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INVESTIGATION OF LARGE SCALE
MULTI-ECHELON SERVICE SYSTEMS

By

A. William Richardson
Faculty of Business
McMaster University

and

Abraham Mehrez
Department of Industrial
Engineering and Management
Ben Gurion University
Beer Sheeva, Israel

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McMASTER UNIVERSITY

1280 Main Street West
Hamilton, Ontario, Canada L8S 4M4
Telephone (416) 525-9140

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A. William Richardson¹ and Abraham Mehrez²

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- (1) Faculty of Business, McMaster University
Hamilton, Ontario, Canada
- (2) Faculty of Business, McMaster University
Hamilton, Ontario, Canada and
Department of Industrial Engineering and Management
Ben Gurion University, Beer Sheeva, Israel

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[RPRSYST5]

ABSTRACT

There exist many instances of large scale systems composed of a number of operational units each having a number of stand alone operating machines experiencing periodic breakdowns. Within this category of systems, there are some which experience relatively severe operating conditions and a high level of utilization, and so have a high demand for maintenance. Studies are required to facilitate the development of managerial policies for the design and operation of such systems. Past work in the operations management and operations research literature has used many restrictive assumptions in order to make optimization studies of these systems feasible. Unfortunately, this has lead to results which are often limited in their applicability. In this paper, simulation analysis is used to investigate the impact of various policies in such systems with a view to testing certain observed practices and intuitively appealing heuristic decision rules, in order to provide some guidance for actual decisions. In particular, the interdependent policies for operating machine replacement, transportation, distribution and maintenance are investigated for a number of different system structures. The analysis leads to some results that agree with intuition and others that do not.

1. INTRODUCTION

The design and use of large scale private and public systems composed of operational units, each have many stand alone machines, and maintenance units involves many managerial decisions. These decisions are concerned, for example, with determining the size of operational units and the capacity of maintenance units, setting operational and maintenance priorities and establishing machine replacement and transportation policies. The elements of these systems are physically and managerially coupled, and a limited information system frequently leads to a restricted decision perspective. The problems and policies relevant to individual issues under different settings have been extensively dealt with in the operations management and operations research literature, e.g. maintenance and replacement policies by Muinzabel and Lee (1986), and inventory issues by Silver (1981) and Wagner (1980). The traditional approach has been to deal with this subject from an optimization point of view. However, the complexity of integrating all these policies into one large scale decision model has necessitated restrictive assumptions, resulting in very narrow analyses. Although some optimal rules can be constructed for individual cases, an applicable and easily understood integrative decision model incorporating all the above elements is lacking.

In light of these limitations, we adopt a different approach here. Rather than using restrictive assumptions to study the underlying process as a stochastic system where optimization of the system is feasible [see, for example, Masayuki (1985) and Mehrez (1985)], we employ simulation analysis to examine a more realistic system for relevant organizational structures

and related assumptions. In this way, we can evaluate the impact of various policies on different long run criteria of system performance.

This paper adopts the approach utilized by Finger and Mehrez (1985) who analyzed maintenance policies by using a simulation approach. This paper extends the previous analysis to focus on the system's interdependencies. The purpose of this paper is two-fold. The first is to provide a better understanding of an operational maintenance system structure. The second is to examine the validity of certain intuitively appealing hypotheses about how decisions should be made for such systems.

The paper is organized as follows. In the next section, we describe the basic system model and discuss the various factors that will be examined in this paper. In the third section, we examine the impact of a limited set of decision policies on a simple system consisting of a single operational unit having a number of operating machines and a single repair shop of unlimited capacity. In the fourth section, we extend the analysis to systems with a number of operational units, each having a number of operating machines, but only a single repair shop with a limited capacity. This allows examination of a wider set of policies. We further extend the analysis by considering two aspects of repair logistics. Two specific policies for transporting failed/repaired machines between operational units and the repair shop and two specific policies for distributing repaired machines from the repair shop to the operational units are examined. In the fifth section, we examine the effects of limited machine life and replacement policies by allowing for machines of different ages and differing mixes of machine ages. We also allow failure rates to vary with the age of the machines in the operational units. Finally, we present our conclusions and discuss future research directions.

2. THE SYSTEM MODEL

2.1 System Components

Figure 1 gives a simplified schematic structure of the interdependent elements for the system under study. The system that we consider here has a fixed number N of operational units and a single repair shop. Each operational unit has a fixed number K of identical machines which operate independently as required to provide a single service or output. The operational units are located at different nodes of a network (e.g. a star configuration). For a given system size (i.e. a fixed total number of machines), the number of operational units (i.e. the number of nodes in the network) may vary.

As seen in the following discussion, we must choose particular values of the system parameters for our simulation analysis. We do not take an exhaustive or optimizing approach in our choices. Rather, we choose reasonable values for the parameters based on the type of system and our observations of practice. This allows us to evaluate the effect on system performance of changes in system parameters from reasonable operating values.

2.2 Machine Replacement Policies

We consider the impact of two major aspects of replacement policies in this analysis. One aspect is the lifetime L of the machines in the system while the second aspect is their age distribution D . Clearly, the particular machine replacement policies adopted will impact upon other system policies discussed below. In addition, the capital cost of machine acquisition and the cost of maintenance over the long run vary inversely as

the machine replacement policies are altered. We consider first machines with unlimited lifetime for simplicity. Then, for illustrative purposes, machines with either a 3 or 4 year life (which are not unrealistic for a type of system under consideration) are considered to examine the effect of machine life. We consider both the homogeneous case, where all machines are of the same age and are replaced at the same time, and the uniform case, where the machines are uniformly distributed over age and an equal number is replaced each year.

2.3 Logistic Policies

A major logistic issue relates to when to transport failed/repaired machines between an operational unit and the repair shop. Clearly, decisions on this issue depend upon the machine replacement policy decisions discussed above. For example, a more intensive machine replacement policy may be used with a less frequent transportation policy to provide an expected level of output or service. We denote the time interval between these shipments ΔT . We consider a fixed time policy, where failed machines are sent for repair and repaired machines are returned at predetermined fixed intervals, and a variable time policy, where machines are transported at an interval depending upon a specified minimum inventory level of operating machines for the operational units. For the latter policy, the minimum inventory level is specified as $\gamma * K$, where γ is the minimum fraction of the original number of machines in the operational units that are required to be in operating condition.

2.4 System Demand Characteristics

A major determinant of the level of maintenance services used in the system is the demand put upon the machines in the operational units. We consider two distributions for illustrative purposes to capture the demand requirements for output in each operational unit. The first is a normal distribution with mean $\alpha \cdot \Delta T \cdot K$ and standard deviation $(\alpha \cdot \Delta T \cdot K)/2$, truncated symmetrically at $0.2 \cdot \alpha \cdot \Delta T \cdot K$ and $1.8 \cdot \alpha \cdot \Delta T \cdot K$. The parameter α is a measure of both the intensity and variability of demand on the system. The second is a uniform distribution over the same range, i.e. with the same mean and upper and lower limits. We choose these two distributions to investigate any sensitivity of the results of our analysis to the form of the distribution.

2.5 Machine Breakdown Characteristics

Each machine in the operational units is assumed to fail periodically due to random machine breakdowns. We assume deterioration of reliability due to aging, leading to an increased expected failure rate for older machines. We assume that the stochastic behaviour of random machine breakdowns, which will vary depending upon the particular type of machines in the system, follows an exponential machine failure distribution with a constant hazard rate λ . The parameter $1/\lambda$ is fixed at 3 or 4 weeks in some analyses, and is allowed to be 1, 2, 3, or 4 weeks, depending upon machine age, in others. These values of $1/\lambda$ reflect a situation in which there is a significant demand for maintenance, as would be observed for machines operating under relatively severe conditions.

