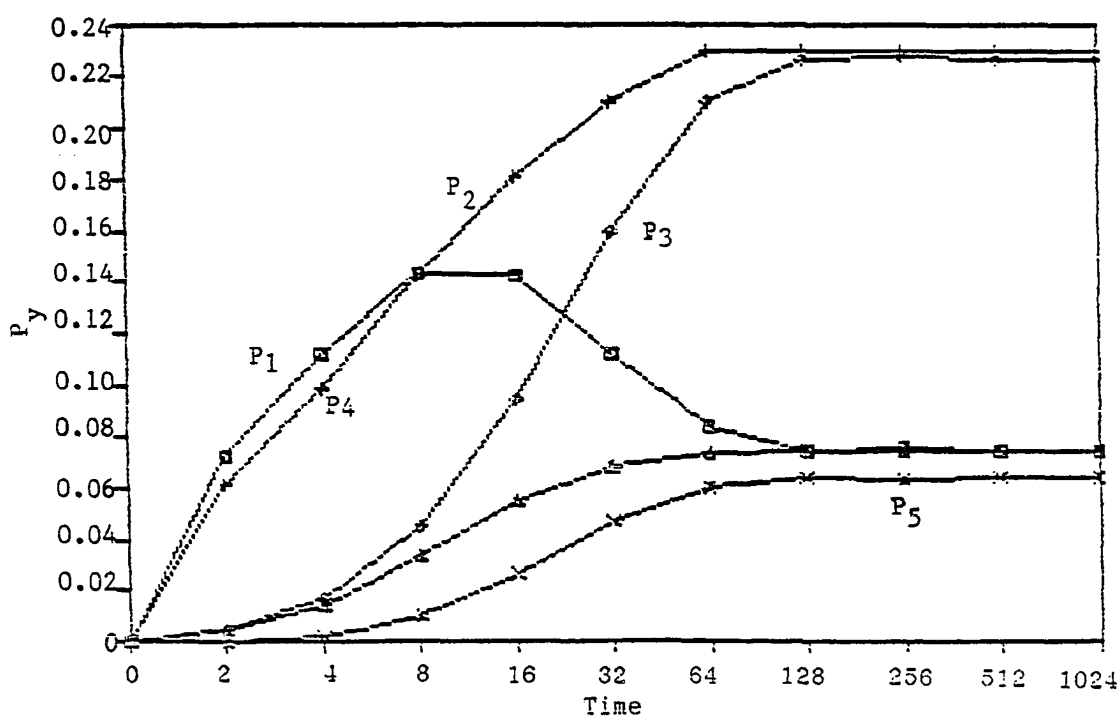

FIGURE E.2. System No. 2,4,7 and 9

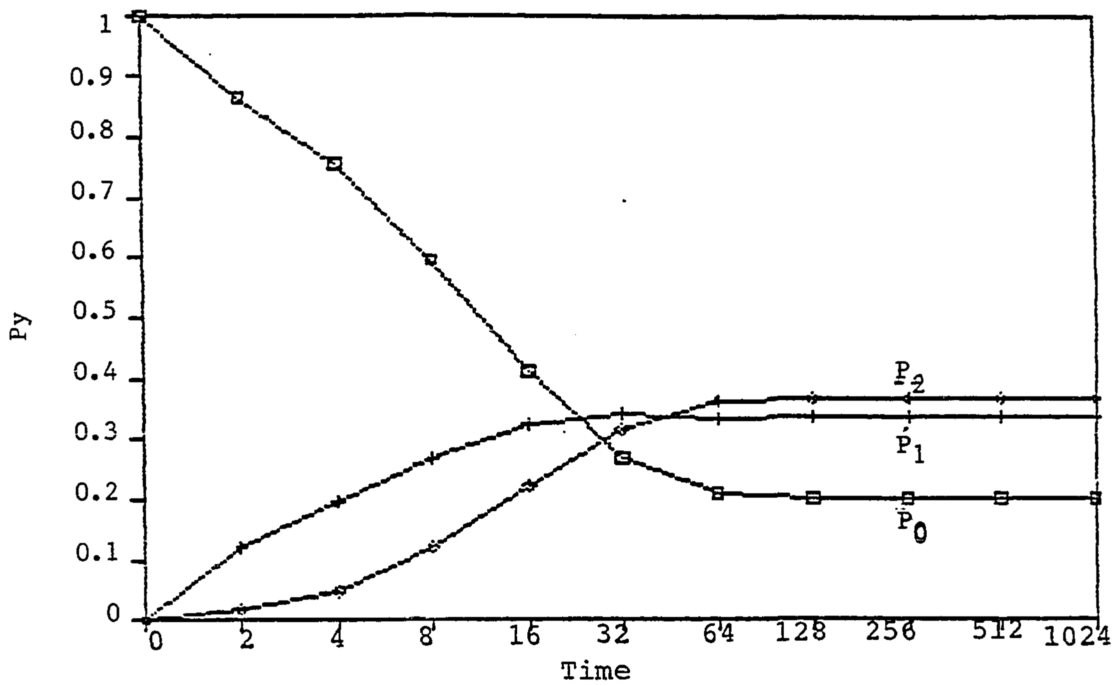

FIGURE E.3. System No. 3

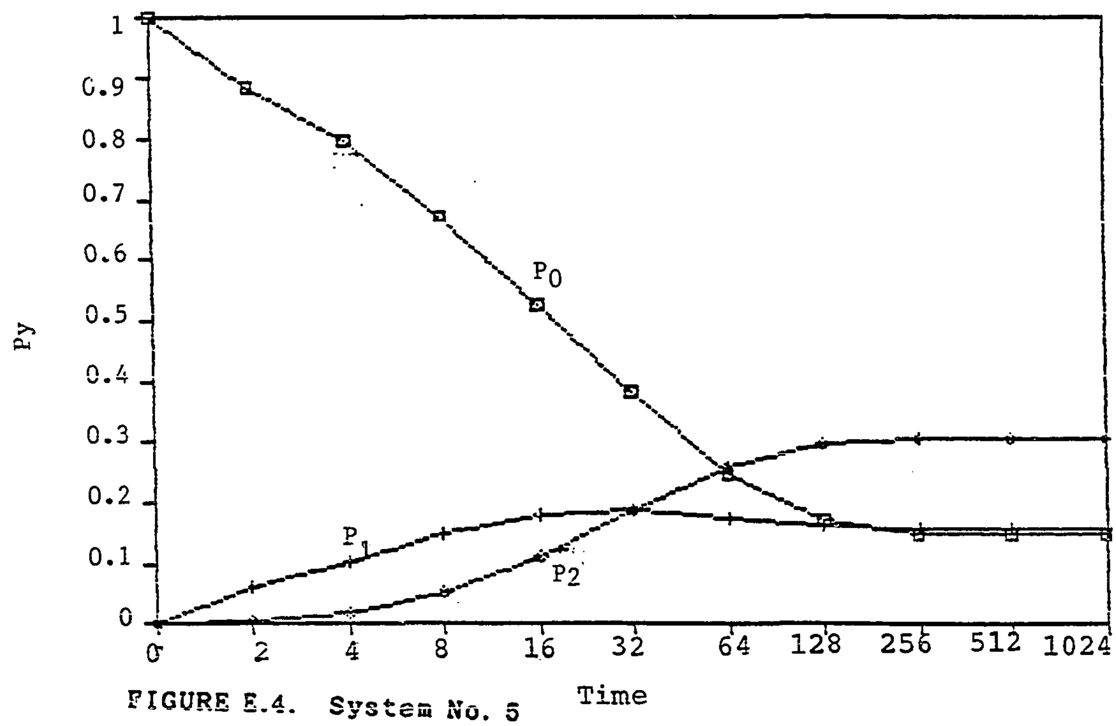

FIGURE E.4. System No. 5

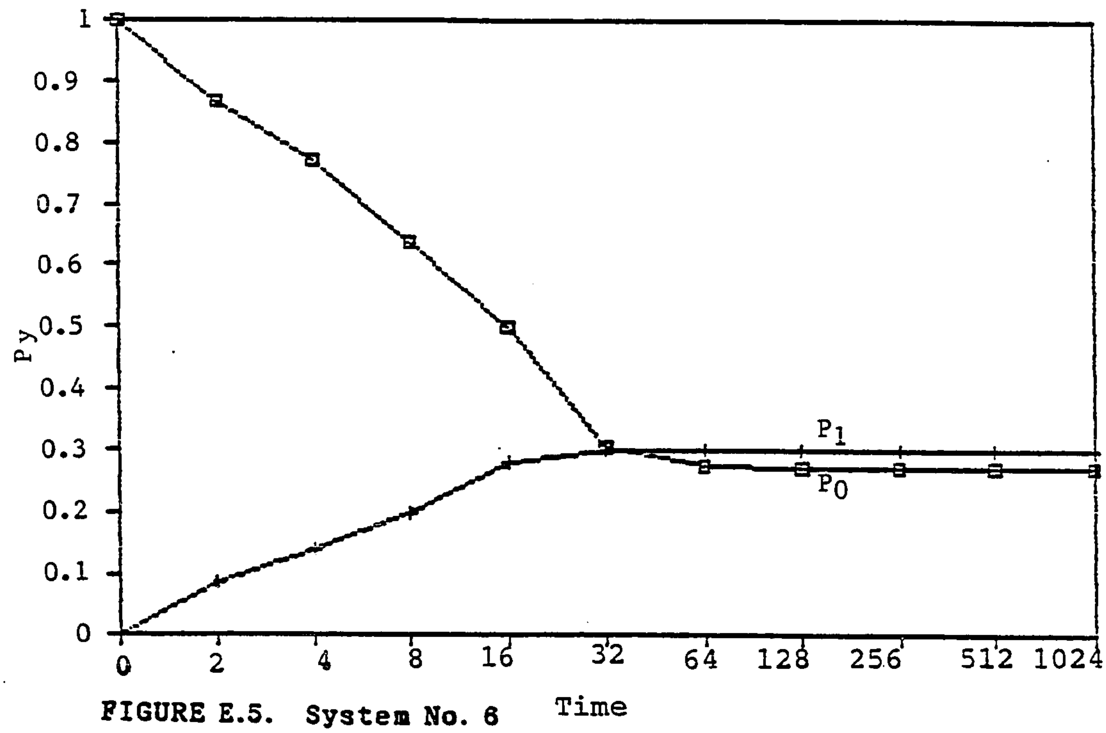

FIGURE E.5. System No. 6