2.6 Repair Shop Characteristics

Repair shop characteristics such as the inventory of repair parts and the ability of the technical staff are also decision variables in the system. We represent these in a simplified way by specifying the capacity of the repair shop in a given time period in terms of a parameter β which is a fraction of the expected number of failures in the period ΔT . We examine the effect of different capacity levels of the repair shop for alternative machine replacement and logistic policies.

2.7 Machine Distribution Policies

Various policies for distributing repaired machines among the operational units could be adopted depending upon the service priorities and the degree of system decentralization. For simplicity, we consider only first-in-first-out (FIFO) service in the repair shop with two types of distribution policies. In the first policy, each machine is sent back to its originating operational unit after repair, i.e. individual operational units effectively maintain ownership of machines. We call this a disbalanced policy. In the second policy, the objective is to maintain, to the extent possible, the same number of operating machines in each operational unit in any time period. Thus, repaired machines are distributed to operational units not according to where the machine originated but to bring each unit to approximately the same operational capacity. We call this a balanced policy.

The time to transport a machine between the operational unit and the repair shop is assumed throughout to be negligible and so to have no effect on system performance. The effect of distribution policy on the overall system performance is unclear and is one of the main research focuses of

this paper. Our initial expectation is that the balanced policy, which provides a reasonably uniform operational capacity throughout the system, will lead to a more efficient use of system resources.

2.8 Summary

The system model described above has at least twelve parameters which can be varied. For practicality, we have selected a number of cases to be studied, based on our expectation of which factors are likely to be important in practice. These cases are summarized in Table 1 and discussed in the following sections of the paper. The values of the system parameters were determined to capture its performance within a reasonable range.

The results of all analyses reported in this paper are based on simulations that were run on a VAX 11/785 computer using programs written in PASCAL.

3. A ONE UNIT SYSTEM

First we consider a very simple system under simple operating policies. The system consists of a single operational unit ($N = 1$) with K machines of unlimited life and a single repair shop. The number of machines K in the operational unit is allowed to take the values 50, 100 and 200. The time period ΔT between two successive shipments of machines to/from the repair shop is fixed at either 1 or 2 weeks. We assume that the time to repair each failed machine is certain and less than T , and that the capacity of the repair shop is sufficiently large to handle all failures in each period. Thus, the repair shop is not a constraint in this simple system. Because there is only one operational unit, the question of machine distribution policy is not relevant.

The truncated normal distribution with the demand parameter α set equal to either 0.6 or 0.8 was used. The former value of α reflects a system operating under a reasonable demand level, while the latter value of α reflects a high demand level with some provision for spare capacity. The demand on the machines of the operational unit for a fixed period ΔT is captured by a random variable X . For simplicity, we deal with the case where the random variable X is observed at the beginning of each period ΔT . Given our assumptions about the repair shop capacity, all machines are available at the beginning of each period and will operate in the period ΔT until the minimum of the failure time and ΔT . Formally, we define the operational time of the machine ($i = 1, \dots, K$) in a given period ΔT by $Z_i = \text{Min}(t_i, \Delta T)$ where t_i is drawn from the assumed exponential failure distribution with a constant hazard rate. The exponential failure distribution has a mean $1/\lambda$ of either 3 or 4 weeks which is independent of

the age of the machines. The total operating time of the unit in a period

ΔT is thus given by $V = \text{Min}(\sum_{i=1}^K Z_i, X)$.

A measure of the unit's performance in a given period ΔT is given by $R = V/X$, where R is a random variable with possible outcomes in the range $[0,1]$. Although analytical expressions for the distribution of R could be numerically computed, we prefer to simulate the distribution of R . Results were obtained by simulating 100 periods for each of the 24 experimental cases which resulted from the possible combinations of K (3), ΔT (2), $1/\lambda$ (2) and α (2) specified above.

The cases that we studied for this single unit system have shown that the distribution of R is generally neither unimodal nor symmetric. The distribution of R is at least bimodal with one peak always at $R = 1$ and another at some value of $R < 1$, with the former peak larger in some cases and the latter peak larger in others. Further, the conditional distribution of R for $R < 1$ is, by and large, skewed to the right. We present in Figures 2 and 3 the results for two cases to illustrate the above observations and to provide empirical support for our use of non-analytical computations. Figures 2 and 3 show that the mode with a higher peak is at an intermediate value of R (i.e. $R < 1$) for the latter case and at $R = 1$ for the former case.

Figures 4, 5 and 6 show the results for $K = 50, 100, 200$, respectively, for fixed values of $\Delta T = 2$, $1/\lambda = 3$, and $\alpha = 0.6$. Figures 7, 8 and 9 present the results for $K = 50, 100, 200$, respectively, for fixed values of $\Delta T = 1$, $1/\lambda = 4$, and $\alpha = 0.8$. These data indicate, as expected intuitively, that $\bar{R}$, the mean of R over the 100 periods ΔT simulated, decreases as the values of ΔT , $1/\lambda$ and α increase. The effect on $\bar{R}$ of increasing K is not

clear. The size of the operational units affects the shape of the distribution of R even through the value of α is kept constant. These two sets of figures do not show a monotonic relationship between the size of the operational unit (i.e. the value of K) and R . Therefore, no general conclusions as to the existence of economies or diseconomies of scale can be made.

It is important to note that, in our analysis, we are dealing with the case for which the demand on the operational units is known at the beginning of each period. The results for this case provide an upper bound for $E(R)$, the expected value of R , as compared to cases where the demand is known only after the start of the period. This result holds because we are dealing with the situation of perfect information, which is also easier to deal with, rather than a situation of imperfect information.

The one unit system treated here represents a first stage in terms of the complexity of the system. The batch demand case that is treated here may arise, for example, in public or private service sectors in which the demand is known at the beginning of each period. The main conclusion regarding the simple one unit system is the non-symmetric and at least bimodal nature of the distribution of R under long run conditions. Additional complexity could be introduced into this case if we were to assume that the demand is unknown at the beginning of the period or to employ a non-exponential failure distribution. These situations would lead conditions where setting priorities as to which machines should operate and when becomes necessary.

4. A MULTIPLE UNIT SYSTEM

4.1 Limited Repair Shop Capacity

The components, environment and parameters assumed for this system are basically the same as for the single unit system considered in the preceding section. As before, shipments of machines are made to or from operational units at fixed time periods ΔT of 1 or 2 weeks. We employ the same exponential failure distribution with mean $1/\lambda$ equal to either 3 or 4 weeks, independent of the age of the machines. there is again a single repair shop where machines are repaired on a FIFO basis. We maintain the assumptions that the time to repair a machine is less than ΔT and the transportation time is negligible. We employ the disbalanced machine distribution policy here.

We have made three changes in order to determine their impact upon the system. One change is that we allow for more than one operational unit by considering $N = 8$ operational units each having $K = 100$ machines of unlimited lifetime. These values of N and K provide for a system of reasonable size for the types of policy and operating decisions of interest here. The demand distribution for each operational unit is the same truncated normal distribution described before; but we consider only the case for the parameter α equal to 0.6. The most significant change is that the capacity of the repair shop is no longer unlimited, but is set equal to $\beta * N * K * \lambda$. Given the exponential failure distribution, the expected number of failed machines in a given period is $N * K * \lambda$. The parameter β , therefore, sets the capacity of the repair shop at some fraction of the expected number of failures and was allowed to take the values 0.4, 0.6, 0.8 and 1.0.

We simulated the system for 100 periods ΔT for the 16 possible cases resulting from the assumed values of ΔT (2), $1/\lambda$ (2) and β (4) specified above. The performance of each operational unit for each period ΔT can be characterized by the mean value $\bar{R}$, in the same way as for the one unit system considered earlier. The performance of the total system for each period ΔT is then summarized by the mean value of the variable $\bar{R}$ calculated for each operational unit.

Figures 10-13 show the distributions for $\beta = 0.4, 0.6, 0.8$ and 1.0 , respectively, for $N = 8$, $K = 100$, $\Delta T = 1$, $1/\lambda = 3$ and $\alpha = 0.6$, which are representative of the results obtained. For all 16 cases examined, the distribution of $\bar{R}$ is unimodal with varying degrees of asymmetry, and the average value of $\bar{R}$ is significantly less than the maximum value of 1. The latter observations differ from those in the preceding section and presumably result, as expected intuitively, because of the averaging of the performance of the 8 operational units.

For each set of 4 cases where β is varied from 0.4 to 1.0 while the other parameters are held constant, the average value of $\bar{R}$ increases but there is a decreasing marginal response to β . These results are in accord with intuition. Comparison of the four cases where β is held constant shows that the average value of $\bar{R}$ are similar but are clearly not the same.

For each set of 8 cases where ΔT increases from 1 to 2, the average value of $\bar{R}$ decreases as expected intuitively. For each set of 8 cases where $1/\lambda$ increases from 3 to 4, there is no fixed relationship of the average values of $\bar{R}$. It appears that the distribution of $\bar{R}$ shifts to the left for lower values of β and to the right for higher values of β as $1/\lambda$ increases

from 3 to 4. This observation suggests a nontrivial relationship between $\bar{R}$ and the repair shop capacity for different values of $1/\lambda$.

These results indicate a relationship between $\bar{R}$ and the system's parameters. However, they do not indicate the form of the relationship or which parameter values should be employed in practice. Cost/benefit considerations, which have not been addressed here, should also be taken into account in the selection of the system's parameters. It is possible that our system, which belongs to a more general class of Markovian structures, could be analyzed using an alternative interactive decomposition approach, developed by Gross, Kioussis and Miller (1987), to deal with the computational difficulties arising from large scale systems, i.e. those having larger values of N and K .

4.2 Differing Machine Distribution Policies

The assumptions of the preceding subsection for a multiple unit system with limited repair shop capacity are maintained in the following analysis except where changes are specifically identified below. There are $N = 4$ or 8 operational units, each having $K = 50$ or 100 machines of unlimited operating life. The parameter α of the truncated normal distribution for the demand on the system takes the values of 0.6 and 0.8. The mean $1/\lambda$ of the exponential machine failure distribution is fixed at 3 weeks. The repair shop parameter β takes the values 0.4, 0.6, 0.8 and 1.0.

The most significant change in this section is that we allow for variation in the policies for transporting failed/repaired machines between the operational units and the repair shop. The timing of shipment follows one of 2 logistic policies. We consider, as before, shipment at fixed periods ΔT of 1 or 2 weeks. But we also allow for a variable period ΔT

between shipments. For this new policy, shipments are made whenever the number of operating machines in an operational unit falls below a desired number, i.e. there is effectively a reorder point. This is accomplished in the computations by setting the desired minimum number of machines in an operational unit to $\gamma * K$, where the parameter γ was allowed to take various values between 0.3 and 0.9. These values provide for consideration of the range likely to be of practical interest.

The second significant variation of the machine distribution policy relates to which operational unit repaired machines are sent to. Previously, only a disbalanced machine distribution unit from which they were sent. We do computations for this assumption here. But we also allow for a balanced machine distribution policy where the goal is to maintain, to the extent possible, the same number of operating machines in each operational unit. To do this, machines are not necessarily sent back to the originating operational unit but to those operational units needing machines to balance capacity.

There are, therefore, four combinations of logistic and machine distribution policies that were examined. Policy one is a fixed period disbalanced policy, i.e. transportation occurs at fixed intervals with the repaired machine going back to the unit that it came from. Policy two is a fixed period balanced policy, i.e. transportation occurs at fixed intervals with repaired machines distributed to maintain a balanced operational capacity in any period. Policy three is a variable period disbalanced policy while policy four is a variable period balanced policy. Policies three and four differ from policies one and two, respectively, in that shipment occurs whenever the number of operating machines in an operational unit falls below the specified minimum level.

There is a large number of possible cases for combinations of the specified values of N , K , α , $1/\lambda$, β , γ , ΔT and the distribution policy. For practicality, sixteen cases, which we considered would facilitate comparative analysis, were selected for computation. Simulations were done for 100 and 200 periods ΔT for the sixteen selected cases under the four logistic/machine distribution policies described above. In each case, the mean $\bar{R}$ and standard deviation $S_{\bar{R}}$ of the system performance variable $\bar{R}$, calculated as described in the preceding section, were computed for use in comparative analysis. In addition, $\bar{\Delta T}$, the mean value of ΔT , was calculated for the 100 and 200 periods simulated under policies three and four where failed/repaired machines are transported under the variable period logistic policy.

Table 2 provides a comparison of the results obtained for simulations of 100 and 200 periods ΔT for a selection of cases studied for the assumptions described above. Examination of the results obtained for a given set of parameters in the two lengths of simulation shows that the values of R agree quite closely -- well within the values of $S_{\bar{R}}$. This suggests that there has been convergence of results by 100 periods ΔT . In the rest of the paper, we present results for simulations of 200 periods ΔT , which should provide a reliable basis for inferences.

The following observations are based on the data in Table 3. Our intention is not to be exhaustive or to provide statistical tests of the results; we do not attempt to reject hypotheses but rather to determine which are not rejected for some cases that we feel are of particular interest. An analysis of the effect of ΔT is not made, as it is trivial.

Also, no detailed analysis of the effect of γ is possible as the nature of the calculations is such that there are relatively few results for doing so.

We first examine the effects of fixed and variable transportation period policies. The data in columns 3, 12 and 14, for which ΔT and $\Delta \bar{T}$ are close to the same, can be used for this comparison. Although there are not enough results to reach firm conclusions, it appears that the fixed transportation policy leads to superior system performance, at least for specific values of γ . The comparison of policies 1 versus 3 and 2 versus 4 for any length of period ΔT indicates that $\bar{R}$ and $S_{\bar{R}}$ are superior for the fixed policies. Clearly this supports the decision to use fixed rather than variable transportation policies as observed in some real applications. This approach likely leads to improved control and lower costs.

We next examine the system performance under the disbalanced and balanced machine distribution policies. We observe that there is no consistent relationship of the performance of the system for policy 1 compared to 2 shown by the data in Table 3. In fact, different sets of parameters lead to superiority of one policy in some cases and the other policy in others. The same conclusions hold for policies 3 and 4, although policy 3 is better than policy 4 except for the parameters of columns 5 (marginally) and 13 (strongly). In practice, other factors, such as ease and cost of control for the disbalanced machine distribution policy, undoubtedly also support its use. Consequently, decision makers should be motivated to prefer a disbalanced machine distribution policy.

For the cases that we examined, the impact of system size on $\bar{R}$ can be examined for four general cases which are summarized below.

<u>CASE</u>	<u>N</u>	<u>K</u>	<u>N.K</u>
a	Increase	Decrease	Constant
b	Constant	Increase	Increase
c	Increase	Constant	Increase
d	Increase	Increase	Increase

There is some suggestion of different kinds of economies of scale which can be explained in terms of differences in the policies. More specific discussion is given below for policies 1 and 2 only. Policies 3 and 4 are not considered because the nature of the systems is such that the results are not entirely comparable.

(a) An important question for system design is how the number of operational units, for a fixed number of operating machines, affects system performance. We compare the results of column 7 versus 11 to determine the effect of changing N and K simultaneously so as to maintain the product $N \cdot K$, i.e. the total number of operating machines, constant. The performance measure $\bar{R}$ is substantially the same for policies 1, 2 and 4, but differs considerably for policy 3. Therefore, we can not reject the hypothesis that there are some economies of scale due to the size of the operational unit for a fixed total number of machines in the system. On balance, this suggest that the decision as to the distribution of a given number of operating machines over operational units should not affect the level of performance. Thus, other considerations, such as cost-benefit, should be primary in this type of decision.