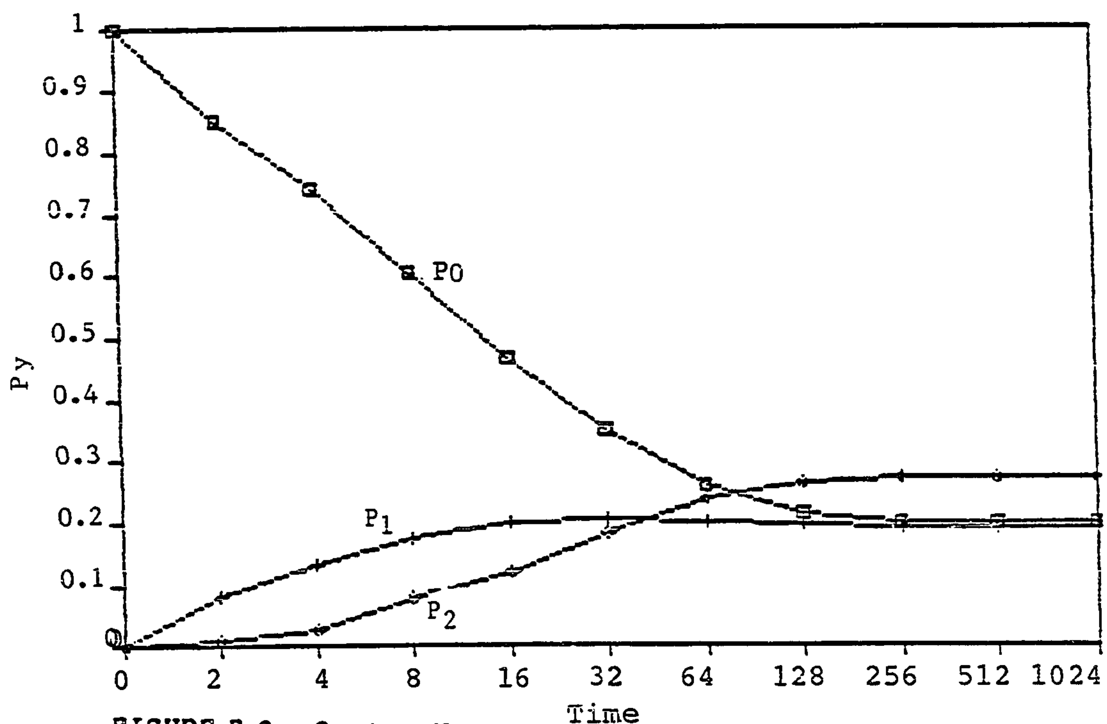

FIGURE E.6. System No. 8

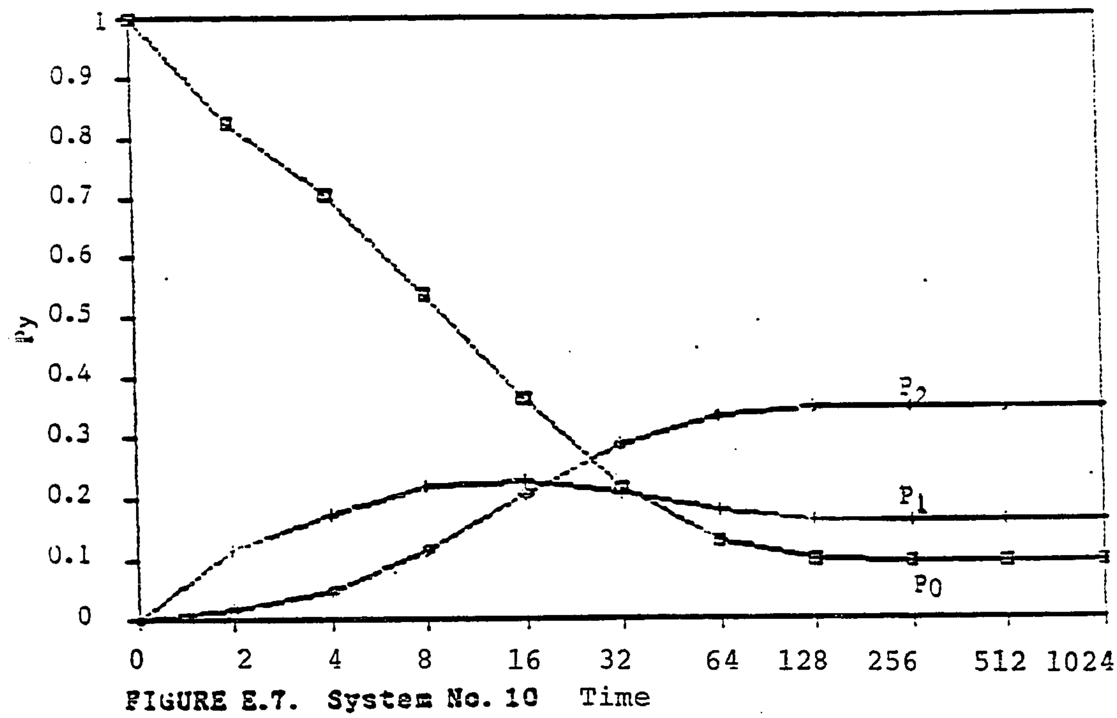

FIGURE E.7. System No. 10

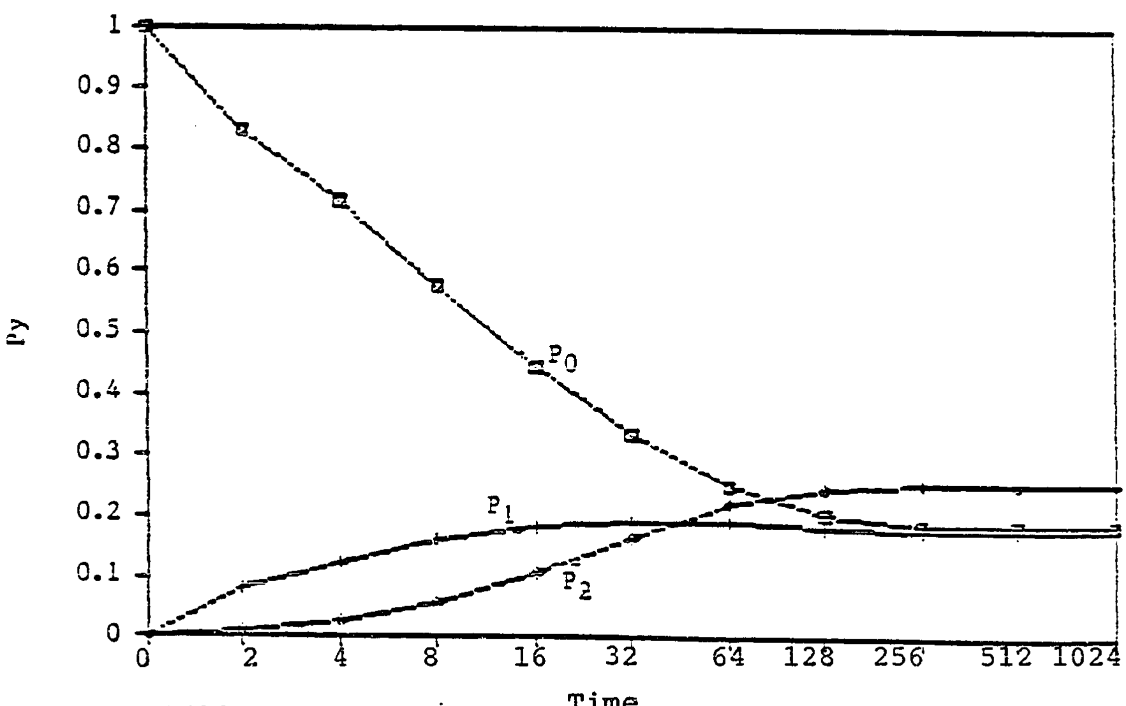

FIGURE E.8. System No. 12

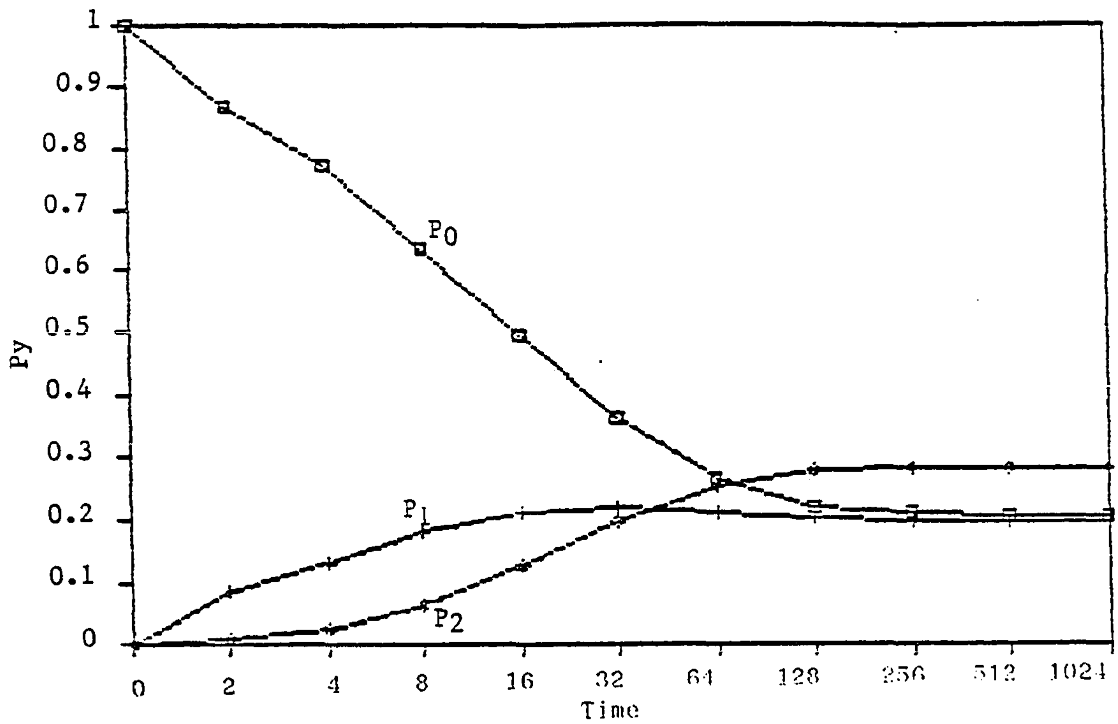

FIGURE E.9. System No. 13 and 14

APPENDIX F:

SYSTEM AVAILABILITY AND SYSTEM EFFECTIVENESS

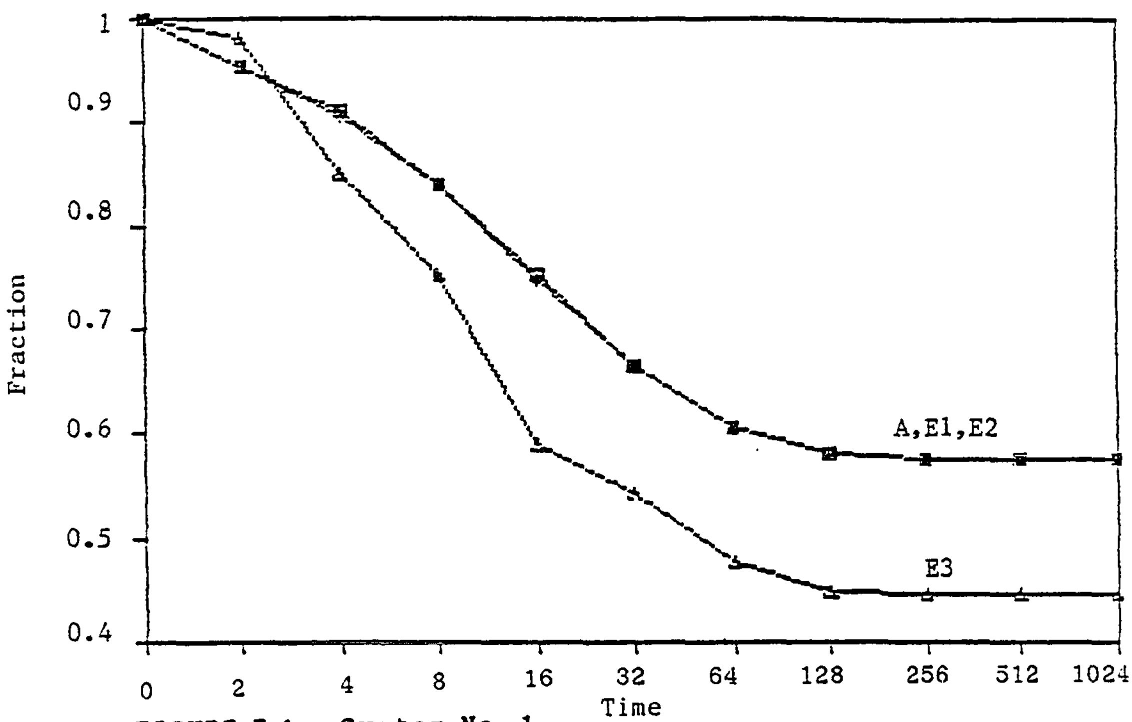

FIGURE F.1. System No. 1

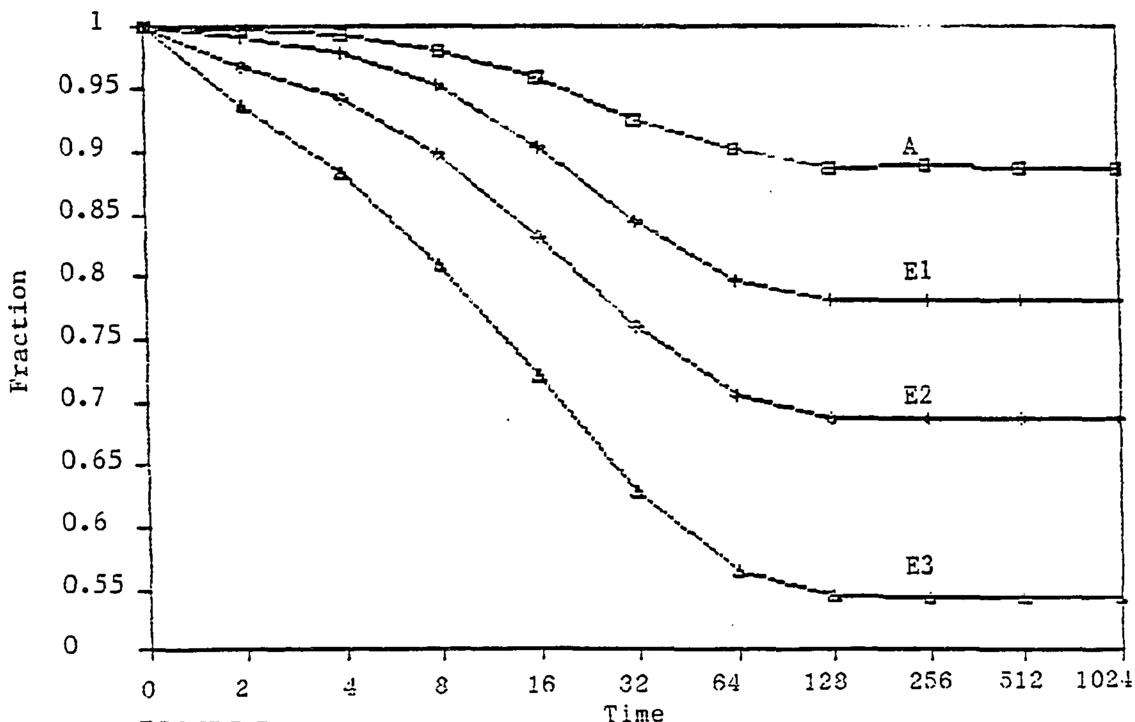

FIGURE F.2. System No. 2

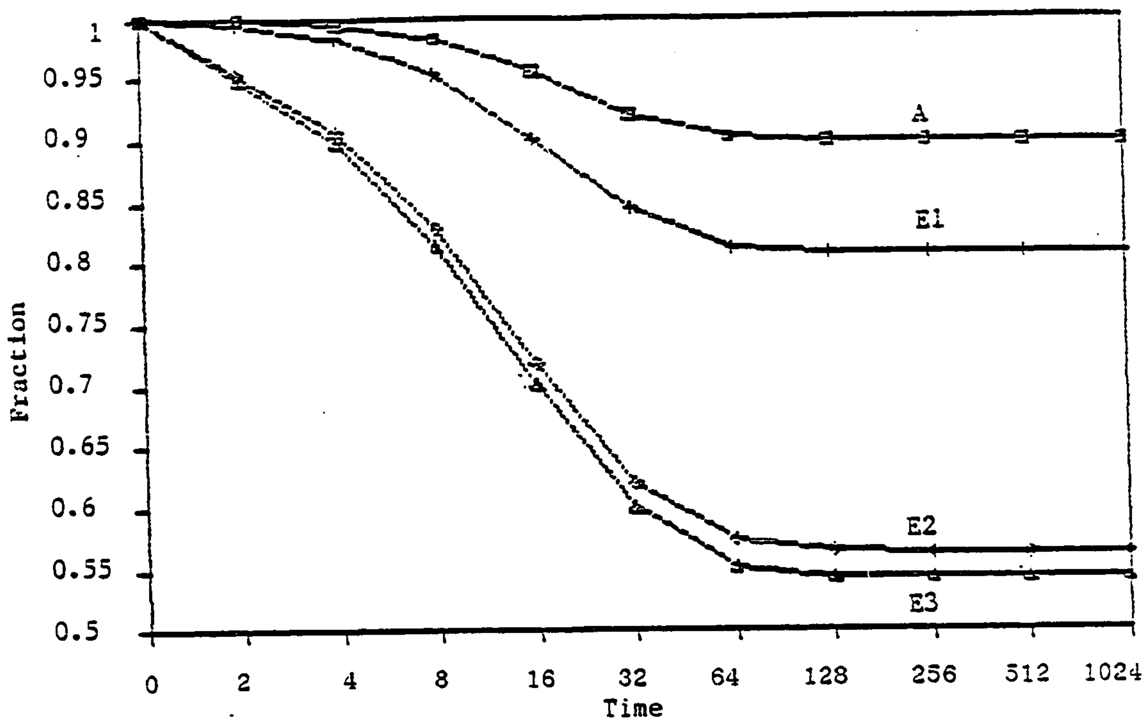

FIGURE F.3. System No. 3

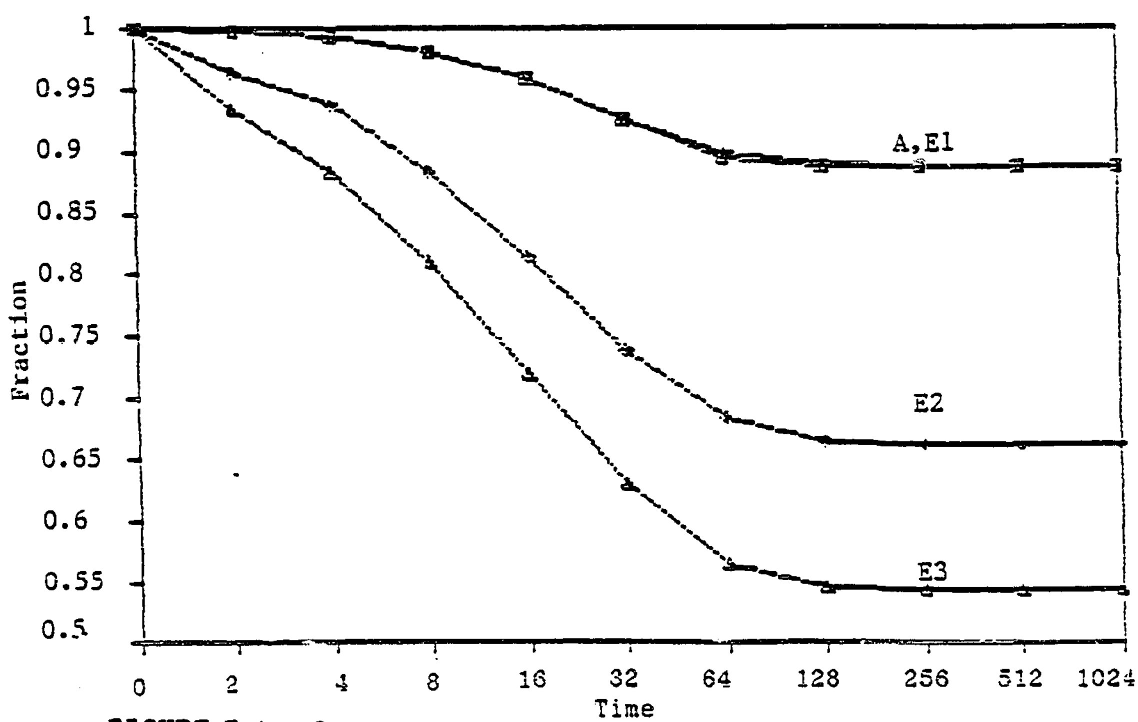

FIGURE F.4. System No. 4

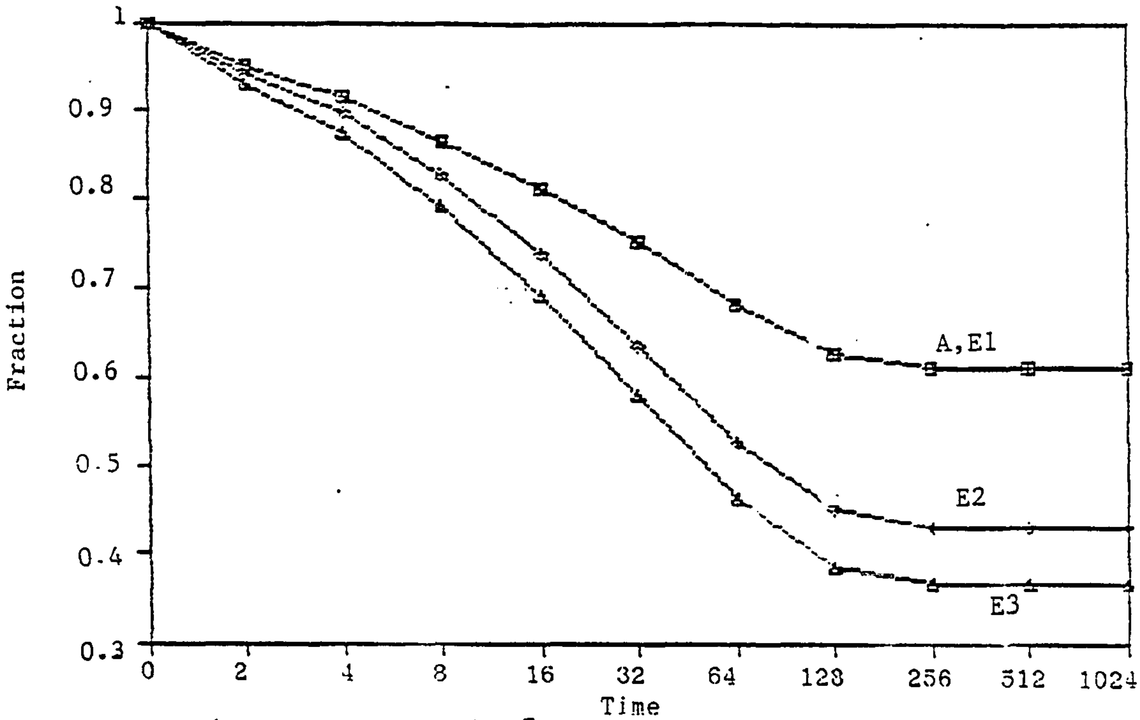

FIGURE F.5. System No. 5

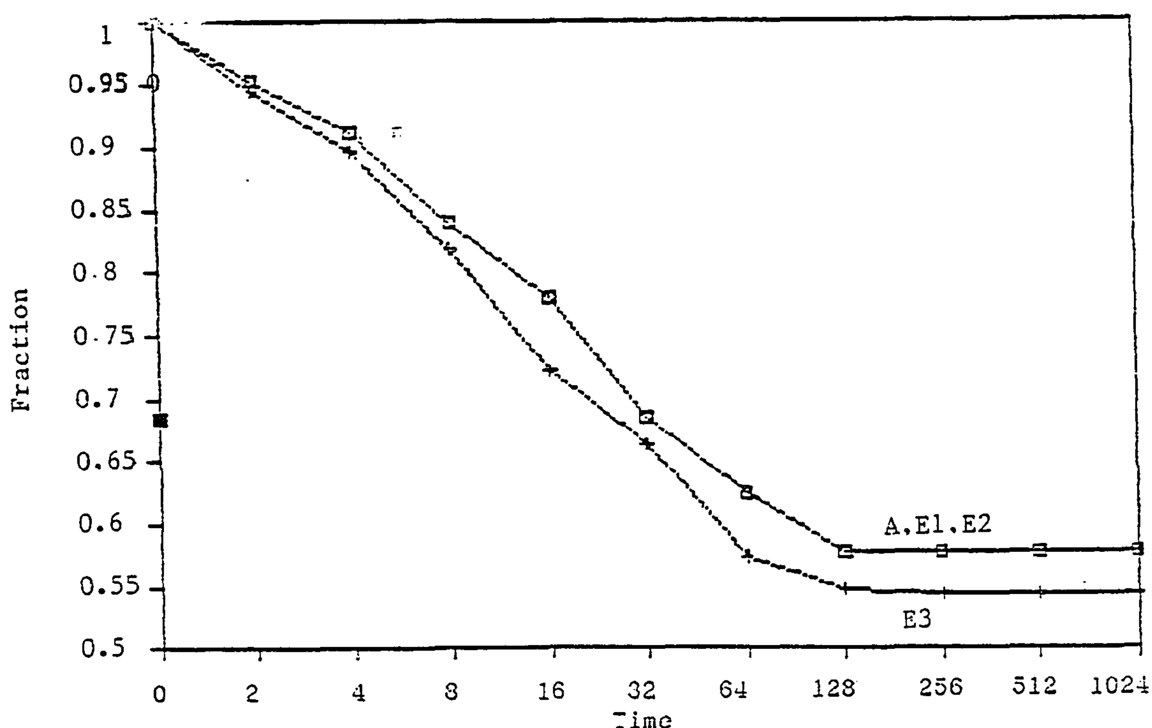

FIGURE F.6. System No. 6

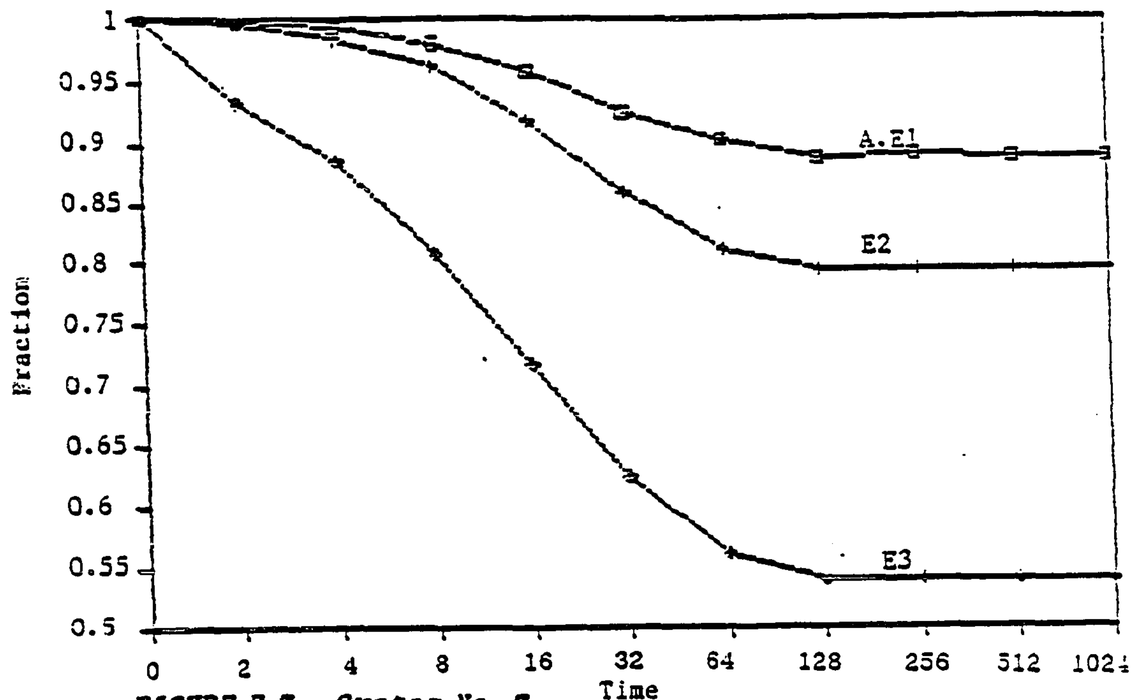

FIGURE F.7. System No. 7

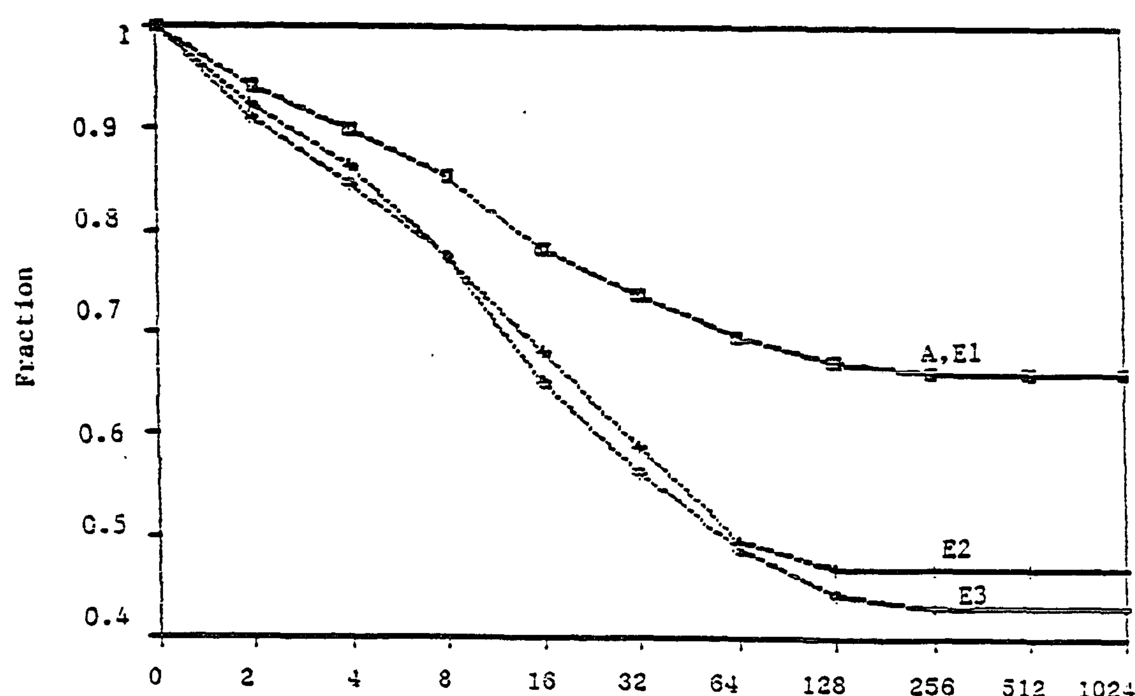

FIGURE F.8. System No. 8

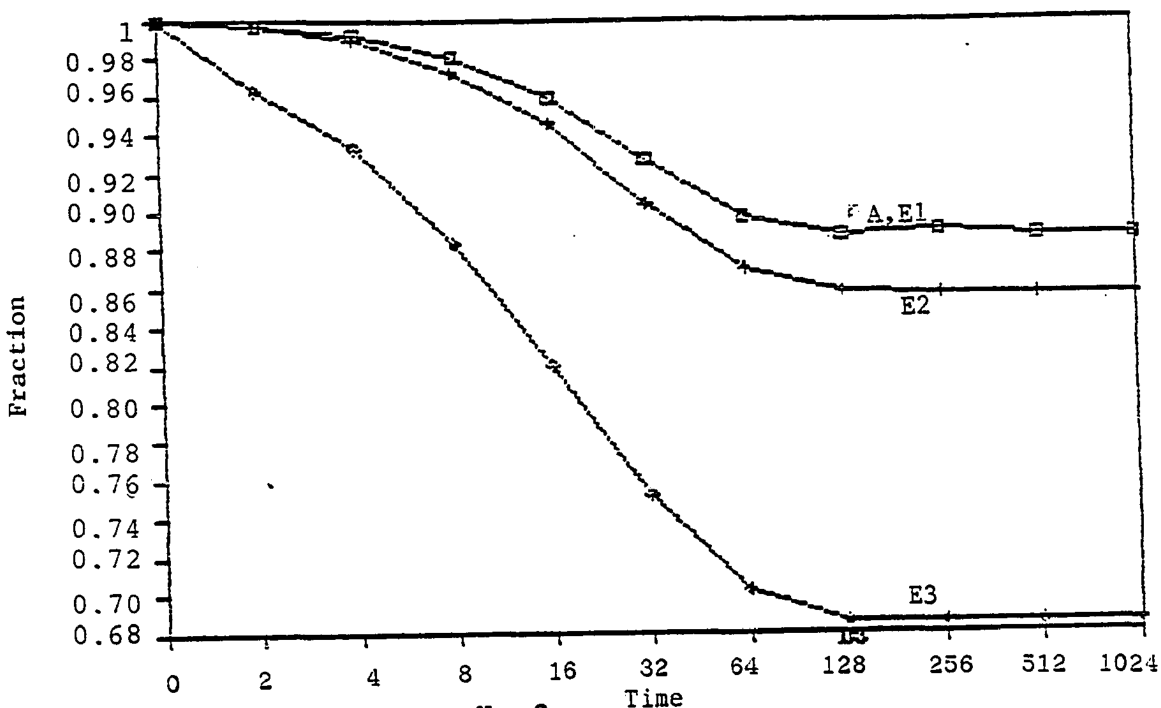