(b) We compare the results of columns 1 versus 11, 2 versus 12, and 3 versus 9 or 13 (9 and 13 have the same parameters for policies 1 and 2) to determine the effects of changing K while holding N constant. The results

suggest little, if any, economies of scale from doing this. However, there is slightly more impact for policy 2 compared to policy 1, which suggests that the fixed period balanced policy is preferred as the number of operating machines in each operational unit increases.

(c) We compare the results of column 1 versus 7 and 11 versus 14 to determine the effect of changing N while holding K constant. Although the changes are not dramatic, it is interesting to note that $\bar{R}$ decreases for policy 1 but increases for policy 2 as the number of operating machines per operational unit increases. This suggests that a balanced machine distribution policy is preferred if this type of increase is to be made.

(d) We compare the results of columns 1 versus 14 and 5 versus 15 to determine the effect of changing simultaneously N and K . Here, the changes in $\bar{R}$ are more dramatic. As expected from the results of the two preceding general cases, $\bar{R}$ decreases as N and K increase under policy 1 but increases under policy 2. Thus, the general conclusion that policy 2 is preferred as either or both of the number of operational units and operating machines per operational units increase.

A comparison of the results under policies 1 and 2 in columns 1 through 4 and columns 11 through 13 suggests that there are decreasing marginal gains in $\bar{R}$ as β is increased, as expected.

As observed for the single unit system discussed in the preceding section, increasing α causes a decrease in $\bar{R}$. This may be seen by comparing the results in columns 5 versus 6 and 9 versus 10.

Finally, we consider whether the shape of the demand distribution has an effect on the system performance. We carried out simulations for 200 periods ΔT with all parameters the same, except for the demand distribution.

In one set of simulations we used the truncated normal distribution and in the other set, we used the uniform distribution, with distribution parameters set to give the same mean and lower and upper bounds for both distributions. The results show that the shape of the demand distribution has a significant effect on the system's performance.* More specifically, in all cases, $\bar{R}$ is larger for the uniform distribution than for the truncated normal distribution. The reason for this result might be the fact that the tails of the uniform distribution, as computed by the kurtosis measure, are lighter than for the truncated normal distribution. thus, the system appears to perform better for a distribution with a smaller probability of outliers, given that everything else is equal.

* The results for the uniform distribution are not presented here in order to keep the length of the paper down. A copy of the results may be obtained from the authors.

5. A MULTIPLE UNIT SYSTEM WITH LIMITED MACHINE LIFE

In this section, the assumptions of the previous section for a multiple unit system are maintained, as summarized below. We consider $N = 4$ or 8 operational units, each with $K = 50$ or 100 operating machines to start. The demand distribution for the system is the same truncated normal distribution with the parameter α taking the value of 0.6 or 0.8 . The single repair shop has a limited capacity equal to $\beta * N * K * \lambda$ where β is equal to 0.4 , 0.6 , 0.8 or 1.0 . The time to repair a machine is less than the period ΔT and the time to transport a machine between an operational unit and the repair shop is negligible. The four combinations of logistic and machine distribution policies described in the preceding section are considered.

The significant difference here is that we now allow machines to have a limited life. In particular, machines are allowed to have a life of 3 or 4 years. Obviously, there could be different mixes of machine ages given a particular machine operating life. We consider two extremes here, namely, the homogeneous case where all machines are the same age and the uniform case where machines are uniformly distributed over the lifetime. For the former case, all machines are replaced simultaneously every 3 or 4 years according to the machine life. For the latter case, if the machines have a $3(4)$ year life, one third (quarter) of the machines have each of ages $0, 1$ and 2 ($0, 1, 2$ and 3) years at the beginning of each year. At the end of each year, one third (quarter) of the machines reach $3(4)$ years old and are replaced.

We maintain the assumption of an exponential failure rate, but make a significant change by allowing the exponential distribution to vary with machine age. We do this by setting the parameter $1/\lambda$ equal to $3, 2, 1$

(4,3,2,1) weeks for machines of age 0,1,2 (0,1,2,3) years at the beginning of each year, respectively, where the machine life is 3(4) years.

Obviously, very many cases result from the possible combinations of values of the parameters. For practicality, we do computations for a limited set of cases that facilitate comparative analysis. For the fixed period logistic policy we used 13 cases and for the variable period logistic policy we used 30 cases. We did simulations for 200 and 600 periods ΔT and computed the mean and standard deviations of the system performance measure R under each of the four policies. We also calculated the mean $\Delta \bar{T}$ for the variable period logistic policy cases.

The results of the simulations of 200 periods ΔT are presented in Table 4A through 4D for policies 1 through 4, respectively. The results for simulations of 600 periods ΔT are substantially the same.

There are a number of observations that are substantially the same for all four policies. We discuss these first. Comparison of the results in columns 1 versus 9 and 7 versus 11 in Table 4A and 4B and in columns 1 versus 21, 2 versus 22 and 3 versus 23 in Tables 4C and 4D all suggest that there is no major change in $\bar{R}$ as N changes. There are some general trends but these are not significant given the observed standard deviations of the calculations. Similarly, comparison of the results in columns 1 versus 7 and 9 versus 11 in Tables 4A and 4B and in columns 8 versus 12 and 9 versus 13 in Tables 4C and 4D shown mixed changes in $\bar{R}$ as K changes, but they are generally not significant.

Comparison of the results in columns 5 versus 6 of Tables 4A and 4B and in columns 12 versus 15, 13 versus 16 and 14 versus 17 shows a substantial decrease in $\bar{R}$ as α increases. This is consistent with intuitive

expectations and the results presented in earlier Tables. Comparison of the results in columns 1 versus 4, 7 versus 8 and 12 versus 13 of Tables 4A and 4B and in columns 1 versus 5, 2 versus 6, 3 versus 7 and 4 versus 8 shown that $\bar{R}$ increases, but with a decreasing marginal effect, as β increases. This is again consistent with intuitive expectations and previously presented results.

We find that there appears to be little significant effect upon $\bar{R}$ as the value of γ , the parameter that controls the level of operating machines under the variable logistic policy, is changed. It is not surprising intuitively that this has little effect on the performance of the system. However, it should be noted that there will undoubtedly be significant effects on the costs of the system, which have been ignored here, and so this is likely to be a significant decision variable in a broader analysis.

For the homogeneous mix of machine lives, we find no consistent reaction of $\bar{R}$ to changes in the machine life for either fixed or variable logistic periods ;and disbalanced or balanced machine distribution policies. This contrasts with the observations for a uniform mix of machine lives where $\bar{R}$ generally decreases by a significant amount as machine life is increased. A comparison of the results for the homogeneous and uniform mix of machine lives, where all other parameters are the same, shows no clear reaction of $\bar{R}$.

Finally, there appears to be no consistent reaction of $\bar{R}$ to a change from policy 1 to 2 or from policy 3 to 4 when other parameters are held constant.

6. CONCLUSIONS

The management of large scale multi-echelon service systems is a difficult task in practice. At both the design and use levels, managers evaluate policies ;and decision by employing simulations and heuristic techniques rather than large scale optimization models. Several reasons lead to this approach: the complexity of the system, the complexity and dynamic nature of the decision making process, the lack of relevant data and the lack of optimization models that are easy to implement. We have observed that, due to the reasons presented above, real world systems are, by and large, planned and controlled according to the manager's experience and perceptions which may be supported by non-analytical approaches. This is true even for relatively simple systems having stand alone machines, a single maintenance centre and a stationary demand. The determinants of the number, location and size of operational units, the capacity of the maintenance centre, machine replacement policies, inventory levels, transportation and distribution policies can not be integrated for the above mentioned systems in the framework of a single solvable large scale optimization model. The search for satisfactory solutions is required but, in some instances, it may lead to mis-specification of policies and decisions. For example, the manager may adopt the so-called policy 1 instead of policies 2, 3 or 4, or he may decide on a less intensive replacement policy and, at the same time, on a smaller maintenance centre. Our study has illustrated the nontriviality of such errors. Namely, it is very difficult, if at all possible, to predict the appropriate policies or to compare their values independent of the system's structure and parameters. for the convenience of the reader, we illustrate these conclusions by restating a few results:

- (a) For a one unit system, the distribution of R is neither unimodal nor symmetric. Thus any analysis that depends upon the normality assumption may be wrong in spite of the scale of the system.
- (b) No general conclusions as to the existence of economies of diseconomies of scale (i.e. the relationship between $\bar{R}$ and K) can be made for a one unit system even though the mean demand per machine is preserved.
- (c) Fixed transportation period policies, which are observed in practice, are not necessarily inferior relative to variable transportation period policies. (The authors observed, but questioned the desirability of, the use of fixed policies in real world systems.)
- (d) Disbalanced policies are not necessarily inferior relative to balanced policies. The remarks made in (c) still hold here.
- (e) The shape of the demand distribution affects the mean of $\bar{R}$. For example, it was found that $\bar{R}$ is negatively related to the kurtosis measure (see the results on the uniform distribution). This observation emphasizes the inappropriateness of decisions based only on the first two moments of the demand distributions.
- (f) Some evidence for economies of scale due to the size of the operational unit were observed. However, the determination of the degree of a system's decentralization based on the number and size of the operational units is not entirely clear. Actually, this type of economy of scale depends on the amount of uncertainties which are reduced by structuring the system, N and K in a desirable way. Here, we conclude that the results shed light on the complexity of this issue.

- (g) Replacement policies and the age distribution of machines in the system (homogeneous versus uniform) are related. This observation clearly indicates that a micro replacement policy which does not take into account macro or aggregated factors such as the age distribution of machines might be misleading.

The above observations as well as other observations do not lead to definite answers. It is obvious that further research in the following directions should be conducted to strengthen the conclusions of this paper:

- (1) Analyses based on different measures of performance which take into account cost and benefit considerations.
- (2) Investigation of other systems which allow, for example, for non-stand alone machines, multiple outputs, nonstationary demand, a multiple unit maintenance subsystem, a hierarchical multi-echelon operational system, a non-negligible transportation time, a more detailed inventory system for parts, the determination of maintenance service time, alternative assumptions regarding machine failure and demand distributions
- (3) Study of alternative logistic policies.
- (4) Relation of the study to analytically known results which are incorporated within the framework of optimization models.
- (5) Evaluation, via simulation models and statistical studies, of the decomposition of the total costs of a system with relationship to maintenance, replacement and transportation costs.
- (6) Consideration of the development of a taxonomy of systems with models classification to support the decision making model.

Finally, we note that the motivation for this study was provided by an observation made by the authors into the decision making process of a multi-echelon military system composed of a number of operational units each

having communication equipment. For different types of systems, see, for example, Hausman and Scuddek (1982) and references therein. These authors dealt with a system which repairs and provides parts for jet engines for commercial and military aircraft. Their description of the problems does not deviate significantly from ours although the nature of their study is significantly different.

Table 1

Summary of Cases Considered

<u>Parameters</u>		<u>Section</u>			
	<u>3</u>	<u>4.1</u>	<u>4.2</u>	<u>5</u>	
<u>1. Operational Units</u>					
N	1	8	4,8	4,8	
<u>2. Machines per Operational Unit</u>					
K	50,100,200	100	50,100	50,100	
<u>3. Machine Lifetime L</u>					
Unlimited	x	x	x		
Limited					x(3,4 years)
<u>4. Machine Age Mix D</u>					
Homogeneous	x	x	x	x	
Uniform				x	
<u>5. Transportation Period ΔT</u>					
Fixed	1,2 weeks	1,2 weeks	1,2 weeks	1,2 weeks	
Variable			x	x	
<u>6. Minimum Fraction of Operating Machines γ</u>					
	N/A	N/A	0.3-0.9	?	
<u>7. Demand Distribution α</u>					
	0.6, 0.8	0.6	0.6, 0.8	0.6, 0.8	
<u>8. Machine Breakdown $1/\lambda$</u>					
	3,4 weeks	3,4 weeks	3 weeks	1-4 weeks (age determined)	
<u>9. Repair Shop Capacity β</u>					
	N/A	0.4-1.	0.4-1	0.4-1	
<u>10. Machine Distribution Policy</u>					
Disbalanced	x	x	x	x	
Balanced			x	x	

Table 2

Comparison of Results for Simulations
of 100 and 200 Periods ΔT for
The Multiple Unit System For Different
Logistic and Machine Distribution Policies

Parameters

N	8	8	4	4
K	100	100	100	100
α	0.6	0.6	0.8	0.8
$1/\lambda$	3	3	3	3
β (2)	0.4	0.4	0.6	0.6
ΔT	1	1	1	1
γ (3)	0.9	0.9	0.7	0.7
Periods	100	200	100	200

OutputPolicy⁽⁴⁾

1	$\bar{R}$	0.3994	0.3917	0.5042	0.5068
	$S_{\bar{R}}$	0.1007	0.0821	0.1389	0.1344
2	$\bar{R}$	0.4481	0.4251	0.4782	0.4666
	$S_{\bar{R}}$	0.1070	0.0975	0.1443	0.1381
<hr/>					
3	$\bar{R}$	0.4372	0.4278	0.5052	0.5000
	$S_{\bar{R}}$	0.0793	0.0835	0.1230	0.1832
4	$\bar{R}$	0.4128	0.4039	0.4892	0.4739
	$S_{\bar{R}}$	0.0723	0.1005	0.1138	0.1212

1. Results are given for only a representative sample of 100 and 200 ΔT simulations.
2. Applicable for policies 1 and 2 only.
3. Applicable for policies 3 and 4 only.
4. Policy Number Logistic Policy Machine Distribution Policy

1	Fixed ΔT	Disbalanced
2	Fixed ΔT	Balanced
3	Variable ΔT	Disbalanced
4	Variable ΔT	Balanced

Table 2(continued)

Comparison of Results for Simulations
of 100 and 200 Periods ΔT for
The Multiple Unit System For Different
Logistic and Machine Distribution Policies (1)

Parameters

N	8	8	4	4
K	50	50	50	50
α	0.6	0.6	0.6	0.6
$1/\lambda$	3	3	3	3
β	0.8	0.8	0.4	0.4
$\Delta T^{(2)}$	1	1	1	1
$\gamma^{(3)}$	0.7	0.7	0.5	0.5
Periods	100	200	100	200

OutputPolicy (4)

1	$\bar{R}$	0.6142	0.6267	0.4259	0.4286
	$S_{\bar{R}}$	0.0936	0.0820	0.1259	0.1200
2	$\bar{R}$	0.5886	0.5734	0.4115	0.3952
	$S_{\bar{R}}$	0.0902	0.0953	0.1580	0.1356
<hr/>					
3	$\bar{R}$	0.4137	0.4095	0.4137	0.4050
	$S_{\bar{R}}$	0.0831	0.0900	0.1437	0.1724
4	$\bar{R}$	0.4013	0.3937	0.3837	0.3724
	$S_{\bar{R}}$	0.0738	0.0769	0.1387	0.1428

1. Results are given for only a representative sample of 100 and 200 period ΔT simulations.
2. Applicable for policies 1 and 2 only.
3. Applicable for policies 3 and 4 only.
4.