FIGURE F.9. System No. 9

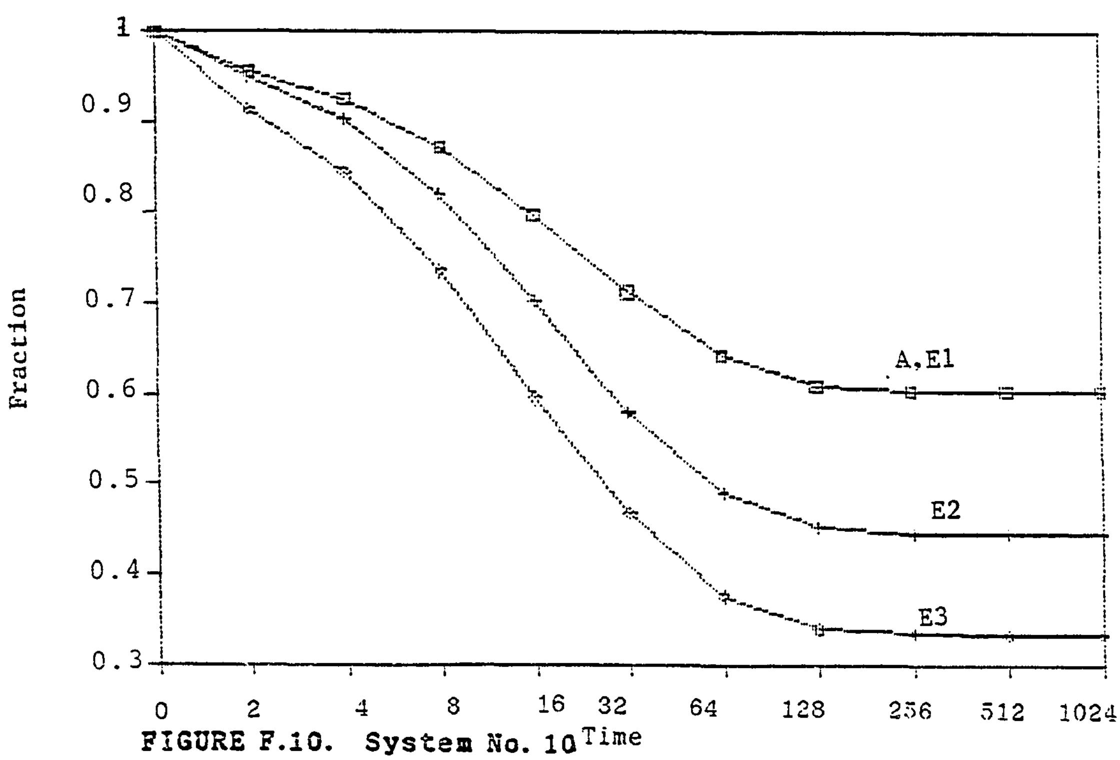

FIGURE F.10. System No. 10

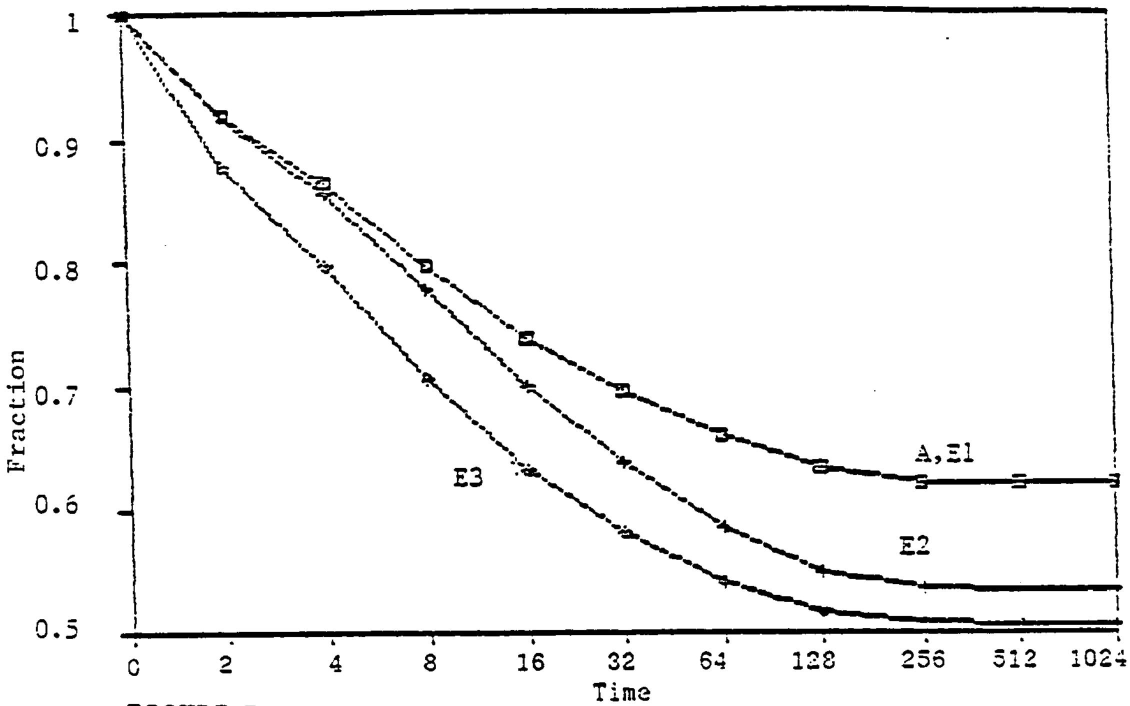

FIGURE F.11. System No. 12

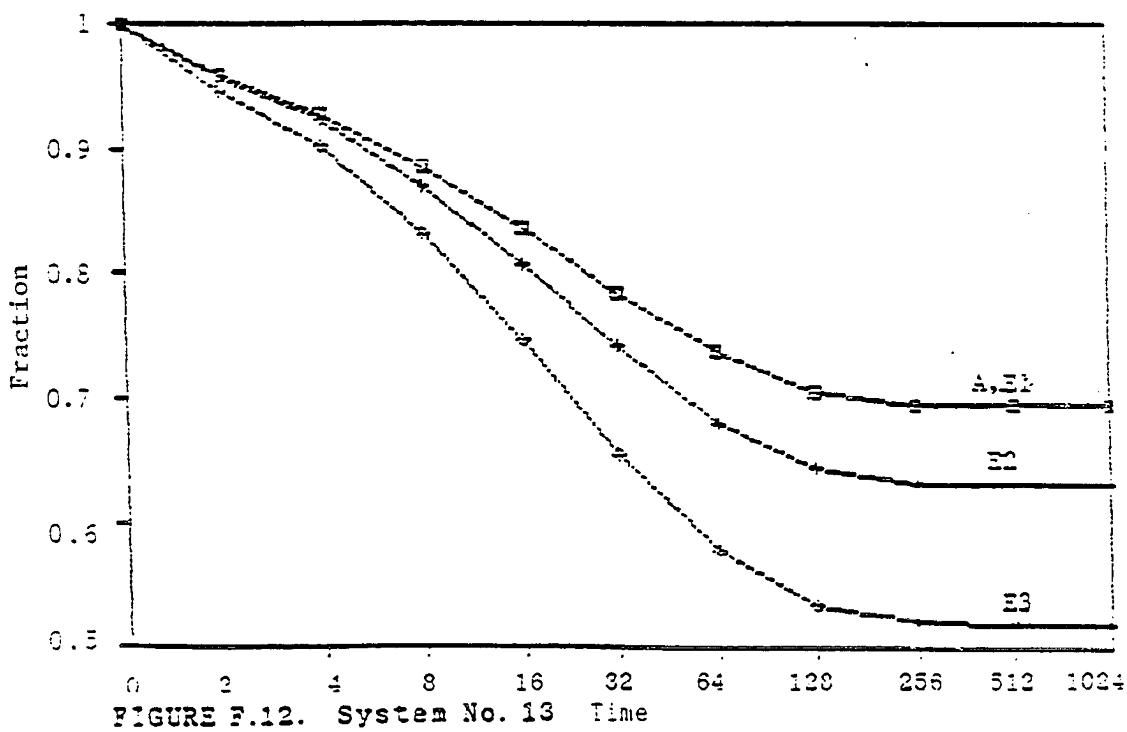

FIGURE F.12. System No. 13

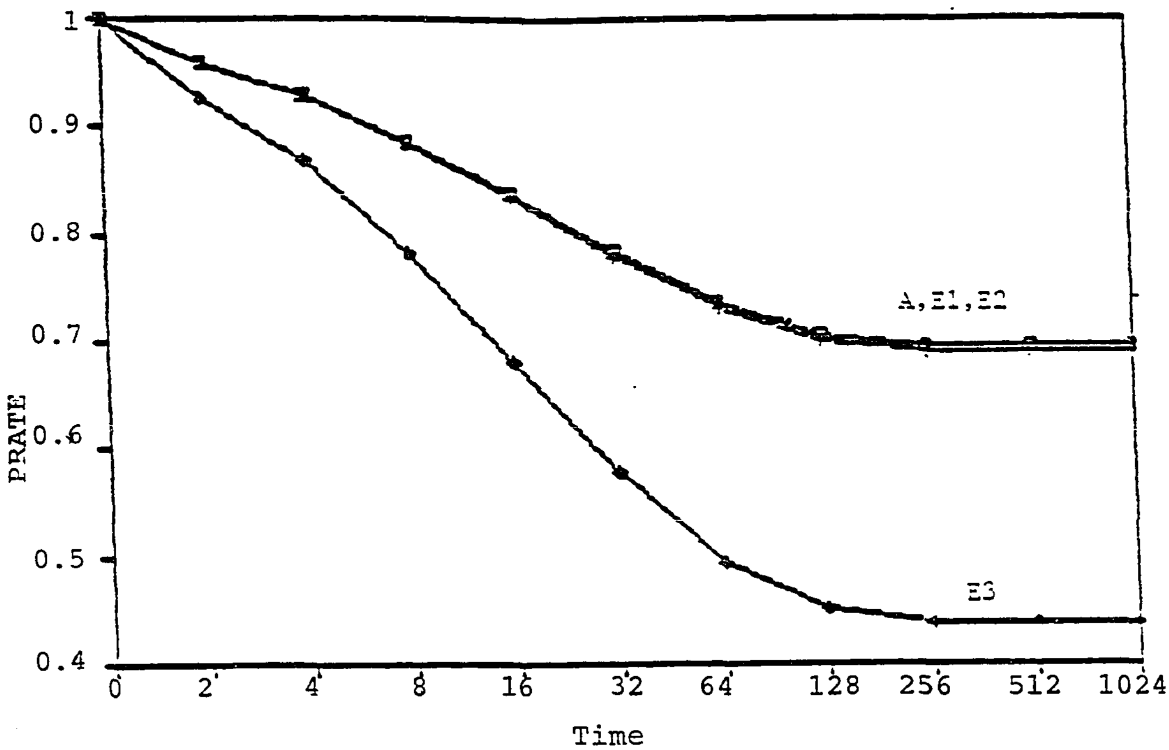

FIGURE F.13. System No. 14

APPENDIX G:

EFFECTS OF DOUT ON PRATE

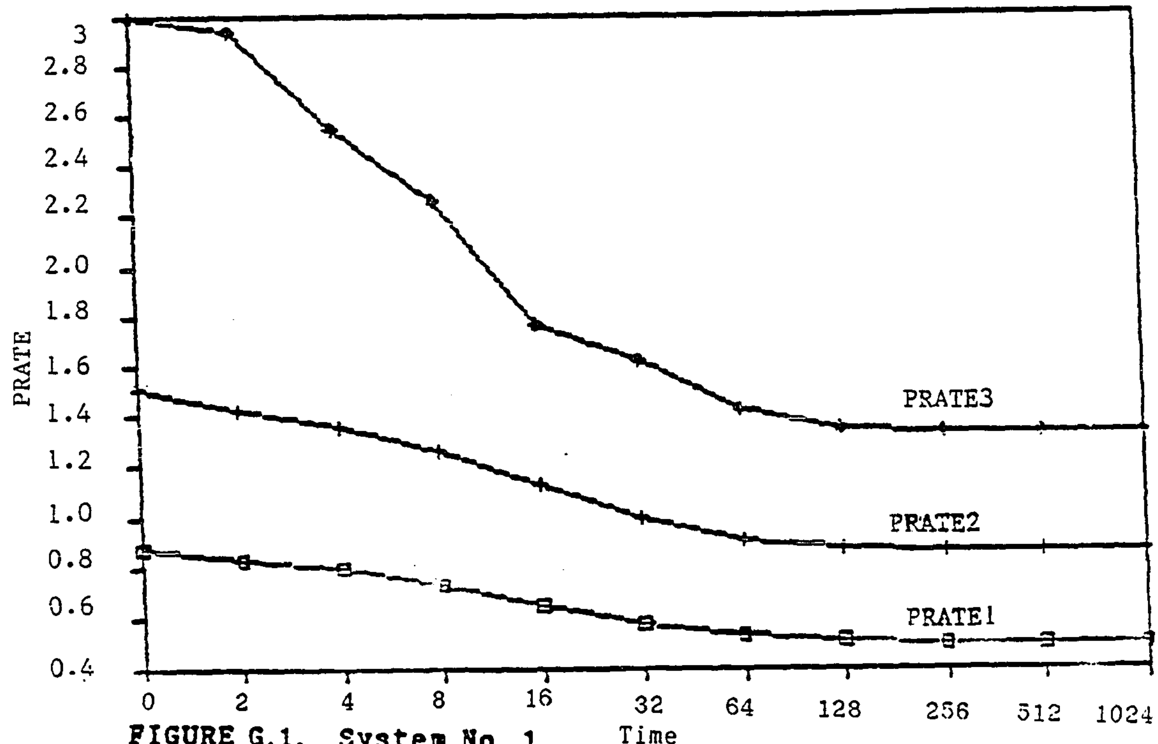

FIGURE G.1. System No. 1

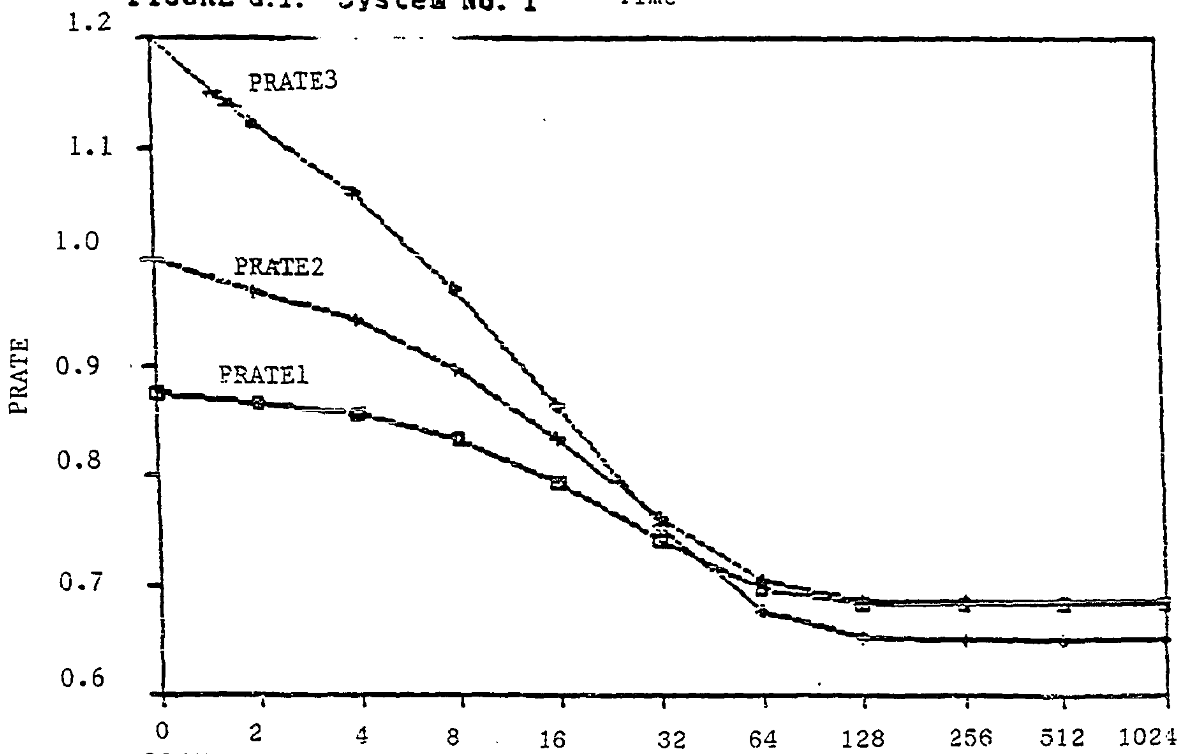

FIGURE G.2. System No. 2

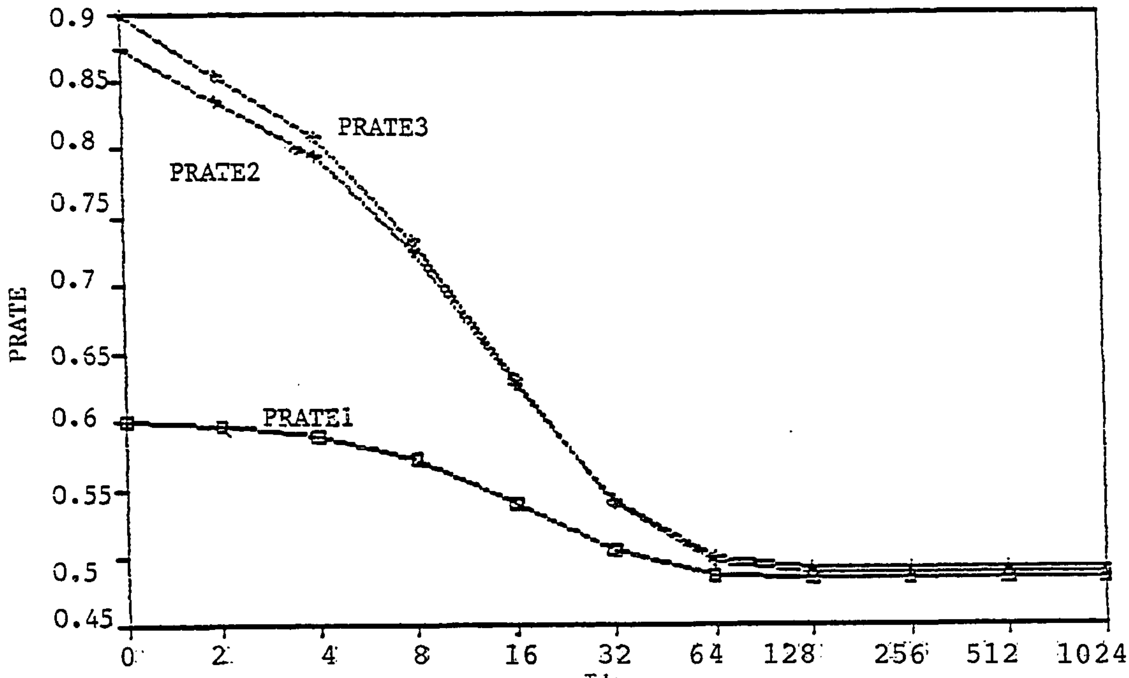

FIGURE G.3. System No. 3

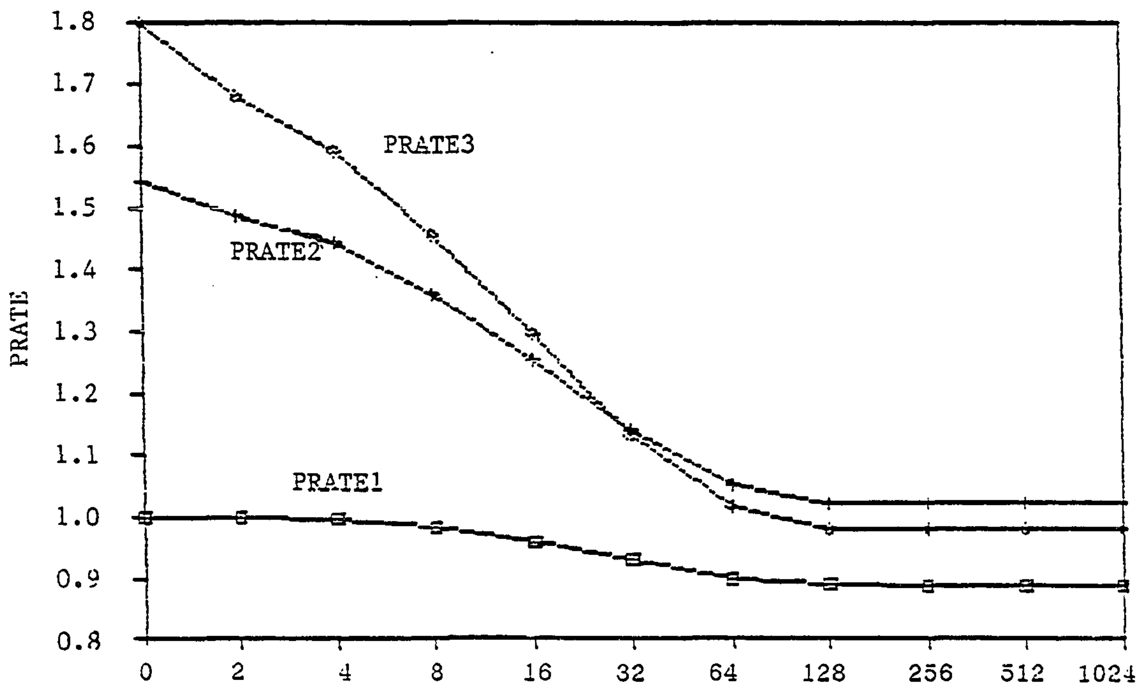

FIGURE G.4. System No. 4