<u>Policy Number</u>	<u>Logistic Policy</u>	<u>Machine Distribution Policy</u>
1	Fixed ΔT	Disbalanced
2	Fixed ΔT	Balanced
3	Variable ΔT	Disbalanced
4	Variable ΔT	Balanced

Table 3

The Multiple Unit System For Different
Logistic and Machine Distribution Policies⁽¹⁾

Parameters

N	8	8	8	8
K	100	100	100	100
α	0.6	0.6	0.6	0.6
$1/\lambda$	3	3	3	3
	0.4	0.6	0.8	1.0

OutputPolicy⁽²⁾

		ΔT ⁽³⁾	1	1	1	1
1	$\bar{R}$		0.3917	0.5687	0.7429	0.7854
	$S_{\bar{R}}$		0.0821	0.0811	0.0784	0.0784
2	$\bar{R}$		0.4251	0.5946	0.7142	0.7865
	$S_{\bar{R}}$		0.0975	0.0927	0.0857	0.0746
<hr/>						
	(4)		0.9	0.7	0.5	0.8
3	$\bar{R}$		0.4278	0.5873	0.5831	0.7754
	$S_{\bar{R}}$		0.0835	0.0863	0.0738	0.0953
4	$\bar{R}$		0.4039	0.4872	0.5638	0.7533
	$S_{\bar{R}}$		0.1005	0.0846	0.1024	0.0759
	$\Delta \bar{T}$ ⁽⁵⁾		0.278	0.872	1.024	0.473

- Results are given for 200 period T simulations.
<u>Policy Number</u>	<u>Logistic Policy</u>	<u>Machine Distribution Policy</u>
1	Fixed ΔT	Disbalanced
2	Fixed ΔT	Balanced
3	Variable ΔT	Disbalanced
4	Variable ΔT	Balanced
- The parameter ΔT is fixed as shown for policies 1 and 2.
- The parameter γ is applicable only for policies 3 and 4.
- The parameter $\Delta \bar{T}$ is calculated as the average of the observed ΔT 's for policies 3 and 4.

Table 3 (continued)

The Multiple Unit System For Different
Logistic and Machine Distribution Policies⁽¹⁾

Parameters

N	8	8	4	4	8	8	8	8
K	100	100	100	100	50	50	50	50
α	0.6	0.8	0.6	0.8	0.6	0.8	0.6	0.6
$1/\lambda$	3	3	3	3	3	3	3	3
β	0.4	0.4	0.4	0.6	0.8	0.8	0.4	0.6

OutputPolicy⁽²⁾

	ΔT	2	2	1	1	1	1	1	1
1	$\bar{R}$	0.4090	0.3401	0.4187	0.5068	0.7507	0.6267	0.4008	0.5613
	$S_{\bar{R}}$	0.0775	0.0812	0.1224	0.1344	0.0857	0.0820	0.0840	0.0801
2	$\bar{R}$	0.4404	0.3514	0.4119	0.4666	0.6925	0.5734	0.4064	0.5705
	$S_{\bar{R}}$	0.1007	0.0866	0.1452	0.1381	0.0871	0.0953	0.1063	0.0969
	γ	0.7	0.7	0.9	0.7	0.9	0.7	0.7	0.5
3	$\bar{R}$	0.4178	0.3639	0.4218	0.5000	0.4375	0.4095	0.4619	0.5037
	$S_{\bar{R}}$	0.0892	0.0728	0.1381	0.1832	0.0927	0.0900	0.1217	0.0800
4	$\bar{R}$	0.4213	0.3035	0.4035	0.4739	0.4111	0.3937	0.4017	0.4930
	$S_{\bar{R}}$	0.0953	0.0862	0.1011	0.1212	0.0725	0.0769	0.0839	0.0733
	$\Delta \bar{T}$	0.873	0.897	0.312	0.867	0.235	0.748	0.706	1.015

Table 3 Continued

13	14	15	16	17
8	4	4	4	4
50	50	50	50	50
0.6	0.6	0.6	0.8	0.8
3	3	3	3	3
0.8	0.4	0.4	0.6	0.8
1	1	2	1	1
0.7400	0.4286	0.4545	0.5054	0.5859
0.0797	0.1200	0.1237	0.1299	0.1251
0.7033	0.3952	0.4019	0.4148	0.5354
0.0874	0.1356	0.1329	0.1371	0.1265
0.7	0.5	0.3	0.7	0.7
0.6645	0.4050	0.3926	0.5038	0.4478
0.1531	0.1724	0.1615	0.1137	0.1015
0.7013	0.3724	0.3711	0.4958	0.4078
0.0957	0.1428	0.1097	0.1521	0.1318
0.832	1.009	1.327	0.795	0.832

Table 4A

The Multiple Unit System With Limited Machine Life
Policy One⁽¹⁾

(Policy 1 = fixed logistic period $\Delta T = 1$ with disbalanced machine distribution)

Parameters

N	8	8	8	8
K	100	100	100	100
α	0.6	0.6	0.6	0.6
β	0.4	0.6	0.8	1.0

Output

<u>Mix</u>	<u>Life</u>		<u>1</u>	<u>2</u>	<u>3</u>	<u>etc.</u>
Homogenous	3	$\bar{R}$	0.4975	0.7145	0.9292	0.9595
		S	0.0795	0.0646	0.0445	0.0355
		$\bar{R}$				
	4	$\bar{R}$	0.5237	0.7575	0.9150	0.9410
		S	0.0867	0.0812	0.0582	0.0517
		$\bar{R}$				
Uniform	3	$\bar{R}$	0.4912	0.7069	0.9271	0.9532
		S	0.0784	0.0637	0.0470	0.0419
		$\bar{R}$				
	4	$\bar{R}$	0.4695	0.6667	0.8627	0.9421
		S	0.0809	0.0669	0.0528	0.0451
		$\bar{R}$				

Results are given for only 200 period ΔT simulations. The 600 period ΔT simulation results are substantially the same.

Table 4A Continued

N	8	8	8	8	4	4	4	4	4
K	50	50	50	50	100	100	50	50	50
α	0.6	0.8	0.6	0.6	0.6	0.8	0.6	0.6	0.8
β	0.8	0.8	0.4	0.6	0.4	0.6	0.4	0.6	0.8
4 3 $\bar{R}$	0.9364	0.9588	0.9588	0.4957	0.5073	0.6540	0.5135	0.6678	0.8566
S $\bar{R}$	0.0465	0.0650	0.0760	0.0679	0.0987	0.0982	0.0974	0.1032	0.0919
4 $\bar{R}$	0.9212	0.8292	0.5133	0.7541	0.5363	0.6903	0.5322	0.6929	0.8298
S $\bar{R}$	0.0577	0.0795	0.0936	0.0831	0.1067	0.1092	0.1055	0.1033	0.1085
ν 3 $\bar{R}$	0.9179	0.8377	0.4842	0.7071	0.4973	0.6494	0.5045	0.6459	0.8355
S $\bar{R}$	0.0532	0.0708	0.0763	0.0599	0.0962	0.0976	0.1015	0.0943	0.0987
4 $\bar{R}$	0.8714	0.7824	0.4732	0.6718	0.4612	0.5971	0.4754	0.6048	0.7939
S $\bar{R}$	0.0710	0.0773	0.0888	0.0696	0.1037	0.0948	0.0947	0.0974	0.1039

Table 4B

The Multiple Unit System With Limited Machine Life
Policy Two⁽¹⁾

(Policy 2 = fixed logistic period $\Delta T = 1$ with balanced machine distribution, for various combinations of system parameters.

(Policy 1 = fixed logistic period $\Delta T = 1$ with disbalanced machine distribution)

Parameters

N	8	8	8	8
K	100	100	100	100
α	0.6	0.6	0.6	0.6
β	0.4	0.6	0.8	1.0

Output

<u>Mix</u>	<u>Life</u>		<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Homogenous	3	$\bar{R}$	0.6372	0.8119	0.9133	0.9503
		S	0.1086	0.0789	0.0577	0.0440
		$\bar{R}$				
	4	$\bar{R}$	0.6102	0.7990	0.8965	0.9387
		S	0.1175	0.0946	0.0707	0.0582
		$\bar{R}$				
Uniform	3	$\bar{R}$	0.6204	0.8105	0.9210	0.9565
		S	0.1207	0.0902	0.0562	0.0402
		$\bar{R}$				
	4	$\bar{R}$	0.6128	0.7420	0.8809	0.9438
		S	0.1742	0.1271	0.0695	0.0415
		$\bar{R}$				

(1) Results are given for only 200 periods ΔT . The 600 period ΔT simulation results are substantially the same.

There could also be reference to the results for the 200 and 600 period simulations for the non-truncated normal distribution.

Table 4B (continued)

N	8	8	8	8	4	4	4	4	4
K	50	50	50	50	100	100	50	50	50
α	0.6	0.8	0.6	0.6	0.6	0.8	0.6	0.8	0.8
β	0.8	0.8	0.4	0.6	0.4	0.6	0.4	0.6	0.8
H 3 $\bar{R}$	0.9031	0.7997	0.6204	0.7955	0.5967	0.6728	0.5830	0.6701	0.7613
S $\bar{R}$	0.0580	0.0764	0.1089	0.0871	0.1407	0.1355	0.1531	0.1322	0.1141
4 $\bar{R}$	0.8752	0.7727	0.5865	0.7717	0.5875	0.6488	0.5699	0.5993	0.7430
S $\bar{R}$	0.0744	0.0971	0.1205	0.1091	0.1500	0.1365	0.1413	0.1477	0.1266
ν 3 $\bar{R}$	0.9016	0.7968	0.5989	0.8066	0.6318	0.7036	0.5636	0.6593	0.7667
S $\bar{R}$	0.0611	0.0846	0.1119	0.0823	0.1566	0.1290	0.1602	0.1302	0.1183
4 $\bar{R}$	0.8695	0.7615	0.5854	0.7355	0.5878	0.6171	0.5840	0.6034	0.7194
S $\bar{R}$	0.0707	0.0898	0.1598	0.1239	0.1886	0.1550	0.1844	0.1754	0.1303

Table 4C

The Multiple Unit System With Limited Machine Life
Policy Three⁽¹⁾

(Policy 3 = variable logistic period $\Delta T = 1$ with disbalanced machine distribution)

Parameters

N	8	8	8	8
K	100	100	100	100
α	0.6	0.6	0.6	0.6
β	0.4	0.6	0.8	1.0

Output

<u>Mix</u>	<u>Life</u>	<u>1</u>	
Homogenous	3	$\bar{R}$	0.6577
		S	0.1223
		$\bar{R}$	
	4	$\bar{R}$	0.6557
		S	0.1223
		$\bar{R}$	
Uniform	3	$\bar{R}$	0.7148
		S	0.1139
		$\bar{R}$	
	4	$\bar{R}$	0.7725
		S	0.0953
		$\bar{R}$	

This is the layout for this table. See the attached 2 pages for the raw data that will be inserted in the table.

Results are given for only 200 periods ΔT . The 600 periods ΔT simulation results are substantially the same.

There could also be reference to the results for the 200 and 600 period simulations for the non-truncated normal distribution.

Table 4C

Unit	1 8	2 8	3 8	4 8	5 8	6 8	7 8	8 8	9 8
Mach	100	100	100	100	100	100	100	100	100
α	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
β	0.4	0.4	0.4	0.4	0.6	0.6	0.6	0.8	0.8
Inv8	0.9	-0.7	-0.5	-0.3	0.9	-0.7	-0.5	0.9	-0.7
Mean	0.6577	0.6326	0.6468	0.6635	0.8361	0.8175	0.8252	0.9189	0.8893
s.d.	0.1223	0.1072	0.0921	0.0895	0.0834	0.0731	0.0774	0.0573	0.0491
Mean	0.6577	0.6332	0.6338	0.6450	0.8211	0.8242	0.8321	0.9251	0.9174
s.d.	0.1223	0.1072	0.0944	0.0915	0.0873	0.0734	0.0687	0.0561	0.0567
Mean	0.7148	0.6394	0.6343	0.6418	0.8623	0.8144	0.8090	0.9366	0.9059
s.d.	0.1139	0.1215	0.1056	0.1000	0.0751	0.0908	0.0803	0.0461	0.0603
Mean	0.7725	0.6877	0.6032	0.6029	0.8766	0.7884	0.7562	0.9344	0.8713
s.d.	0.0953	0.1328	0.1635	0.1243	0.0704	0.1250	0.1222	0.0487	0.0774

Unit	11 8	12 8	13 8	14 8	15 8	16 8	17 8	18 8	19 8
Mach	100	50	50	50	50	50	50	50	50
α	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.6	0.6
β	1.0	0.8	0.8	0.8	0.8	0.8	0.8	0.4	0.6
Inv8	0.7	0.0	-0.7	-0.5	0.9	-0.7	-0.5	0.4	0.6
	0.9580	0.9218	0.9186	0.9155	0.8068	0.8148	0.8297	0.6264	0.8072
	0.0403	0.0517	0.0549	0.0503	0.0888	0.0744	0.0684	0.1010	0.0801
	0.9607	0.9206	0.9123	0.9195	0.8076	0.8123	0.8187	0.6341	0.8104
	0.0384	0.0579	0.0569	0.0514	0.0829	0.0818	0.0759	0.1045	0.0779
	0.9557	0.9304	0.9125	0.9108	0.8305	0.7919	0.8078	0.6126	0.8043
	0.0402	0.0487	0.0548	0.0525	0.0694	0.0877	0.0731	0.1060	0.0881
	0.9408	0.9186	0.8628	0.8695	0.8196	0.7535	0.7639	0.5819	0.7354
	0.0434	0.0522	0.0842	0.0631	0.0795	0.1119	0.0834	0.1455	0.1382
Unit	21 4	22 4	23 4	24 4	25 4	26 4	27 4	28 4	29 4
Mach	100	100	100	100	100	100	50	50	50
α	0.6	0.6	0.6	0.6	0.8	0.8	0.6	0.6	0.8
β	0.4	0.4	0.4	0.4	0.6	0.6	0.4	0.4	0.6
Inv8	0.9	-0.7	-0.5	-0.3	0.7	0.5	0.9	0.7	0.6
	0.6328	0.6369	0.6249	0.6352	0.6685	0.7013	0.6093	0.5934	0.6668
	0.1595	0.1492	0.1337	0.1301	0.1243	0.1275	0.1390	0.1465	0.1305
	0.6072	0.6089	0.6395	0.6368	0.6865	0.6967	0.6392	0.6127	0.6587
	0.1694	0.1428	0.1233	0.1366	0.1189	0.1273	0.1642	0.1507	0.1252
	0.6898	0.6416	0.6225	0.6287	0.6677	0.6683	0.6899	0.6125	0.6471
	0.1458	0.1592	0.1470	0.1346	0.1370	0.1326	0.1520	0.1633	0.1598
	0.7717	0.6817	0.5718	0.5906	0.6579	0.6209	0.7136	0.6426	0.5973
	0.1251	0.1510	0.1825	0.1644	0.1647	0.1516	0.1545	0.1495	0.1569

Table 4D

The Multiple Unit System With Limited Machine Life
Policy Four⁽¹⁾

(Policy 4 = variable logistic period $\Delta T = 1$ with balanced machine distributi

Parameters

N	8
K	100
α	0.6
β	0.4
γ	0.9

Output

	<u>Mix</u>	<u>Life</u>	
Homogeneous	3	$\bar{R}$	0.7831
		$S_{\bar{R}}$	0.1416
	4	$\bar{R}$	0.7632
		$S_{\bar{R}}$	0.1038
Uniform	3	$\bar{R}$	0.6962
		$S_{\bar{R}}$	0.1389
	4	$\bar{R}$	0.5132
		$S_{\bar{R}}$	0.0740

This is the layout for this table. See the attached 2 pages for the raw data that will be inserted in the table.