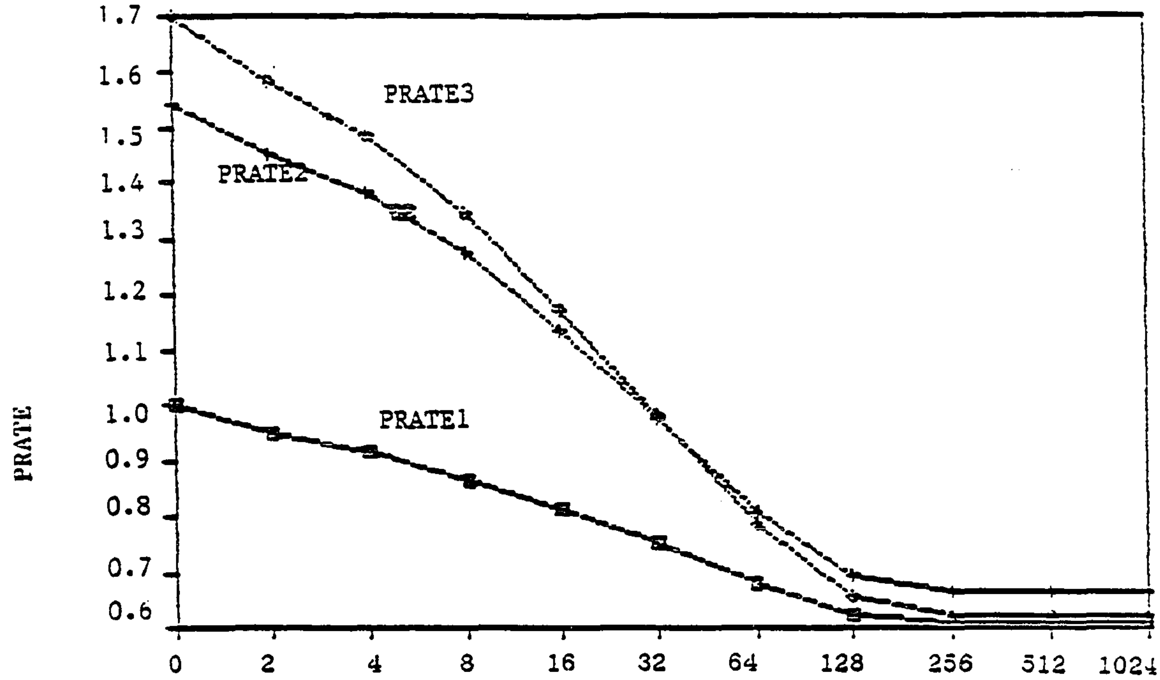

FIGURE G.5. System No. 5

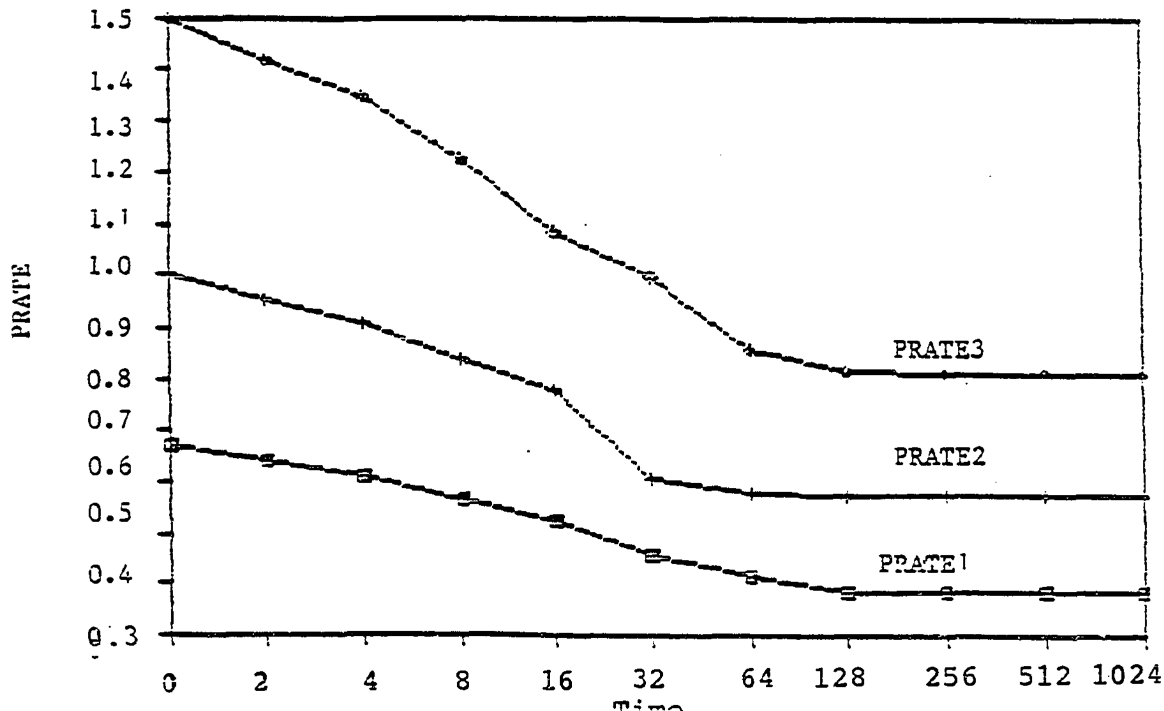

FIGURE G.6. System No. 6

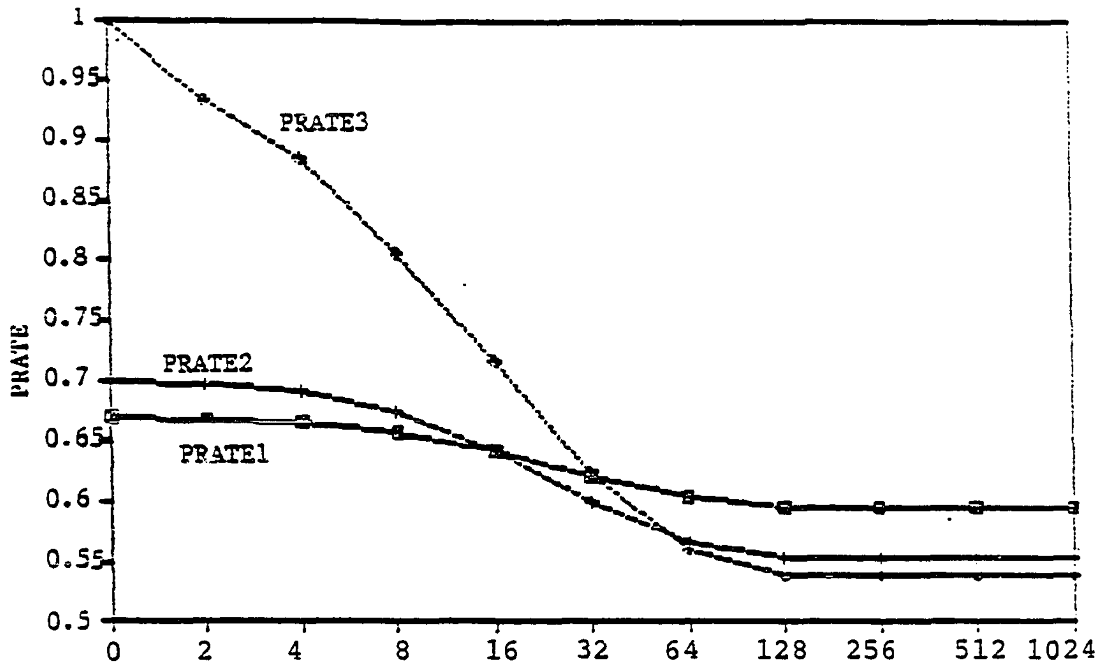

FIGURE G.7. System No. 7

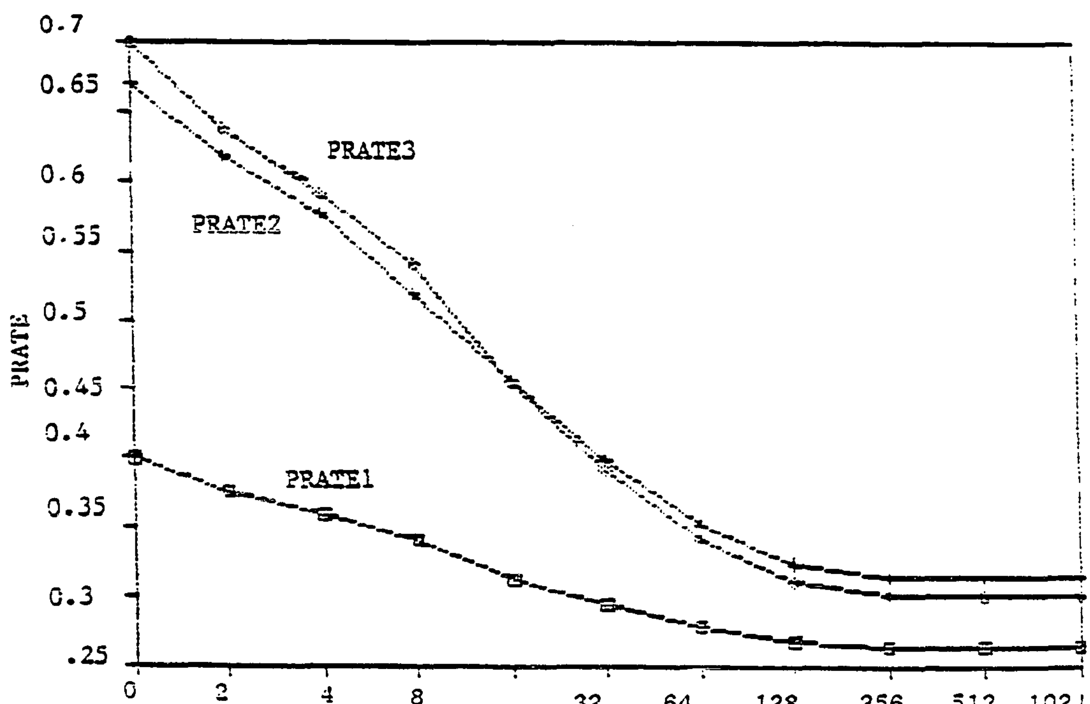

FIGURE G.8. System No. 8

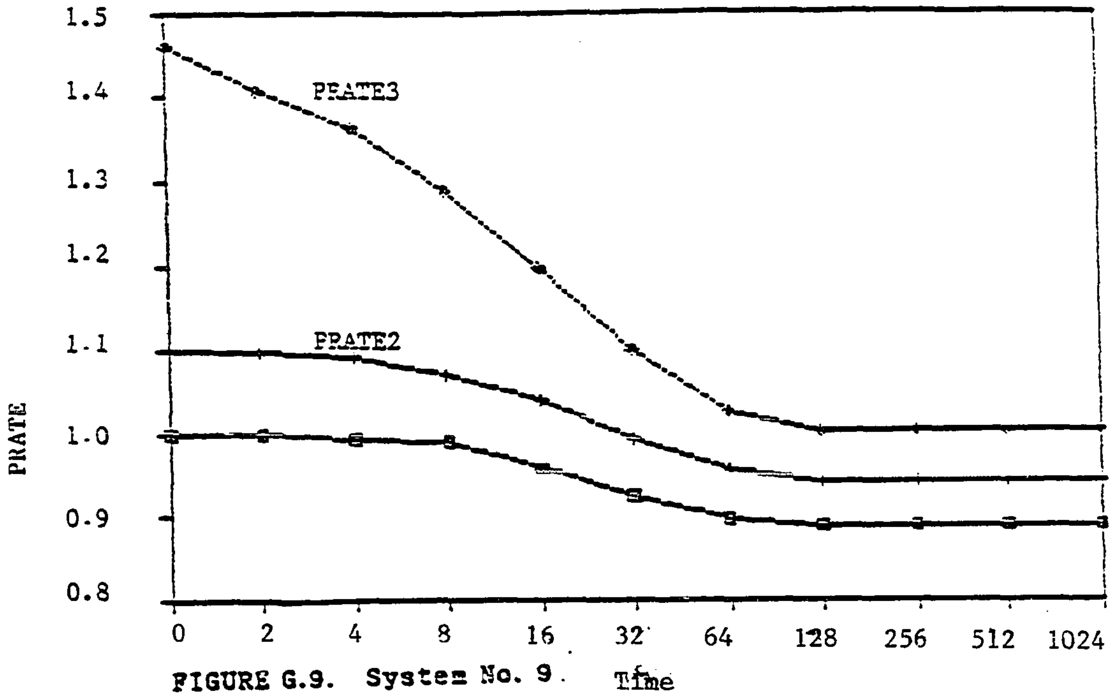

FIGURE G.9. System No. 9

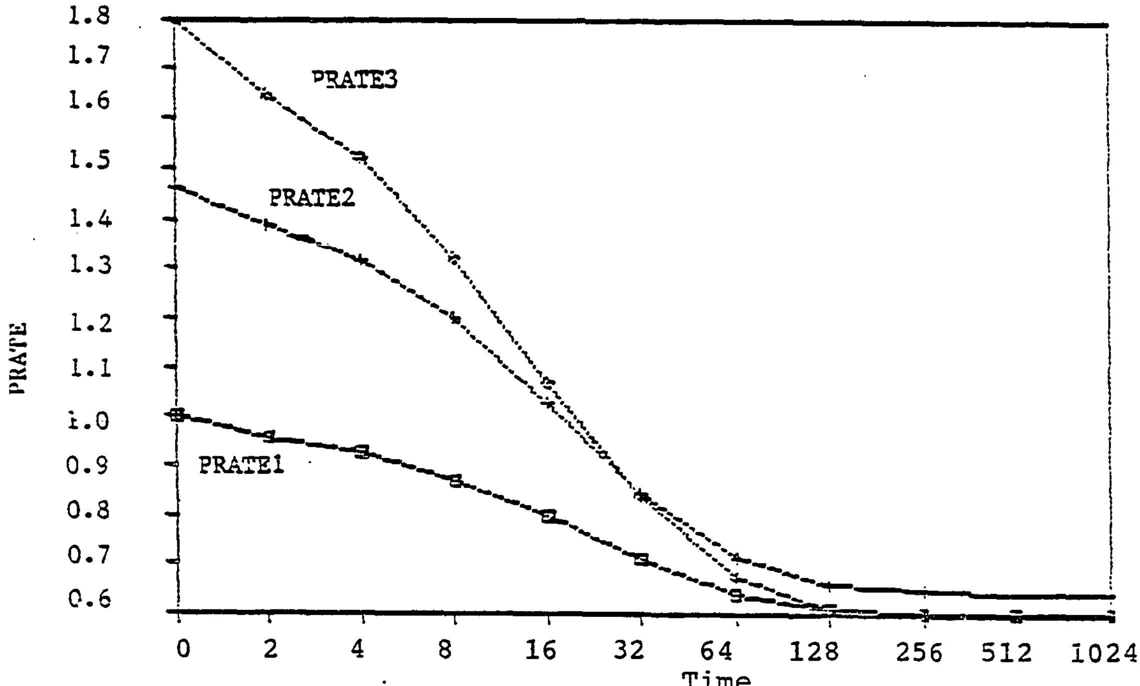

FIGURE G.10. System No. 10

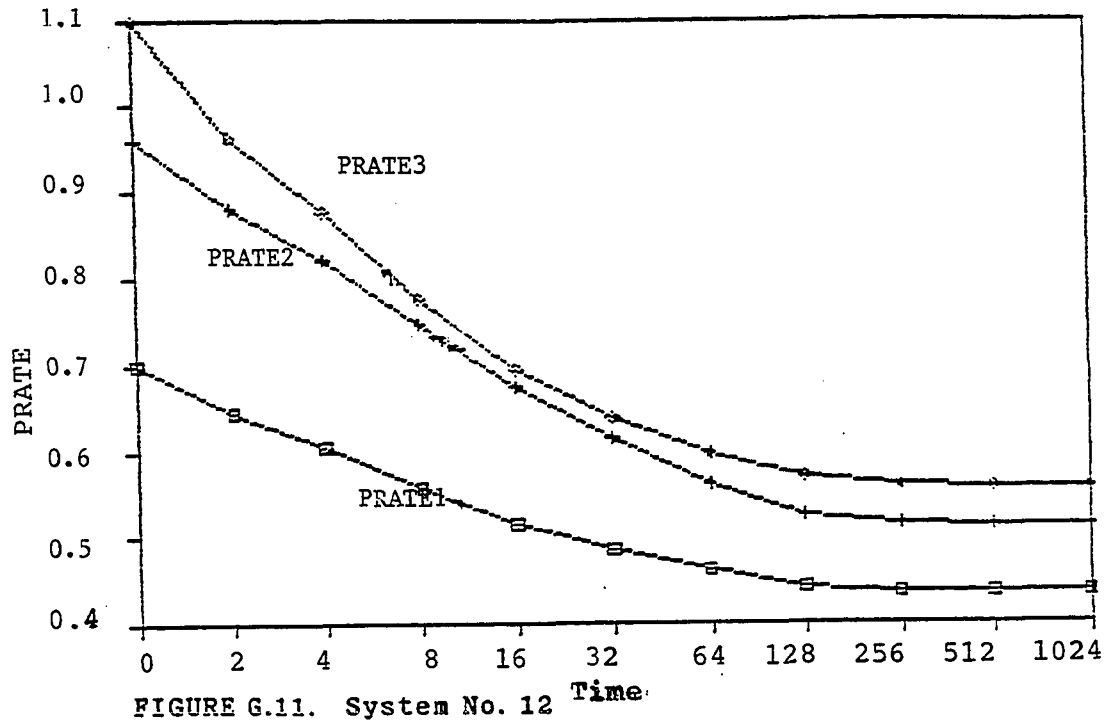

FIGURE G.11. System No. 12

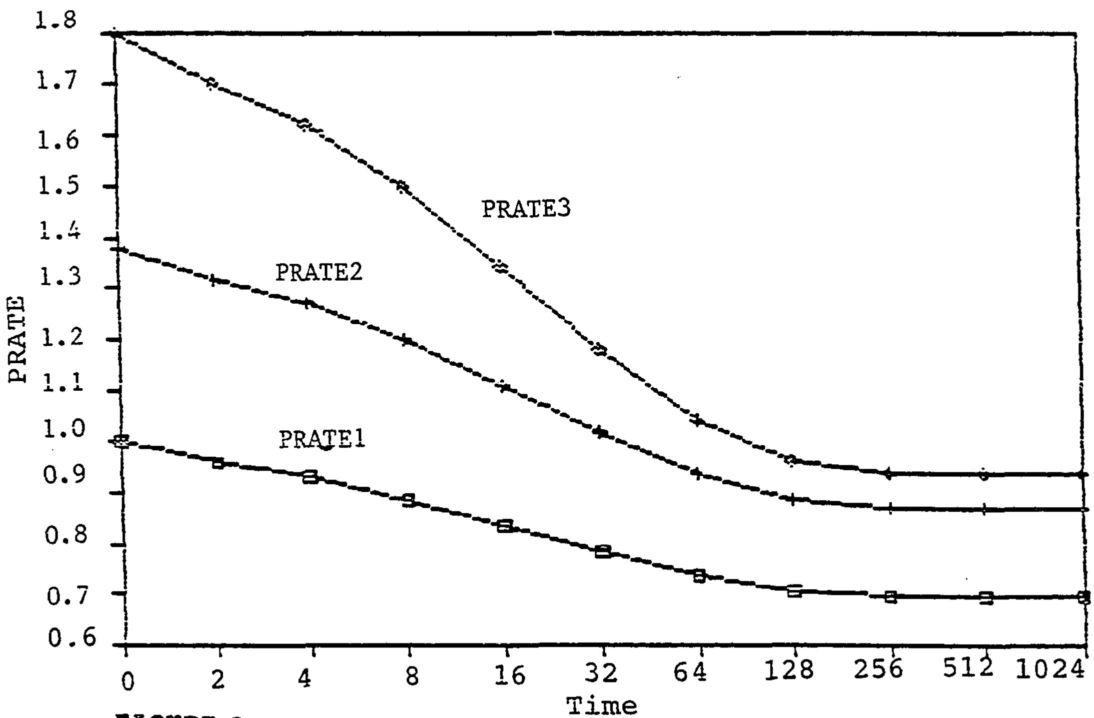

FIGURE G.12. System No. 13

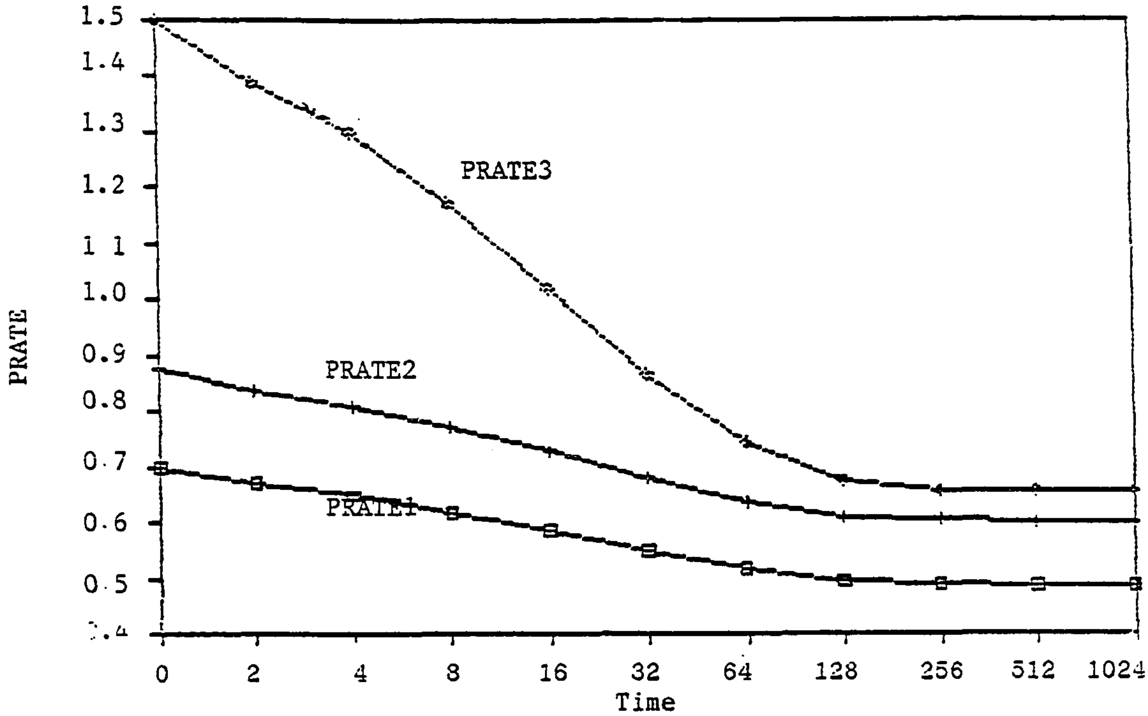

FIGURE G.13. System No. 14