Results are given for only 200 period ΔT simulations. The 600 period ΔT simulation results are substantially the same.

There could also be reference to the result for the 200 and 600 period simulations for the non-truncated normal distribution.

Table 4D

Unit	8	8	8	8	8	8	8	8	8
Mach	100	100	100	100	100	100	100	100	100
α	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
β	0.4	0.4	0.4	0.4	0.6	0.6	0.6	0.8	0.8
Inv8	0.9	0.7	0.5	0.3	0.9	0.7	0.5	0.9	0.7
	0.7831	0.5887	0.5383	0.5012	0.8392	0.7108	0.6945	0.9177	0.8662
	0.1416	0.1755	0.1603	0.1363	0.1131	0.1224	0.0994	0.0601	0.0691
	0.7632	0.5727	0.5783	0.4988	0.8273	0.7078	0.6837	0.8798	0.8279
	0.1038	0.1634	0.1074	0.1362	0.1321	0.1315	0.0927	0.0803	0.0594
	0.6962	0.5904	0.5120	0.5392	0.7658	0.6904	0.6322	0.9056	0.8526
	0.1389	0.0822	0.0766	0.0699	0.0921	0.0649	0.0546	0.0595	0.0508
	0.5132	0.4803	0.4550	0.4528	0.6829	0.6239	0.6196	0.8234	0.7650
	0.0740	0.0853	0.0921	0.1516	0.0648	0.0713	0.1109	0.0538	0.0772
Unit	8	8	8	8	8	8	8	8	8
Mach	50	50	50	50	50	50	50	50	50
α	0.6	0.6	0.6	0.8	0.8	0.8	0.6	0.6	0.6
β	0.8	0.8	0.8	0.8	0.8	0.8	0.4	0.6	0.8
Inv8	0.9	0.7	0.5	0.9	0.7	0.5	0.4	0.6	0.8
	0.9596	0.8913	0.8544	0.9193	0.8398	0.8074	0.5263	0.7116	0.8780
	0.0367	0.0542	0.0565	0.0579	0.0722	0.0645	0.1325	0.0978	0.0621
	0.9236	0.8713	0.8349	0.9078	0.8025	0.7839	0.5063	0.6839	0.8527
	0.0335	0.0524	0.0385	0.0537	0.0732	0.0628	0.1327	0.0837	0.0529
	0.9046	0.8406	0.7379	0.9376	0.8217	0.8435	0.5181	0.7095	0.8669
	0.0648	0.0528	0.0464	0.0710	0.0661	0.0725	0.0735	0.0650	0.0557
	0.8977	0.8241	0.7592	0.7980	0.7484	0.7106	0.5009	0.6627	0.8002
	0.0576	0.0568	0.0730	0.0742	0.0759	0.0818	0.0752	0.0709	0.0690

Unit	4	4	4	4	4	4	4	4
Mach	100	100	100	100	50	50	50	50
α	0.6	0.6	0.8	0.8	0.6	0.6	0.8	0.8
β	0.4	0.4	0.6	0.6	0.4	0.4	0.6	0.8
Inv8	0.5	0.3	0.7	0.5	0.9	0.7	0.6	0.8
	0.5495	0.5266	0.6870	0.6461	0.7818	0.6090	0.6355	0.9154
	0.1478	0.1418	0.1197	0.1276	0.1692	0.1740	0.1237	0.074
	0.5231	0.5079	0.6638	0.6319	0.7521	0.5635	0.6255	0.8
	0.1438	0.1131	0.1079	0.1078	0.1728	0.1650	0.1312	0.08
	0.5231	0.5093	0.6929	0.6666	0.5160	0.5035	0.6581	0.816
	0.1031	0.0914	0.0935	0.1013	0.1264	0.1065	0.0928	0.093
	0.4704	0.5213	0.6185	0.6170	0.5174	0.4711	0.6187	0.7
	0.0844	0.1005	0.1073	0.1074	0.1470	0.1049	0.1067	0.10

Figure 1

A Schematic Description of the System

<hr/> 1. System Capacity (Number and distribution of operational units and machines) N K <hr/>	
<hr/> 2. Machine Replacement Policies (Machine lifetime and age distribution) L D <hr/>	<hr/> 7. Machine Distribution Policies (Distribution of repaired machines) Disbalanced Balanced γ <hr/>
<hr/> 3. Logistic Policies (Fixed or variable transportation intervals) ΔT <hr/>	<hr/> 6. Repair Shop Characteristics (Capacity) Unlimited Limited β <hr/>
<hr/> 4. System Demand Characteristics (Stochastic distribution) Demand Intensity α <hr/>	<hr/> 5. Machine Breakdown Characteristics (Stochastic distribution) Hazard Rate $1/\lambda$ <hr/>

GLOSSARY

N number of operational units (=1,4,8)
K number of machines per operational unit (=50,100,200)
L machine lifetime (unlimited; limited=3 years, 4 years)
D age distribution of machines (homogeneous; uniform)
 ΔT transportation interval (=1,2 weeks)
 γ fraction of operating machines (=0.3, 0.5, 0.7, 0.9)
 α demand parameter (=0.6, 0.8)
 $1/\lambda$ breakdown parameter (homogeneous=3, 4 weeks;
uniform=1,2,3,4 weeks)
 β repair shop capacity (=0.4, 0.6, 0.8, 1)

FIGURE 2: SINGLE UNIT SYSTEM

$N=1$, $K=50$, $DT=1$, $1/L=4$, $A=0.6$

FIGURE 3: SINGLE UNIT SYSTEM

$N=1$, $K=200$, $DT=2$, $1/L=3$, $A=0.8$

FIGURE 4: SINGLE UNIT SYSTEM

$N=1$, $K=50$, $DT=2$, $1/L=3$, $A=0.6$

FIGURE 5: SINGLE UNIT SYSTEM

$N=1, K=100, DT=2, 1/L=3, A=0.6$

FIGURE 6: SINGLE UNIT SYSTEM

$N=1$, $K=200$, $DT=2$, $1/L=3$, $A=0.6$

FIGURE 7: SINGLE UNIT SYSTEM

$N=1$, $K=50$, $DT=1$, $1/L=4$, $A=0.8$

FIGURE 8: SINGLE UNIT SYSTEM

$N=1$, $K=100$, $DT=1$, $1/L=4$, $A=0.8$

FIGURE 9: SINGLE UNIT SYSTEM

$N=1$, $K=200$, $DT=1$, $1/L=4$, $A=0.8$

FIGURE 10: MULTIPLE UNIT SYSTEM.

$N=8$, $K=100$, $DT=1$, $1/L=3$, $A=0.6$, $B=0.4$

FIGURE 11: MULTIPLE UNIT SYSTEM

$N=8$, $K=100$, $DT=1$, $1/L=3$, $A=0.6$, $B=0.6$

FIGURE 12: MULTIPLE UNIT SYSTEM

$N=8$, $K=100$, $DT=1$, $1/L=3$, $A=0.6$, $B=0.8$

FIGURE 13: MULTIPLE UNIT SYSTEM.

$N=8$, $K=100$, $DT=1$, $1/L=3$, $A=0.6$, $B=1.0$

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